Designing a Systems Engineering Educational Program Using Academic/Industry Collaboration

Mark A. Turnquist
Cornell University
School of Civil and Environmental Engineering
Ithaca, NY 14853

Raffaelo D'Andrea
Cornell University
Sibley School of Mechanical and Aerospace Engineering
Ithaca, NY 14853

Albert R. George
Cornell University
Sibley School of Mechanical and Aerospace Engineering
Ithaca, NY 14853

Peter Jackson
Cornell University
School of Operations Research and Industrial Engineering
Ithaca, NY 14853

Linda K. Nozick
Cornell University
School of Civil and Environmental Engineering
Ithaca, NY 14853

Donna Rhodes
Lockheed Martin Federal Systems
Owego, NY 13827

Robin Roundy
Cornell University
School of Operations Research and Industrial Engineering
Ithaca, NY 14853

Bart Selman
Cornell University
Department of Computer Science
Ithaca, NY 14853

Christine A. Shoemaker
Cornell University
School of Civil and Environmental Engineering
Ithaca, NY 14853

Robert J. Thomas
Cornell University
School of Electrical Engineering
Ithaca, NY 14853

Abstract. In concert with a fundamental precept in systems engineering, that system design should be driven by customer requirements, Cornell University is collaborating with industry in the development of a Master of Engineering program in Systems Engineering. This paper describes the underlying philosophy of Cornell's program, the collaborative process through which it has been developed, and the resulting curriculum, with a particular focus on the interaction between Cornell and Lockheed Martin Federal Systems (LMFS).

INTRODUCTION

A basic tenet of systems engineering is that system design should be driven by customer requirements. An educational program is certainly a system, and in creating the Master's program in Systems Engineering at Cornell University, there has been an active process of engaging some of the major customers of the program – companies that need access to such a program for their current engineers and who will also hire other graduates of the program – to define the requirements and help focus the program direction.

This paper describes the process that has been followed to define Cornell's program, with a particular focus on the interaction between Cornell and Lockheed Martin Federal Systems (LMFS). Cornell has brought to this collaboration an underlying educational philosophy for Master's degree education. The industrial partners, including LMFS, have provided the applications focus for that philosphy. Together, we are forging an innovative educational solution. We believe that publicizing this process can provide useful information for other universities and companies that are seeing the need for systems engineering education, and trying to create effective solutions to that need.

PROGRAM DEFINITION

The Need. Many of the most important problems being faced by our society are systems problems. Technological change drives shorter system life cycles as well as the need for more effective development of manufactured products, services, military systems, software systems, etc. At the same time, we are increasingly concerned about our environment as well as the basic infrastructure systems of our society that provide among other things, electricity, water, gas, telephone and communication services.

Our advancing society demands systems of increasing complexity. These systems are often designed to perform complicated functions with minimal and/or simple inputs from the person(s) using them. For example, we expect the cellular phone system to "find us" when someone calls our number, regardless of what cell we happen to be in. As another example, automated automotive suspension systems "tune" themselves to changes in road surface as we drive, with only a twist of a single knob from the driver to indicate whether a "sport" or "touring" ride quality is desired. To meet customer expectations for reliable performance of complex systems, a wide variety of complicated elements have to work together correctly.

Educating engineers to deal with systems engineering problems is a critical need, as is the development of new systems engineering methods and tools. These needs can be addressed through both teaching and research at a major research university like Cornell.

Functional Requirements. Our most basic functional requirement is to educate "T-shaped" engineers – that is, engineers who have both depth in an engineering discipline (the vertical part of the "T"), and the breadth to see across disciplinary boundaries and be able to fit the pieces of a system together (the horizontal part of the "T"). The Master of Engineering program at Cornell, as a professionally-oriented degree, is an ideal venue to increase both the depth and breadth of an engineering education, and to develop graduates who are well-adapted to take on systems engineering challenges in subsequent jobs. One of the unique aspects of Cornell's M.Eng. program is the project experience that is required, and the projects offer an exceptional opportunity to build teamwork and systems engineering skills in our graduates.

