Engineering Elegant Systems: Design at the System Level

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Outline

◆ Understanding Systems Engineering
  • Postulates
  • Hypothesis
  • Principles

◆ Systems Engineering Domain
  • System Integration
    – System State Variables
      • Goal Function Tree
      • State Analysis Model
    – System Value Model
    – System Integrating Physics
    – System Autonomy
    – Multidisciplinary Design Optimization (MDO)
    – Engineering Statistics
    – Methods of System Integration

  • Discipline Integration
    – Sociological Concepts in Systems Engineering
    – Information Flow
    – Systems Thinking (Cognitive Science)
    – Policy and Law
    – System Dynamics

◆ Summary
Understanding Systems Engineering
Motivation

◆ System Engineering of Complex Systems is not well understood

◆ System Engineering of Complex Systems is Challenging
  • System Engineering can produce elegant solutions in some instances
  • System Engineering can produce embarrassing failures in some instances
  • Within NASA, System Engineering does is frequently unable to maintain complex system designs within budget, schedule, and performance constraints

◆ “How do we Fix System Engineering?”
  • Michael D. Griffin, 61st International Astronautical Congress, Prague, Czech Republic, September 27-October 1, 2010
  • Successful practice in System Engineering is frequently based on the ability of the lead system engineer, rather than on the approach of system engineering in general
  • The rules and properties that govern complex systems are not well defined in order to define system elegance

◆ 4 characteristics of system elegance proposed as:
  • System Effectiveness
  • System Efficiency
  • System Robustness
  • Minimizing Unintended Consequences
Definition – System Engineering is the engineering discipline which integrates the system functions, system environment, and the engineering disciplines necessary to produce and/or operate an elegant system.

- Elegant System - A system that is robust in application, fully meeting specified and adumbrated intent, is well structured, and is graceful in operation.

Primary Focus
- System Design and Integration
  - Identify system couplings and interactions
  - Identify system uncertainties and sensitivities
  - Identify emergent properties
  - Manage the effectiveness of the system
- Engineering Discipline Integration
  - Manage flow of information for system development and/or operations
  - Maintain system activities within budget and schedule

Supporting Activities
- Process application and execution
Postulate 1: Systems engineering is product specific and context dependent

Postulate 2: The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment

Postulate 3: The function of Systems Engineering is to integrate engineering disciplines in an elegant manner

Postulate 4: Systems engineering influences and is influenced by organizational structure and culture

Postulate 5: Systems engineering influences and is influenced by budget, schedule, policy, and law

Postulate 6: Systems engineering spans the entire system life-cycle

Postulate 7: Understanding of the system evolves as the system development or operation progresses

Postulate 7 Corollary: Understanding of the system degrades during operations if system understanding is not maintained.
**Systems Engineering Principles**

- **Principle 1:** Systems engineering integrates the system and the disciplines considering the budget and schedule constraints.

- **Principle 2:** Complex Systems build Complex Systems.

- **Principle 3:** The focus of systems engineering during the development phase is a progressively deeper understanding of the interactions, sensitivities, and behaviors of the system.
  - Sub-Principle 3(a): Requirements and models reflect the understanding of the system.
  - Sub-Principle 3(b): Requirements are specific, agreed to preferences by the developing organization.
  - Sub-Principle 3(c): Requirements and design are progressively defined as the development progresses.
  - Sub-Principle 3(d): Hierarchical structures are not sufficient to fully model system interactions and couplings.
  - Sub-Principle 3(e): A Product Breakdown Structure (PBS) provides a structure to integrate cost and schedule with system functions.
  - Sub-Principle 3(f): As the system progresses through development, a deeper understanding of the organizational relationships needed to develop the system are gained.

- **Principle 4:** Systems engineering has a critical role through the entire system life-cycle.
  - Sub-Principle 4(a): Systems engineering obtains an understanding of the system.
  - Sub-Principle 4(b): Systems engineering models the system.
  - Sub-Principle 4(c): Systems engineering designs and analyzes the system.
  - Sub-Principle 4(d): Systems engineering tests the system.
  - Sub-Principle 4(e): Systems engineering has an essential role in the assembly and manufacturing of the system.
  - Sub-Principle 4(f): Systems engineering has an essential role during operations and decommissioning.
Principle 5: Systems engineering is based on a middle range set of theories

