Systems Engineering: Roles and Responsibilities

Annapolis, MD

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Making Decisions With Uncertainty

- Engineers are relatively good at logical decisions
  - The problem is with the assumptions ...
- Testing the assumptions is the most important trait of a good systems engineer - Remember you are the easiest one to fool
- In most cases, an 80% solution is good enough, but not always!

**Navigation B-Plane Plot**

- **3 Sigma Target Ellipse**
- **This is where the “Data” said we were**
- **This is where we really were!**
- **Controllability Limit**
- **Solutions should have tighter overall grouping! (Hindsight)**
Systems Engineering Key Lessons

• Truth of DeLuca’s Law (from Political Savvy)
  – [Space System development is] Not a rational system that happens to involve humans, but a human system attempting to act rationally

• Configuration control is good
  – Even very early in project life cycle

• All mistakes are stupid
  – We miss the obvious

• Test Like You Fly (TLYF)/Test at System Level cannot be the only verification approach
  – Need to do things right the first time (at lowest level)

• Distraction can be dangerous
  – We miss the critical while focused on the urgent

• Non-linear affect of requirements creep
Lessons Which We Must Not Re-Learn!

Mars ’98 Project

Science
Fixed
(Growth)

Risk
Only
Variable

Inadequate
Margins

Schedule
Fixed

Cost
Fixed

Launch Vehicle
Fixed
(Some Relief)
Systems Engineering Precepts

• Working Definition: The art and science of guiding the end-to-end engineering of complex space systems
  – Art because it involves extensive people skills and leadership
  – Science because it requires rigorous applications of tools and methodologies

• Key Objectives
  1. Employ First Principles Approach
     • Keep the critical-to-customer requirements always in mind
     • Everything else supports these
  2. Bring the entire project together
     • Big Tent, end-to-end, Diversity of ideas are good
  3. Vertical and horizontal integration
  4. Verification and validation
     • Separate disciplines
     • Little “i” V&V
Systems Engineering Leads the Technical Execution of the Project!

• Accomplished by Establishing the Technical Rhythm (Cadence) by Which the Project Marches

• This is the Weekly/Periodic Procedure that:
  – Controls Changes to the Technical Baseline
  – Matures the System through the Project Life-Cycle
  – Reduces/Accepts System Risk
  – Directly affects the Life-Cycle Cost Outcome

• Needs to be In-Place at Contract Start
  – Can be Tailored for Early Phases in the Life-Cycle

• Must Not Strangle the Project with Many Meetings
  – Attendance and Periodicity Carefully Architected
  – Everyone Hates Long, Fruitless, Unstructured Meetings
    • Except for Dilbert’s “Meeting Moth” ....
Systems Engineering P³

- People, Processes, Products

People

• Leaders
• Integrators (Subsystem Superstars)
• Analysts
• Open Culture
• Inclusive
### Developing System of Systems Engineers

<table>
<thead>
<tr>
<th>General Characteristics</th>
<th>Elements of Training</th>
<th>Seen in Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalist, Architect, Firefighter</td>
<td>On the job training, how work gets done, mentoring</td>
<td>Know what they know and what they don’t know</td>
</tr>
<tr>
<td>Intellectually curiosity, self-confident, energetic</td>
<td>Hands-on experience, end-to-end ownership develops judgment</td>
<td>Big picture, end-to-end, concept to operations, the <em>Systems View</em></td>
</tr>
<tr>
<td>Big picture oriented, end-to-end and concept-to-operations thinker</td>
<td>Working across subsystems and with new technologies</td>
<td>Tracks and knows state of key technical /program resources and their margin</td>
</tr>
<tr>
<td>Comfortable with change and uncertainty</td>
<td>Classes for fundamentals, familiarity with tools, lessons learned</td>
<td>Understands difference between requirements &amp; capabilities</td>
</tr>
<tr>
<td>Good communicator and listener</td>
<td>Learn processes as useful tools</td>
<td>Knows processes are tools, and not an end to themselves</td>
</tr>
<tr>
<td>Healthy paranoia</td>
<td>Multiple job and project experience</td>
<td>Builds in robustness, overlapping capability</td>
</tr>
<tr>
<td>Team player, works well as part of a diverse team</td>
<td>Test and tune decision making skills and judgment</td>
<td>Conducts objective trade studies, balances technical and programmatic</td>
</tr>
</tbody>
</table>