The strong multi-department support that has characterized the systems engineering development effort at Cornell provides a means through which we can improve on the single-department focus of several other universities (e.g., systems efforts within departments of industrial engineering at several universities, within departments of electrical engineering at others, or in the creation of separate systems engineering departments). We believe that systems engineering should be an explicit cross-disciplinary program, "matrixed" (in an organizational sense) with existing engineering departments, rather than either being contained within one of those departments, or defined as its own departmental "silo."

The status of systems engineering as a cross-disciplinary program in the College of Engineering creates the opportunity for core courses to be co-taught by faculty from different engineering departments, leading to important cross-fertilization of ideas among the faculty as well as the students. It also emphasizes the breadth of application of the central ideas of systems engineering, and creates an incentive for the program to be continually in touch with advances in the various disciplinary fields as well as with advances in systems engineering methods and techniques.

Conceptual Design. Our educational philosophy embraces both contextual learning (learning in context) and teamwork. It is our conjecture that students learn systems engineering best by induction, reasoning from the specific to the general. Systems engineering concepts in the abstract are of little value unless the student can relate the concepts to practical experience. Consequently, we place a heavy emphasis on contextual learning by motivating the abstractions with case studies, illustrating the methodologies with application, and integrating the learning through structured projects.

For example, a team project in the first core course in the program (Applied Systems Engineering I) requires a team of four students who have different disciplinary engineering backgrounds to create a proposal for a hybrid (solar-gasoline) powered cruising boat for a charter service on New York's State Canal System (what was once the original Erie Canal). This project requires an integrated conceptual design of subsystems for solar energy collection, on-board electric power storage, shore-based recharging, and a gasoline-powered engine for back-up and peak power use, as well as shore facilities and tour packages that make economic sense as a business enterprise. The team as a whole must understand the requirements for the complete system, how those requirements are derived, and how the work that each individual does on one or another of the subsystems fits into the overall picture.

This type of project activity emphasizes our view that in the professional world into which our students will graduate, work is organized around teams of specialists with diverse skills. Hence, we make teamwork an intrinsic part of the curriculum and challenge the students to excel at communication and coordination.

A master's level program in systems engineering should be available to both on-campus and off-campus students. Our program design involves integrating on-campus and off-campus activities and studies, and therefore involves both substantial "distance learning" components and on-campus "laboratory" exercises for off-campus students.

IMPORTANCE OF INDUSTRY/UNIVERSITY COLLABORATION

Collaboration between industry and universities has become increasingly important to achieve common goals:

1. Further the development of systems engineering;
2. Grow tomorrow's engineering workforce;
3. Combine resources to achieve advanced research objectives; and
4. Ensure educational experience is aligned with future engineering challenges.

In the past, many companies felt they could afford to satisfy educational needs for their engineering staff by creating and conducting comprehensive internal education programs. However, streamlined organizations, attention to affordability, and the complexity of education required by today's engineering professionals are driving companies to abandon the goal of providing most or all of the continuing engineering education from within. While consultants and commercial education providers can fill some of the training needs, universities are best suited to providing a full educational experience and the means to ensure young engineers expand their base knowledge by obtaining advanced degrees.

From the other side, universities are finding collaboration to be critical to ensuring their programs are relevant to the needs of students from industry. As universities better understand the needs of industry, they can provide students with improved educational offerings that employers are seeking. Industry can also provide universities with access to case studies, funding for mutually beneficial research projects, and industry internship experiences for both faculty and students.