- Sub-Principle 5(a): Systems engineering has a physical/logical basis specific to the system
- Sub-Principle 5(b): Systems engineering has a mathematical basis
  - Systems Theory Basis
  - Decision & Value Theory Basis (Decision Theory and Value Modeling Theory)
  - Model Basis
  - State Basis (System State Variables)
  - Goal Basis (Value Modeling Theory)
  - Control Basis (Control Theory)
  - Knowledge Basis (Information Theory)
  - Predictive Basis (Statistics and Probability)

- Sub-Principle 5(c): Systems engineering has a sociological basis specific to the organization

Principle 6: Systems engineering maps and manages the discipline interactions within the organization

Principle 7: Decision quality depends on the coverage of the system knowledge present in the decision-making process

Principle 8: Both Policy and Law must be properly understood to not overly constrain or under constrain the system implementation

Principle 9: Systems engineering decisions are made under uncertainty accounting for risk
Principle 10: Verification is a demonstrated understanding of all the system functions and interactions in the operational environment
- Ideally requirements are level and balanced in their representation of system functions and interactions
- In practice requirements are not balanced in their representation of system functions and interactions

Principle 11: Validation is a demonstrated understanding of the system’s value to the system stakeholders

Principle 12: Systems engineering solutions are constrained based on the decision timeframe for the system need
System Engineering Hypotheses

◆ Hypothesis 1: If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context
  • Hamilton’s Principle shows this for a physical system
    \[ \int_{t_1}^{t_2} (\delta T - \delta V + \delta W) dt = 0 \]

◆ Hypothesis 2: System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs

◆ Hypothesis 3: Key Stakeholders preferences can be accurately represented mathematically

◆ Hypothesis 4: The real physical system is the perfect model of the system
  • Kullback-Liebler Information shows the actual system is the ideal information representation of the system
    \[ I(f, g) = \int f(x) \log(f(x)) \, dx - \int f(x) \log(g(x|\theta)) \, dx = 0 \]
Methods of System Design and Integration

Goal: Techniques to Enable Integrated System Design and Assessments by the Systems Engineer
System Models Contain an Understanding of the System

- Allow systems engineers to:
  - Define system functions based on the system state variables
  - Understand stakeholders expectations on system value (i.e., capabilities)
  - Integrate discipline engineering models into a system level physics based model (e.g., system exergy)
  - Design and Analyze system responses and behaviors at the System level

- MagicDraw Enterprise (SysML)
- Matlab
- Matlab StateFlow
- Microsoft Excell
System Value

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution
A System Value Model is a mathematical representation of Stakeholders Preferences (Expectations) for the system
- The basic structure is straightforward
- The sociology/psychology of representing the Preferences can be a challenge

The System Value Model is the Basis of System Validation!!!
- The Requirements and Design Models form the basis of System Verification
- The System Value Model forms the basis of System Validation

Constructing an SLS Value Model to compare to System Validation results
- Can expand to Integrated Stack with input from MPCV and GSDO

System Value model also provides basis for a measure of System Robustness
- How many mission types are supported by the system?
Launch Vehicle Value Model

- **Launch Vehicle Value related to impact to national GDP**
- **Rockets are thermodynamic systems, there thermo-economics can be applied**

\[
\dot{c}_T = \sum_i c_{ei} \dot{e}_i + \sum_n \dot{Z}_n
\]

\[
c_{ei} = \frac{kg}{J/kg} \rightarrow \left(\frac{\text{propellant cost}}{\text{exergy}}\right) = $/J
\]

\[
\dot{e}_i = \frac{kg}{yr} \left(\frac{J}{kg}\right) \rightarrow \left(\frac{\text{mass}}{\text{year}}\right) \times \text{HHV} = \frac{J}{yr}.
\]

\[
\dot{Z}_n = L_R \times \text{unit cost} + \frac{\text{manufacturing base cost}}{yr}
\]

Mission Reliability is an important value

\[
R_{mission} (R_m) = R_{launch} \times A_0 \times R_{flight}
\]

