ENES 489P Hands-On Systems Engineering Projects

Introduction to Systems Engineering

Mark Austin
E-mail: austin@isr.umd.edu

Institute for Systems Research, University of Maryland, College Park
SYSTEMS ENGINEER: “BEST JOB IN AMERICA”

Money Magazine

Best Jobs in America by Donna Rosato with Beth Braverman and Alexis Jeffries. Oct. 9, 2009
Source: MoneyOnCNNMoney.com

“Money and PayScale.com, a leading online provider of employee-compensation data, surveyed 35,000 people online about what makes a great job, they rated intellectual challenge, a passion for the work, and flexibility just as highly as security.

1. Systems Engineer
   - Median salary (experienced): $87,100
   - Top pay: $130,000
   - Job growth (10-year forecast): 45%
   - Sector: Information Technology

What they do: They’re the “big think” managers on large, complex projects, from major transportation networks to military defense programs. They figure out the technical specifications required and coordinate the efforts of lower-level engineers working on specific aspects of the project.

Why it’s great: Demand is soaring for systems engineers, as what was once a niche job in the aerospace and defense industries becomes commonplace among a diverse and expanding universe of employers, from medical device makers to corporations like Xerox and BMW. Pay can easily hit six figures for top performers, and there’s ample opportunity for advancement. But many systems engineers say they most enjoy the creative aspects of the job and seeing projects come to life. "The transit system I work on really makes a tangible difference to people," says Anne O’Neil, chief systems engineer for the New York City Transit Authority.

Drawbacks: Long hours are common; project deadlines can be fierce.

Pre-reqs: An undergrad engineering degree; some jobs might also require certification as a certified systems engineering professional (CSEP).

Systems engineering is a discipline that lies at the cross-roads of engineering and business concerns.

Specific goals are to provide:

1. A balanced and disciplined approach to the **total integration** of the system building blocks with the surrounding environment.

2. A methodology for systems development that focussed on **objectives**, **measurement**, and **accomplishment**.

3. A systematic means to acquire information, and sort out and identify areas for **trade-offs** in cost, performance, quality etc....
Typical concerns on the design side:

1. What is the required functionality?
2. How well should the system perform?
3. What about cost/economics?
4. How will functionality/performance be verified and validated?

Typical concerns on the management side:

1. What processes need to be in place to manage the development?
2. What kind of support for requirements management will be needed?

Learning how to deal with these concerns in a systematic way is a challenging proposition driven, in part, by a constant desire to improve system performance and extend system functionality.
Focus on:

...liaison among disciplines, supported by formal methods for systems analysis and design.
Systems are developed by teams of engineers – the team members must be able to understand one-another’s work.
Several important developments that have rendered systems engineering methodologies, tools, and educational programs critical. They are:

1. Increase demand for limited resources;
2. Rapid changes in technology;
3. Fast time-to-market most critical;
4. Increasing higher performance requirements;
5. Increasing complexity of systems/products;
6. Increasing pressure to lower costs;
7. Increased presence of embedded information and automation systems that must work correctly;
8. Failures due to lack of systems engineering.
Increasing Demand for Limited Resources

Trends in World Population Growth

![World population growth graph]

Fertility rates are declining, the United Nations says, but not fast enough to stop population growth. The U.N.'s medium-level projection is for the world's population to reach 9.2 billion by 2050 but still more than 3 billion higher since the turn of the century. Population activists say that's too much for the world to handle.

Sources: United Nations; Sustainable Scale Project; World Resources Institute; NationMaster.com

* Projection
We now have the ability to measure, sense, and see the exact condition of almost everything (IBM, 2009):

   By the end of 2010 there will be 1 billion transistors per human and 30 billion RFID (radio frequency id) tags;

   Due to transformational advances in (wireless) communications technology, people, systems and objects can communicate and interact with each other in entirely new ways. Consider:
   We are heading toward one trillion connected objects (Internet of Things).

   More intelligent behavior means an ability to respond to changes quickly, accurately and securely, predicting and optimizing for future events.
Observation: Humans perceive change as being a linear phenomena, but mathematics tells us that rates of change are constant and actual change is exponential ...
Information-Age Systems

Developed under the premise that advances in

- Computing,
- Sensing, and
- Communications

technologies will allow for

... new types of systems where human involvement is replaced by automation.

and where critical constraint values in the design space are relaxed, e.g.,

- Autofocus camera,
- Driverless automobiles.
Pathway from sensing and data collection to ... action ... improved performance

Chain of dependency relationships:

1. improved performance \(\leftarrow\) actions
2. actions \(\leftarrow\) good decision making
3. good decision making \(\leftarrow\) ability to identify events
4. identify events \(\leftarrow\) data processing
5. data processing \(\leftarrow\) types and quality of data
6. data types and quality \(\leftarrow\) sensor design and placement.
Case Study A: Sensing in Aerospace Systems

During the past three decades aerospace systems have seen...

... increased use of electrical systems to achieve functionality.

Example. F-16 and F-35 Military Jets

Summary: F-16 System (1970s):

- 15 subsystems; $O(10^3)$ interfaces.
- Less than 40% of the functions managed by software.