IMPLEMENTING THE COLLABORATIVE PROCESS

The relationship between Cornell University and LMFS-Owego is an excellent example of successful collaboration in the formation and growth of a systems engineering program. This relationship has evolved from initial contact to a more formal relationship:

- Initial Meeting. In the early stages of developing a systems engineering specialization in its M.Eng. program, Cornell initiated an information exchange with LMFS-Owego. The initial meeting involved presentations from each side: Cornell presented the approach and strategy for the systems engineering initiative within the College of Engineering. LMFS-Owego shared its engineering educational needs and current educational programs. In this stage, LMFS-Owego was able to convey key needs to Cornell.
- Industry Exchange Meeting. The initial meeting grew to a multi-participant exchange meeting with several other companies involved. Industry participants were presented with the details of the Cornell strategy and curriculum plans, and were briefed on student projects. Following these sessions, industry representatives met in a facilitated session to develop industry comments on the program. At this point in time, LMFS-Owego was able to influence the program in early stages to better meet its future needs.
- Industry Advisory Meeting. Following this meeting, Cornell created a more formal Industry Advisory Board. Industry comments from the previous meeting were used to improve upon the initial program design. For example, industry recommended Cornell do some "benchmarking" against similar programs in other universities, which resulted in findings that were of considerable interest to both the university and involved industry participants. LMFS-Owego benefited from discussions with Cornell and other companies on various topics – for example, discussions on common educational needs, key skills needed by systems engineers, and the need for case studies as part of the educational experience. These meetings are continuing with an expanding participant base. LMFS-Owego is a contributor to the formation of Cornell's systems engineering program, and is a beneficiary of the results this program yields. The opportunity to dialogue with industry peers in a non-competitive situation is also extremely beneficial.

LMFS is also gaining secondary benefits from its collaboration with Cornell. By assisting Cornell in the development of case studies, LMFS is forced to take a more introspective look at itself, and thereby captures lessons learned and best practices in a manner that provides benefit to future programs. Collaboration also permits preferred access to top-notch students through involvement related to internships and sponsored research.

Table 1 summarizes the exchange involved in the university/industry collaboration.

CURRICULUM ELEMENTS

The systems engineering curriculum that has resulted from the interactions between Cornell and its industrial partners focuses particular attention on eight major elements:

- Requirements analysis
- Functional, behavioral and structural analysis
- Simulation, optimization and multicriteria decision making
- Risk assessment and management
- Life cycle analysis
- Teamwork and project management
- Information flow in systems
- Feedback control.

These elements are closely related to the set of

	Industry Provides to University	***University Provides to Industry***
Educated Workforce	• Present/future skill needs for engineers • Internship opportunities	• Delivery of degree programs and continuing education courses • Internship candidates
Applicatio n	• Case study information	• Formalized case studies embedded in courses
Research	• Research funding/priorities	• Conduct of research projects and resulting innovations
Formal exchange	• Participation in the university sponsored Industry Advisory Board	• Opportunity to influence curriculum • Opportunity to learn about peer company education needs/plans

"core" subject matter for systems engineering identified by INCOSE (Panitz, 1997), but include additional emphasis on modeling (especially optimization models), information flows in systems, and feedback control, reflecting particular expertise and experience among the Cornell faculty.

The approach we are taking to functional, behavioral and structural analysis emphasizes connections between traditional tools (functional flow block diagrams and N^2 diagrams, for example) and the object-oriented perspective that is widely favored in software engineering (Oliver, *et al*., 1997). Making these connections is important for students who will become system engineers and who will need to communicate effectively with both hardware engineers and software engineers.

We place particular emphasis on optimization and multicriteria decision making because decisions on tradeoffs in system design are at the heart of effective system engineering. The underlying goal is nearly always to make the "best" decisions (hence the focus on optimization), and there are nearly always multiple, often conflicting, criteria that must be included in the decision. Emphasis on these topics provides the students with the ability to structure decision-making problems they will face, as well as specific tools to help resolve some of those problems.

The first five of the eight elements listed above are emphasized across a two-term course sequence in Applied Systems Engineering. These two courses are team-taught, and include faculty from all five of the major participating departments (civil & environmental engineering, electrical engineering, mechanical & aerospace engineering, operations research & industrial engineering, and computer science).