Value to Satellite Industry can be used as a basis for value

<table>
<thead>
<tr>
<th>Δ diameter:</th>
<th>diameter:</th>
<th>Satellite Benefit (value of payload)</th>
<th>$ Value (Billions)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>Commercial Communications:</td>
<td>$45.69</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Optical Sensing:</td>
<td>$24.80</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Interplanetary Missions:</td>
<td>$6.53</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Astronomical Telescope:</td>
<td>$1.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Human Exploration:</th>
<th>(measured by using % of US GDP)</th>
<th>$ Value:</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Renown:</td>
<td>0.06</td>
<td>$1,116,000,000,000.00</td>
</tr>
<tr>
<td>Extended Science:</td>
<td>0.1</td>
<td>$1,860,000,000,000.00</td>
</tr>
<tr>
<td>Technological Gains:</td>
<td>0.056</td>
<td>$1,041,600,000,000.00</td>
</tr>
<tr>
<td>Medical Advances:</td>
<td>0.1</td>
<td>$1,860,000,000,000.00</td>
</tr>
</tbody>
</table>
Launch Vehicle Value based on 3 factors (currently)

- Value is not cost!!!! It includes cost.
- Industry Value

- Mission Reliability (96%)
  - \( V_2 = R_m \) (Value of Satellite Benefit)
  - \( V_L = (1 - R_m) \) (Value of Satellite Benefit)
  + Unit Cost + Satellite Cost

- Payload Accommodation
  - \( V_3 = \Delta \text{diameter} \times \left( \frac{\Delta \text{value of payload}}{\text{meter}} \right) \)

Launch Vehicle Value

<table>
<thead>
<tr>
<th>Launch Vehicle Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue Value (V1)</td>
<td>$3,017,881,093,091.75</td>
</tr>
<tr>
<td>Mission Reliability Value (V2)</td>
<td>$66,294,779,977.80</td>
</tr>
<tr>
<td>Payload Size Value (10m Fairing) (V3)</td>
<td>$78,320,964,000.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Launch Vehicle Value</th>
<th>Benefit - Ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value to Scientific Uses</td>
<td>$63,008,431,752.36</td>
</tr>
<tr>
<td>Value to Commercial Services</td>
<td>$20,584,576,252.36</td>
</tr>
<tr>
<td>Value to Resource Mining</td>
<td>($2,252,876,665.31)</td>
</tr>
<tr>
<td>Value to Human Exploration</td>
<td>$2,936,540,961,752.35</td>
</tr>
<tr>
<td>Total Value</td>
<td>$3,017,881,093,091.75</td>
</tr>
</tbody>
</table>

| V2 (Commercial Communication)        | $43,859,739,840.00           |
| V2 (Optical Sensing)                 | $23,809,573,056.00          |
| V2 (Interplanetary)                  | $6,265,677,120.00           |
| V2 (Astronomical Telescope)          | $1,253,135,424.00           |
| total V2                             | $75,188,125,440.00          |

<table>
<thead>
<tr>
<th>Value Lost from Failed Mission</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>V(L) (Commercial Communication)</td>
<td>$7,995,274,012.95</td>
</tr>
<tr>
<td>V(L) (Optical Sensing)</td>
<td>$6,538,291,607.03</td>
</tr>
<tr>
<td>V(L) (Interplanetary)</td>
<td>$3,732,182,001.85</td>
</tr>
<tr>
<td>V(L) (Astronomical Telescope)</td>
<td>$2,930,436,400.37</td>
</tr>
<tr>
<td>total Value Lost</td>
<td>$21,196,184,022.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Satellite Benefit (SB)</th>
<th>4 meters</th>
<th>5 meters</th>
<th>8 meters</th>
<th>10 meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Communications:</td>
<td>$45.69</td>
<td>$45.69</td>
<td>$45.69</td>
<td>$45.69</td>
</tr>
<tr>
<td>Optical Sensing:</td>
<td>$12.40</td>
<td>$24.80</td>
<td>$24.80</td>
<td>$24.80</td>
</tr>
<tr>
<td>Interplanetary Missions:</td>
<td>$2.61</td>
<td>$5.87</td>
<td>$6.53</td>
<td>$6.53</td>
</tr>
<tr>
<td>Astronomical Telescope:</td>
<td>$0.00</td>
<td>$0.00</td>
<td>$0.13</td>
<td>$1.31</td>
</tr>
<tr>
<td>Total:</td>
<td>$60.70</td>
<td>$76.36</td>
<td>$77.15</td>
<td>$78.32</td>
</tr>
</tbody>
</table>
System Physics and System Integrating Physics

Goal: Utilize the key system physics to produce an elegant system design
**System Integrating Physics**