Summary: F-35 System (2006-):

The F-35 offers 3-8 times the operational capability of the F-16 and F-18. The key to the F-35’s targeting capability is ...

... sensor systems to support situational awareness and targeting; sensor integration and data fusion.

This innovation has come at the cost of increased technical complexity:

- 130 subsystems; $O(10^5)$ interfaces.
- 90% of its functions are managed by software.
Case Study B: Behavior of Diverless Cars at a Busy Traffic Intersection

Stop signs and traffic lights are replaced by mechanisms for vehicle-to-vehicle communication (Adapted from http://citylab.com).
Goals

Model-based systems engineering (MBSE) development is an approach to systems-level development in which

... the focus and primary artifacts of development are models (as opposed to documents).

Approach and Benefits

MBSE procedures provide a formal basis for:

- Closing the gap between what is needed and how the system will work
- Assisting in the management of complex systems.
- Early and formal approaches to system validation and verification.
Orchestration of Good Design Solutions

1. Semi-Formal Models
   To allow for the efficient representation of ideas (e.g., goals and scenarios), representations for preliminary/tentative design need to be based on semi-formal models (e.g., UML and SysML).

2. Formal Models
   To help prevent serious flaws in detailed design and operation, design representations and validation/verification procedures need to be based on formal languages having precise semantics.

3. Abstraction
   Abstraction mechanisms eliminate details that are of no importance when evaluating system functionality, system performance, and/or checking that a design satisfies a particular property.
**Established Strategies of Development**

**Function before Physical**

We promote the description of systems in two orthogonal ways:

- The function that the systems is intended to provide,
- Candidate architectures for realizing the functionality.

**Function-Architecture Co-Design**

Map models of system behavior onto system structure alternatives.

[Diagram showing the process of mapping models to system design and evaluation]

Identify measures of effectiveness. Then evaluate and rank design alternatives.
**Layered Approach to Development**

The tenet of “breadth before depth” leads to a layered approach to development.

<table>
<thead>
<tr>
<th>Level of Concern</th>
<th>Requirements</th>
<th>Models</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Level</td>
<td>Requirements</td>
<td>System Behavior</td>
<td>System Validation / Verification</td>
</tr>
<tr>
<td></td>
<td>feedback</td>
<td>System Structure</td>
<td>delivery</td>
</tr>
<tr>
<td>Interface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subsystem Level</td>
<td>Requirements</td>
<td>Subsystem Behavior</td>
<td>Subsystem Validation / Verification</td>
</tr>
<tr>
<td></td>
<td>feedback</td>
<td>Subsystem Structure</td>
<td>delivery</td>
</tr>
<tr>
<td>Interface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component Level</td>
<td>Requirements</td>
<td>Component Behavior</td>
<td>Component Validation / Verification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Component Structure</td>
<td></td>
</tr>
</tbody>
</table>
**Problem Definition.** Development of an Operations Concept.
Pathway from goals and scenarios to simplified models of behavior and requirements.

- High-Level Requirements.

<table>
<thead>
<tr>
<th>Req 1</th>
<th>Req 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Activity Diagrams

- Use Case Diagram
- Sequence of tasks
- Sequence of messages between objects.

Sequence Diagrams

- Use Case 1
  - scenario 1
  - scenario 2
- Use Case 2
  - scenario 3
  - scenario 4

Individual Use Cases and Scenarios

Models of System Behavior and System Structure.
Key Points:

- The functional description dictates what the system must do. Here, we employ a combination of use cases (and use case diagrams), textual scenarios, and activity and sequence diagrams to elicit and represent the required system functionality.

- A complete system description will also include statements on minimum levels of acceptable performance and maximum cost. Since a system does not actually exist at this point, these aspects of the problem description will be written as design requirements/constraints.

- Further design requirements/constraints will be obtained from the structure and communication of objects in the models for system functionality (e.g., required system interfaces).
**Problem Solution.** Pathway from Requirements to Models of System Behavior/Structure and System Design

- **Goals and Scenarios**
  - Traceability via use cases.
- **Operations Concept**
- **System Behavior**
  - Traceability
- **Performance Attributes**
  - Mapping
- **System Structure**
  - Selection of System Architecture
- **Objects and Attributes**
  - Mapping
- **System Design**
- **System Evaluation**
  - Traceability
- **System Specification**
  - Detailed description of the system’s capabilities.
  - Iteration strategy to satisfy constraints.

- **Project Requirements**
- **Problem Domain**
- **Solution Domain**
Key Points:

• Requirements are organized according to the role they will play in the system-level design.

• Models of behavior specify what the system will actually do.

• Models of structure specify how the system will accomplish its purpose.

• The nature of each object/subsystem will be captured by its attributes. Attributes includes:
  • The attributes of the physical structure of the design,
  • The attributes of the environmental elements that will interact the the system.
  • Attributes of the system inputs and system outputs

• We create the system-level design by mapping fragments of system functionality/behavior onto specific subsystems/objects in the system structure.