Our approach to teaching teamwork and project management skills uses a team-taught course with one faculty member who is an engineer and another who is a sociologist. This has yielded a project management course that places equal emphasis on the "technical" skills of project management (planning, scheduling, budgeting, etc.) and the "people" skills (team-building, motivation, conflict resolution, etc.). The result is an innovative and comprehensive view of project management that serves students very well.

Finally, our emphasis on feedback control and information flows in systems reflects the growing sophistication of manufactured products and services in the commercial sector, as well as defense-related systems. Almost all types of systems are using greater software-hardware integration, and a growing proportion of total system cost is devoted to automated sensing, information management within the system, as well as automated control of system functions. These topics are addressed through a variety of elective courses.

THE ROLE OF PROJECT EXPERIENCES

Systems engineering is a set of skills that must be learned by practicing, using case studies and project experiences as an integral part of the educational program. The Master of Engineering degree at Cornell has a requirement for a substantial project experience, and this project experience is vital for students in systems engineering. There are several team project activities each year, but one example can serve to illustrate the important integrative role that these projects play.

In the 1998-99 academic year, a Cornell team first entered the International RoboCup Competition, where teams of robots play soccer against one another. The competition has basic rules about allowable size of robots, for example, and rules of play (e.g., robots cannot "shelter" the ball). However, the rules leave wide latitude for creative design of both the robots themselves and the larger system (including global vision of the field and strategy controllers, for example) that makes up the complete team effort for effective competition.

A total of 24 students participated in this effort, in two teams of 12. Each student team designed and built a team of robots, to compete against each other, but the two teams collaborated in design of the global vision system, in anticipation of forming an effective Cornell entry in the international competition. The teams went through a careful systems engineering effort during the fall semester of 1998, doing requirements analysis, functional and behavioral analysis, simulation to test out different conceptual designs, etc. Actual construction of the robots began in February, 1999. By early May, competitive intramural games were played between the two teams, and decisions were made on final modifications prior to the international competition in Stockholm, Sweden, in late July.

The careful systems approach used by the Cornell team paid dramatic dividends, when in their first year of entering the competition the Cornell team emerged as the World Champion, defeating teams from South Korea, Singapore, New Zealand, Portugal, and Germany en route to the championship. This kind of project experience allows the students to "live" the process of systems engineering, putting the otherwise abstract tools into practice, and seeing the effects in a direct and dramatic way.

There are also other projects that are directly sponsored by industrial partners that allow students to engage in activities that have a direct and meaningful impact on real operations in those companies. These projects take on a different "flavor" than the RoboCup project, for example, and they are also important models for systems engineering project activities.

SUMMARY AND CONCLUSIONS

We have described the effort by Cornell University and several industrial partners to jointly develop a systems engineering educational program that contains several innovative and effective features. We have focused particularly on the interaction between Cornell and Lockheed Martin Federal Systems (LMFS). Cornell has brought to this collaboration an underlying educational philosophy for Master's degree education. The industrial partners, including LMFS, have provided the applications focus for that philosphy. Together, we are forging an innovative educational solution.

The curriculum that has resulted from this collaborative process contains the elements identified by INCOSE as the "core" material for systems engineering programs, as well as additional emphasis on material that reflects particular expertise among the Cornell faculty. One of the hallmarks of the program is a strong concentration on project activities as being central to systems engineering education.

We believe that publicizing this collaborative process and its outcome can provide useful information for other universities and companies that are seeing the need for systems engineering education, and trying to create effective solutions to that need.

REFERENCES

Panitz, Beth, "Training Technology's Maestros," *ASEE Prism*, November 1997, pp. 18-24.

Oliver, D.W., T.P. Kelliher and J.G. Keegan, Jr., *Engineering Complex Systems with Models and Objects*. McGraw-Hill, New York, 1997.

BIOGRAPHIES

Dr. Mark Turnquist is a professor of Civil and Environmental Engineering at Cornell University. His research interests are in large-scale network optimization for logistics, transportation and production systems. He received his B.S. from Michigan State University in 1971, and S.M. and Ph.D. degrees from MIT in 1972 and 1975, respectively.