- **Consortium is researching the significance of identifying and using the System Integrating Physics for Systems Engineering**
  - First Postulate: Systems Engineering is Product Specific.
    - States that the Systems are different, and therefore, the Integrating Physics for the various Systems is different

- **Launch Vehicles**
  - Thermodynamic System

- **Spacecraft**
  - Robotic
    - Integrated through the bus which is a thermodynamic system
      - Each Instrument may have a different integrating physics but integrates with the bus thermodynamically
  - Crew Modules
    - Integrated by the habitable volume (i.e., ECLSS)
      - A thermodynamic system
  - Entry, Descent, and Landing (EDL)
    - Integrated by thermodynamics as spacecraft energy is reduced in EDL

- **Other Thermodynamic Systems**
  - Fluid Systems
  - Electrical Systems
  - Power Plants
  - Automobiles
  - Aircraft
  - Ships

- **Not all systems are integrated by their Thermodynamics**
  - Optical Systems
  - Logical Systems
    - Data Systems
    - Communication Systems
  - Biological Systems

- **System Integrating Physics provides the engineering basis for the System Model**
Launch Vehicle and Crew Module System Exergy Balance

Launch Vehicle Exergy Balance

\[
\Delta m_{prop} \sum_{\text{stage}} \left( h_{prop} + \frac{V_e^2}{2} \right) - X_{des}
\]

\[= \left( M_{\text{vehicle,final}} \frac{V_{\text{vehicle,final}}^2}{2} - M_{\text{vehicle,initial}} \frac{V_{\text{vehicle,initial}}^2}{2} \right) + \left( \frac{GM_E M_{\text{vehicle,initial}}}{r_{\text{altitude,initial}}} - \frac{GM_E M_{\text{vehicle,final}}}{r_{\text{altitude,final}}} \right) \]

\[\eta_{ex} = 1 - \frac{X_{des}}{X_{expend}}
\]

Crew Module Exergy Balance

\[
\Delta X_{ECLS} = \Delta X_{ACS} + \Delta X_{AR} + \Delta X_{THC} + \Delta X_{W\text{RM}} + \Delta X_{WM}
\]

\[
\sum_{\text{process}} m_{fluid} \left( h_{final} - h_{cabin} \right) - T_{cabin} \left( s_{final} - s_{cabin} \right) + \left( \frac{V_{\text{final}}^2}{2} \right)
\]

\[= \sum_{\text{process}} m_{fluid} \left( h_{initial} - h_{cabin} \right) - T_{cabin} \left( s_{initial} - s_{cabin} \right) + \left( \frac{V_{\text{initial}}^2}{2} \right)
\]

\[= \sum \left( 1 - \frac{T_{cabin}}{T_{\text{crew}}} \right) Q_{\text{crew}} - \sum \left( \frac{T_{\text{cabin}} - T_{\text{coolant}}}{T_{\text{coolant}}} \right) Q_{\text{TMS}} + \sum W_{\text{EPS}}
\]

\[- p_{\text{cabin}} \left( V_{\text{final}} - V_{\text{initial}} \right)
\]

\[+ m_{in} \left( h_{in} - h_{cabin} \right) - T_{cabin} \left( s_{in} - s_{cabin} \right) + \left( \frac{V_{in}^2}{2} \right)
\]
Spacecraft Exergy Balance

\[\Delta m_{\text{propellant,engine}} \left( h_{\text{prop,engine}} + \frac{V^2_{e,engine}}{2} \right)\]

\[+ \Delta m_{\text{propellant,thruster}} \left( h_{\text{prop,thruster}} + \frac{V^2_{e,thruster}}{2} \right)\]

\[+ \sum_{t} (\sigma A e (T^4_{\text{radiator}} - T^4_{\text{space}}) + V_{\text{bus}} I_{\text{bus}} \cos (\theta)) \Delta t - X_{\text{des}}\]

\[= \left( M_{\text{vehicle,final}} \left( \frac{l_{c,final} \omega^2_{\text{vehicle,final}}}{2} + \frac{V^2_{\text{vehicle,final}}}{2} \right) \right)\]

Optical Transfer Function

\[\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \psi_{\text{obj}} s dx dy\]

\[= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \psi_{\text{obj}} (x_0 + \epsilon x, y_0 + \epsilon y) e^{i \frac{k e}{2} \left(x^2 + y^2\right)} \cos (x + \Delta x + \delta x, y + \Delta y + \delta y) dx dy\]