*System of Systems Engineering: Innovations for the 21st Century, Edited by Jamshidi, Ch.14, Jolly and Muirhead, Wiley 2009*
Processes

• Baseline Control
• V&V (as separate processes)/“i” V&V
• Configuration Control
• Trades
• System Design Team/Engineering Change Board
## Comparing Roles of the PI/PM to SE

<table>
<thead>
<tr>
<th>Planning</th>
<th>Project Management</th>
<th>SE Management</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Project Management Plan,</td>
<td>Systems Engineering Management Plan (SEMP)</td>
</tr>
<tr>
<td></td>
<td>Integrated Master Plan &amp;</td>
<td>IMP / IMS (tech), Processes</td>
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<tr>
<td></td>
<td>Schedule (IMP/IMS)</td>
<td></td>
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<tr>
<td>Organizing</td>
<td>Project Org. Chart</td>
<td>SE Org. Chart</td>
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<tr>
<td></td>
<td>Work Breakdown Structure (WBS)</td>
<td>Working Groups, Reviews, Risk Management</td>
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<tr>
<td>Staffing</td>
<td>Project Manpower Plan, Roll-on/Roll-off, Project</td>
<td>SE Recruiting, Training, Team Building</td>
</tr>
<tr>
<td></td>
<td>Office Staff</td>
<td></td>
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<tr>
<td>Controlling</td>
<td>Earned-Value Management System (EVMS), Project</td>
<td>EVMS, Eng. Change Board (ECB), Tech Metrics,</td>
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<td></td>
<td>Reviews, Monthly Management Reviews</td>
<td>Baseline Control, System Design Team Meetings</td>
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<tr>
<td>Directing</td>
<td>Policies, Procedures, Training, Supervising,</td>
<td>Reqt’s Development, Verification and Validation,</td>
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<tr>
<td></td>
<td>Performance Appraisals</td>
<td>Performance Appraisals</td>
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<tr>
<td></td>
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</tbody>
</table>
“Danger Will Robinson! Danger …”

Why can’t the system be calculated to a first-order on a white board? Why only by Sims and Monte Carlo’s …
There are thousands of ways to fail … most have not been explored
## Technical Performance Measures Management

<table>
<thead>
<tr>
<th>System Resource/Mission Phase</th>
<th>SDR</th>
<th>PDR</th>
<th>CDR</th>
<th>ATLO start</th>
<th>Launch</th>
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<tbody>
<tr>
<td>Mass</td>
<td>25%</td>
<td>20%</td>
<td>15%</td>
<td>10%</td>
<td>3%</td>
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<tr>
<td>Energy/Power</td>
<td>30%</td>
<td>20%</td>
<td>15%</td>
<td>10%</td>
<td>10%</td>
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<tr>
<td>Power Switches</td>
<td>35%</td>
<td>30%</td>
<td>20%</td>
<td>15%</td>
<td>10%</td>
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<tr>
<td>CPU Utilization</td>
<td>75%</td>
<td>60%</td>
<td>50%</td>
<td>30%</td>
<td>20%</td>
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<tr>
<td>Memory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSR (Bulk storage)</td>
<td>30%</td>
<td>20%</td>
<td>20%</td>
<td>15%</td>
<td>10%</td>
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<tr>
<td>DRAM</td>
<td>75%</td>
<td>60%</td>
<td>50%</td>
<td>30%</td>
<td>20%</td>
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<tr>
<td>NVM (Flash)</td>
<td>75%</td>
<td>60%</td>
<td>50%</td>
<td>40%</td>
<td>30%</td>
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<tr>
<td>SFC EEPROM</td>
<td>75%</td>
<td>60%</td>
<td>50%</td>
<td>40%</td>
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<td>Avionics</td>
<td></td>
<td></td>
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<tr>
<td>Serial Port Assignments</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Bus Slot Assignments</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Discrete I/O</td>
<td>30%</td>
<td>20%</td>
<td>15%</td>
<td>12.50%</td>
<td>10%</td>
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<tr>
<td>Analog I/O</td>
<td>30%</td>
<td>20%</td>
<td>15%</td>
<td>12.50%</td>
<td>10%</td>
</tr>
<tr>
<td>Earth to S/C Link (C)</td>
<td>3 dB</td>
<td>3 dB</td>
<td>3 dB</td>
<td>3 dB</td>
<td>3 dB</td>
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<tr>
<td>Link Margin Bit Error Rate (3 sigma)</td>
<td>1.00E-06</td>
<td>1.00E-05</td>
<td>1.00E-05</td>
<td>1.00E-05</td>
<td>1.00E-05</td>
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<tr>
<td>Bus Bandwidth</td>
<td>60%</td>
<td>60%</td>
<td>55%</td>
<td>55%</td>
<td>50%</td>
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<tr>
<td>Mission Data Volume</td>
<td>20%</td>
<td>20%</td>
<td>15%</td>
<td>10%</td>
<td>10%</td>
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<tr>
<td>ASIC/FPGA Gates Remaining</td>
<td>40%</td>
<td>30%</td>
<td>20%</td>
<td>15%</td>
<td>10%</td>
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<tr>
<td>Crew IVA Time</td>
<td>40%</td>
<td>30%</td>
<td>20%</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Products