Dr. Raffaelo D'Andrea is an Assistant Professor in the Sibley School of Mechanical and Aerospace Engineering at Cornell University. His research interests are in theoretical, computational, and experimental issues associated with the control of mechanical and aerospace systems. He received his B.Sc. From the University of Toronto in 1991 and his M.S. and Ph.D. from the California Institute of Technology in 1992 and 1997, respectively.

Dr. Albert George is the J.F. Carr Professor of Mechanical and Aerospace Engineeering at Cornell University. His research interests are the aerodynamics of aircraft and ground vehicles. Aeroacoustic noise mechanisms and the aerodynamic performance and design of aircraft, automobiles and fans are particularly emphasized. Other interests involve manufacturing systems. Dr. George received his B.S. and Ph.D. degrees from Princeton in 1959 and 1964, respectively.

Dr. Peter Jackson is an Associate Professor of Operations Research and Industrial Engineering at Cornell University. His research interests are in material logistics in manufacturing systems. He is also an expert in the development of experiential games for education. His games are in active use at several corporations for training as well as in current courses taught at Cornell. He receievd his B.A. from Western Ontario University in 1975 and his M.S. and Ph.D. from Stanford in 1980.

Dr. Linda Nozick is an Associate Professor of Civil and Environmental Engineering at Cornell University. Her research interests are in the development and effective use of mathemeatical models to design and operate systems. Particular systems of interest are manufacturing, transportation and health care systems. She received her B.S. from George Washington University in 1989 and her M.S. and Ph.D. from the University of Pennsylvania in 1990 and 1992, respectively.

Dr. Donna Rhodes is Senior Manager of Systems Engineering Technology at Lockheed Martin Federal Systems in Owego, New York. She consults with numerous projects on systems engineering practices, technologies, and methods, and oversees the engineering excellence program. She is President of the International Council on Systems Engineering (INCOSE) and is an Associate Editor of the INCOSE journal, *Systems Engineering*. Dr. Rhodes has had an active role in evolving the practice of systems engineering over the past decade through corporate and inductry involvement. She has authored over 30 technical papers, and co-authored many corporate and industry standards and guidebooks on Systems Engineering. Dr. Rhodes received her M.S. and Ph.D. in Advanced Technology/Systems Science from Binghamtom University.

Dr. Robin Roundy is an Associate Professor in Operations Research and Industrial Engineering at Cornell University. His research interests are in the development of algorithms for decision-making in supply chains, manufacturing and distribution systems. His current research efforts are focused on capacity planning in the semiconductor industry and on issues of supplier integration. He received his B.A. and M.A. from Brigham Young University in 1978 and 1980 respectively. He received his Ph.D. from Stanford in 1984.

Dr. Bart Selman is an Associate Professor of Computer Science at Cornell University. His research interests are in artificial intelligence and computer science including tractable inference, knowledge representation, search, constraint satisfaction, planning, scheduling, default reasoning, and natural language understanding. He has a M.Sc. and a Ph.D. in Computer Science from the University of Toronto and a M.Sc. in Physics from Delft University.

Dr. Christine Shoemaker is a Professor of Civil and Environmental Engineering at Cornell University. Her research interests are in the development of numerically efficient optimization algorithms for large-scale problems and the application of optimization and modeling procedures to problems arising in environmental management. A major empahsis in her current research is on groundwater contamination and remediation. She received her B.S. from the University of California at Davis in 1966 and her M.S. and Ph.D. degrees from the University of Southern California in 1969 and 1971, respectively.

Dr. Robert Thomas is a Professor of Electrical Engineering at Cornell University. His research interests are in the area of analysis and control of nonlinear continuous and discrete-time systems with applications to large-scale electric utility systems and electromechanical-drive systems. He received his B.S.E.E., M.S.E.E. and Ph.D. degrees from Wayne State University in 1968, 1969, and 1973, respectively.