Where

\[\epsilon x = 1.22 \lambda_0 \left( \frac{f_1}{d_0 + \epsilon x + \epsilon y \Delta t} \right) + v_x \Delta t + \omega \epsilon \Delta t\]

\[\epsilon y = 1.22 \lambda_0 \left( \frac{f_1}{d_0 + \epsilon x + \epsilon y \Delta t} \right) + v_y \Delta t + \omega \epsilon \Delta t\]

\[f_1 = -\frac{R}{2} = -\frac{\sqrt{(x + \Delta x + \delta x)^2 + (y + \Delta y + \delta y)^2 + (z + \Delta z + \delta z)^2}}{2}\]

\[\Delta x = \alpha x \Delta T\]

\[\Delta y = \alpha y \Delta T\]

\[C^2 > 4 M k \quad \text{Over Damped}\]

\[\delta x = c_1 e^{-\left( \frac{C}{2 M} \sqrt{C^2 - 4 M k} \right) t} + c_2 e^{-\left( \frac{C}{2 M} \sqrt{C^2 - 4 M k} \right) t}\]

\[C^2 = 4 M k \quad \text{Critically Damped}\]

\[\delta x = (c_1 + c_2) e^{-\left( \frac{C}{2 M} \right) t}\]

\[C^2 < 4 M k \quad \text{Under Damped}\]

\[\delta x = c_3 e^{-\left( \frac{C}{2 M} \right) t} \cos \left( \sqrt{4 M k - C^2} t - \varphi \right)\]

\[\tan(\varphi) = \frac{x'(0)}{x(0) \sqrt{k M}}\]

\[c_3^2 = \frac{x(0)^2 + \frac{M}{k} x'(0)^2}{\sqrt{}}\]
Mars Interplanetary Exergy Analysis

\[
e_{\text{transfer}} = 1 - \frac{r_{\text{periapsis}}}{a_{\text{transfer}}}
\]

\[
V_{\text{periapsis,transfer}} = \sqrt{\frac{\mu_{\text{planet}}}{2}} \left( \frac{2}{r_{\text{periapsis}}} - \frac{1}{a_{\text{transfer}}} \right)
\]

\[
V_{\text{periapsis,parking}} = V_{\text{periapsis,transfer}} - \Delta V
\]

\[
a_{\text{parking}} = 1/\left( \left( \frac{2}{r_{\text{periapsis}}} - \frac{v_{\text{periapsis,parking}}^2}{\mu_{\text{planet}}} \right) \right)
\]

\[
e_{\text{parking}} = 1 - \frac{r_{\text{periapsis,parking}}}{a}
\]

\[
r_{\text{apoapsis}} = r_{\text{periapsis}} \left( \frac{1 + e_{\text{parking}}}{1 - e_{\text{parking}}} \right)
\]
\[ \sum_{\text{stages}} \left[ \Delta m_{\text{propellant}} \left( h_{\text{prop}} + \frac{v_e^2}{2} \right) \right] - X_{\text{des}} = \sum_{\text{stages}} \left[ \left( \frac{V_{\text{vehicle,final}}^2}{2} - m_{\text{vehicle,initial}} \right) - \frac{GM_E m_{\text{vehicle,final}}}{r_{\text{altitude,final}}} \right] + \left( \frac{GM_E m_{\text{vehicle,initial}}}{r_{\text{altitude,initial}}} \right) \]
747-400 lifting a 2 stage rocket to launch altitude and velocity

\[ \Delta m_{\text{propellant,aircraft}} H_{\text{total,aircraft}} + \sum_{\text{stages}} \left[ \Delta m_{\text{propellant}} \left( h_{\text{prop}} + \frac{v_e^2}{2} \right) \right] - \]

\[ X_{\text{des}} = \sum_{\text{stages}} \left( M_{\text{vehicle,final}} \frac{v_{\text{vehicle,final}}^2}{2} \right) - \]
Methods of Engineering Discipline Integration

Goal: Understand How Organizational Structures influence Design and Operations Success of Complex Systems
Sociological Concepts in Systems Engineering

- Specification of Ignorance is important in the advancement of the understanding of the system

- Consistent use of Terminology is important for Communication within the Organization

- Opportunity Structures
  - Provide opportunity to mature ideas
    - Task teams, working groups, communities of practice, etc.