- Design Reference Mission (OpsCon or CONOP)
- Master Equipment List
- Technical Performance Measures (TPMs)
- Requirements and Verification Database (DOORS)
- ICDs
- System Failure Mode and Effects Analysis (Fault Tree approach is best practice)
- Risk Reduction Test Program
- Numerous Systems Analyses
Example of Time-Domain CONOP/DRM, Phoenix Mars Scout Entry, Descent and Landing (NASA)

- **Entry**: E-0s, L-435s, 125 km*, r=3522.2 km, 5.7 km/s, $\gamma = -13$ deg

- **Peak Heating**: 44 W/cm²
  - Peak Deceleration: 9.25G

- **Radar Activated**: E+295 s, L-140s

- **Heat Shield Jettison**: E+235 s, L-200s, 11 km, 130 m/s

- **Parachute Deployment**: E+220 s, L-215 s, 13 km, Mach 1.7
  - Leg Deployments: E+245 s, L-190s
  - Radar Activated: E+295 s, L-140s
  - Lander Separation: E+399 s, L-36 s, 0.93 km, 54 m/s

- **Throttle Up**: E+402 s, L-33 s, 0.75 km
  - Constant Velocity Achieved: E+425 s, L-10 s, 0.025 km, 2.5 m/s
  - Touchdown: E+435 s, L-0s, 0 km, v=2.5 ±1 m/s, h<1.4 m/s

- **Vent Pressurant**: L+7 Sec
  - Dust Settling/Gyrocompassing: L+0 to L+15 min
  - Solar Array Deploy: L+15min
  - Fire Pyros for Deployments: ASAP

- **Entry Parameter Update**: E-12hr; Entry State Initialization: E-10min
- **Cruise Stage Separation**: E-7min
- **Entry Turn Starts**: E-6.5 min. Turn completes by E-5min...
- **Lander Separation**: E+399 s, L-36 s, 0.93 km, 54 m/s
- **Throttle Up**: E+402 s, L-33 s, 0.75 km
- **Constant Velocity Achieved**: E+425 s, L-10 s, 0.025 km, 2.5 m/s
- **Touchdown**: E+435 s, L-0s, 0 km, v=2.5 ±1 m/s, h<1.4 m/s

Note: Nominal Entry Shown. Dispersions exist around all values.

* Entry altitude referenced to equatorial radius.
  All other altitudes referenced to ground level

Landing at -3.4 km Elevation (MOLA relative)

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Fault Tree Mapped Effects to Potential Causes

- Mars Orbit Insertion Failure
  - Problem Starting Burn
  - Burn Ends Too Early
  - Low Propulsion Performance
    - Burn In Wrong Direction
    - Problem Maintaining Control During Burn
    - FSW Terminates Burn Early
      - Processor Resets
    - MEA Valves Close Prematurely
  - Excessive ACS use of hydrazine during MOI (ID XX-01)
  - Excessive hydrazine use during cruise phase (ID XX-02)
  - Low mixture ratio (ID XX-03)
Risk Reduction Testing Played Huge Role

FSW/Ops Product Program Test Flow
Steps indicative of total fidelity (H/W+FSW+SIM+OPS Products)
Some SE-Specific Management Pitfalls

• Everybody is a Systems Engineer
• Only Complex Interfaces Need Managing
• Requirements Creep Only Comes From the Customer
• Government/Customer Furnished Equipment
• SE is Only Level-of-Effort for Earned-Value Management
• The SEMP (System Engineering Management Plan) is for simps!
• Technical Rules! Cost and Schedule are secondary …
• There are Totally Unbiased Recommendations
• The Project Manager can Double as the Lead SE or a Project Engineer