- Socially Expected Durations will exist about the project

- Both Manifest and Latent Social Functions exist in the organization

- Social Role Sets
  - Individuals have a set of roles for their position

- Cultural Subsets will form
  - i.e., disciplines can be a subset within the organization
  - Insider and Outsider attitudes can form
    - Be Aware of the Self-Fulfilling Prophecy, Social Polarization

- Reconsiderations Process (i.e., Reclama Process)
  - Provides ability to manage social ambivalence
  - Must be able to recognize social beliefs that may be contributing to the disagreement
  - Helps to avoid putting people in to social dysfunction or complete social anomie
    - Conformity
    - Innovation
    - Ritualism
    - Retreatism
    - Rebellion
Unintended Consequences are the result of human mistakes.  
• Physics do not fail, we do not recognize the consequences.

Based on sociology, followed the work of Robert K. Merton in classifying unintended consequences.  
• “The Unanticipated Consequences of Social Action”, 1936

Classification
• Ignorance (limited knowledge of the problem)  
• Historical Precedent (confirmation bias)  
• Error (mistakes in calculations, working from habit)  
• Short Sightedness (imperious immediacy of interest, focusing on near term and ignoring long term consequences)  
• Cultural Values (cultural bias in what can and cannot happen)  
• Self Defeating Prophecy (by stating the hypothesis you induce a set of conditions that prevent the hypothesis outcome)
Information Flow

- Information Flow through a program/project/activity is defined by Information Theory
  - Organizational communication paths
  - Board Structure

- Decision Making follows the First Postulate
  - Decision Process is specific to the decision being made
  - Tracked 3 SLS CRs, with 3 separate task team processes, all had equally rated effectiveness

- Margin is maintained by the Organization, not in the margin management tables
  - Biased Information Sharing
  - Margin Management is focused on Managing the Disciplines (informed by the System Integrating Physics)

- SLS Organizational Structure was defined by the LSE as a recommendation to the Chief Engineer and the Program Manager
Discipline Integration Models

- Organizational Values
- Goal Function Tree (GFT)
- System Functions
- Value Attributes
- Value Model
- Agent Based Model (ABM)
- Discrete Event Simulation

- MagicDraw Enterprise (SysML)
- Matlab
- Matlab StateFlow
- JAVA
- Anylogic
- Extend

- Allow systems engineers to:
  - Understand information flow through the development and/or operations organization
  - Integrate discipline information into a system level design
  - Analyze information flow, gaps, and blind spots at the System level
Summary

◆ Discussed approach to Engineering an Elegant System

◆ Systems Engineering Framework and Principles
  • System Integration
  • Engineering Discipline Integration

◆ Several methods and tools are available for conducting integrated system design and analysis
  • System Integration
    – System State Variables
      • Goal Function Tree
      • State Analysis Model
    – System Value Model
    – System Integrating Physics
    – Topics Not Discussed
      • System Autonomy
      • Multidisciplinary Design Optimization (MDO)
      • Engineering Statistics
  
  • Discipline Integration
    – Sociological Concepts in Systems Engineering
    – Information Flow
    – Topics Not Discussed
      • Systems Thinking (Cognitive Science)
      • Policy and Law
      • System Dynamics Modeling

◆ Systems Engineering Approach defined in two documents
  • “Engineering Elegant Systems: The Practice of Systems Engineering”

◆ Send requests for documents to: michael.d.Watson@nasa.gov
Consortium

◆ Research Process
  • Multi-disciplinary research group that spans systems engineering areas
  • Selected researchers who are product rather than process focused

◆ List of Consortium Members
  • Michael D. Griffin, Ph.D.
  • Air Force Research Laboratory – Wright Patterson, Multidisciplinary Science and Technology Center: Jose A. Camberos, Ph.D., Kirk L. Yerkes, Ph.D.
  • George Washington University: Zoe Szajnfarber, Ph.D.
  • Iowa State University: Christina L. Bloebaum, Ph.D., Michael C. Dorneich, Ph.D.
  • Missouri University of Science & Technology: David Riggins, Ph.D.
  • NASA Langley Research Center: Anna R. McGowan, Ph.D., Peter A. Parker, Ph.D.
  • The University of Alabama in Huntsville: Phillip A. Farrington, Ph.D., Dawn R. Utley, Ph.D., Laird Burns, Ph.D., Paul Collopy, Ph.D., Bryan Mesmer, Ph.D., P. J. Benfield, Ph.D., Wes Colley, Ph.D.
  • Doty Consulting: John Doty, Ph.D.
  • The University of Michigan: Panos Y. Papalambros, Ph.D.
  • Ames Research Center: Peter Berg
  • Glenn Research Center: Karl Vaden

◆ Previous Consortium Members
  • Massachusetts Institute of Technology: Maria C. Yang, Ph.D.
  • The University of Texas, Arlington: Paul Componation, Ph.D.
  • Texas A&M University: Richard Malak, Ph.D.
  • Tri-Vector Corporation: Joey Shelton, Ph.D., Robert S. Ryan, Kenny Mitchell
  • The University of Colorado – Colorado Springs: Stephen B. Johnson, Ph.D.
  • The University of Dayton: John Doty, Ph.D.
  • Stevens Institute of Technology – Dinesh Verma
  • Spaceworks – John Olds (Cost Modeling Statistics)
  • Alabama A&M – Emeka Dunu (Supply Chain Management)
  • George Mason – John Gero (Agent Based Modeling)
  • Oregon State – Irem Tumer (Electrical Power Grid Robustness)
  • Arkansas – David Jensen (Failure Categorization)

~40 graduate students and 5 undergraduate students supported to date
System State Variables

Goal: Utilize system state variables to understand the interactions of the system in relation to system goals and system execution
System State Models

System Stage Models represent the system as a whole in terms of the hardware and software states that the system transitions through during operation.

Goal Function Tree (GFT) Model
- “Middle Out” model of the system based on the system State Variables
- Shows relationship between system state functions (hardware and software) and system goals
- Does not contain system physical or logical relationships and is not executable

System State Machine Model
- Models the integrated State Transitions of the system as a whole (i.e., hardware states and software states)
- Confirms system functions as expected
  - Checks for system hazardous, system anomalies, inconsistent state progression, missing states, improper state paths (e.g., short circuits in hardware and/or software design)
  - Confirms that the system states progress as stated in the system design
- Executable model of system
The state analysis model is split into two main components:
- Manager software model
- System Plant

Modeled using MATLAB Stateflow
- Allows the software model to look like the SysML Activity Diagrams
- Allows the System Plant to be modeled as State Machines
- Allows those two models to interact with each other within the MATLAB environment
  - Facilitates the ability to generate custom analysis tools

Reads in command sequence to execute model
State Analysis Model for SLS M&FM

- 14% of R12 modeled
- Over 7,200 Transitions in the Vehicle and Software
- Over 3,500 States in the Vehicle
System Design and Optimization

Goal: Apply system design and optimization tools to understand and engineer system interactions
Multidisciplinary Design Optimization

Engineering Statistics

Goal: Utilize statistical methods to understand system uncertainties and sensitivities

Systems Engineering makes use of Frequentist Approaches, Bayesian Approaches, Information Theoretic Approaches as appropriate
Optimal Sensor Information Configuration

◆ Applying Akaike Information Criteria (AIC) corrected (AICc) to assess sensor coverage for a system

\[
AICc(F) = -2 \left( I^K_L(F|G) \right) + 2K + \frac{2K(K+1)}{n-K-1}
\]

◆ Two Views of Information Content
  • AIC Information
    – Information is viewed as the number of meaningful parameters
      • Parameters with sufficient measurements to be reasonable estimates
  • Fisher Information Matrix
    – Defines information as the matrix of partial second derivatives
      • Information is the amount of parameters with non zero values (so provides an indication of structure)
      • This value converges to a maximum as the number of parameters goes to infinity
      • Does not contain an optimum, always increases with added parameters

◆ AIC/AICc has an adjustment factor to penalize sensor arrangements where:
  number of sensors < 3x(number of measurements)

◆ Provides an optimization tool for use with System Models
Methods of System Integration

Goal: System Design and Analysis
System Design and Integration

- Mission Requirements
  - Level 1 Requirements, Needs, Goals, and Objectives (NGOs)
- System Concept of Operations
- Goal Function Tree (GFT)
- System Value Model
- System Capability Model
- System Integrating Physics Model
- Uncertainties, Sensitivities
- System State Transition Model
- Engineering Statistics

Design Information
- Concept/Architecture Selection
- Preliminary Design
- Critical Design
- Verification and Validation