National Aeronautics and Space Administration

Engineering Elegant Systems: Design at the System Level

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Space Launch System

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**

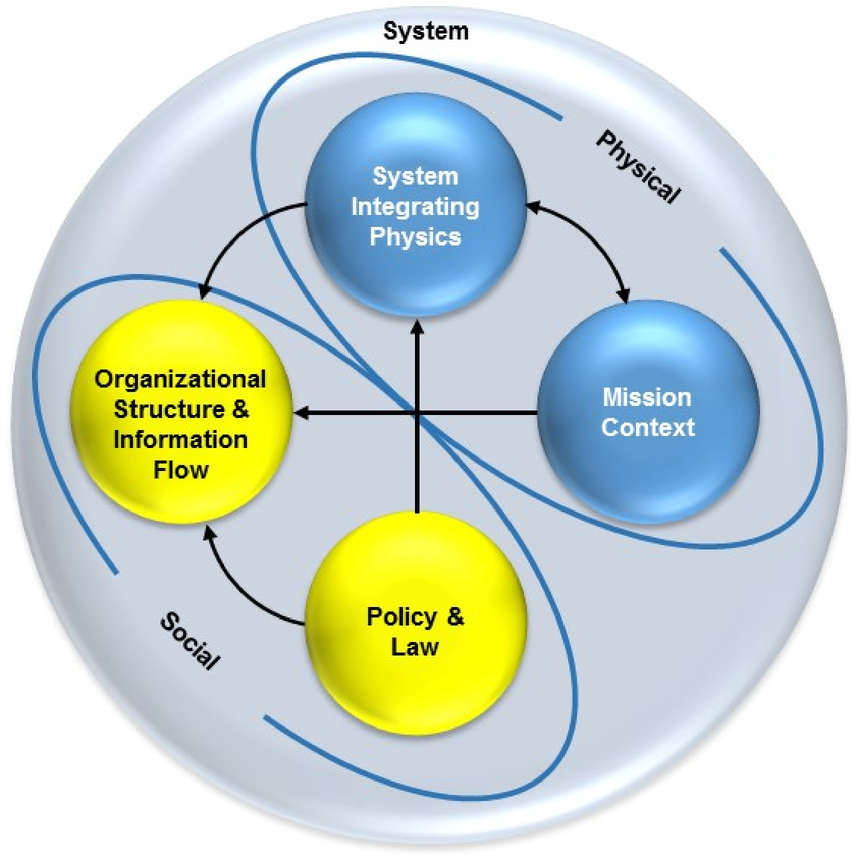
- **System Engineering of Complex Systems is Challenging**
  - System Engineering can produce elegant solutions in some instances
  - System Engineering can produce embarrassing failures in some instances
  - Within NASA, System Engineering does is frequently unable to maintain complex system designs 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

Understanding Systems Engineering

- **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

Systems Engineering Postulates

System Integration (physical/logical system)
Discipline Integration (social system)
Both System and Discipline Integration

- **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

Systems Engineering Principles

- **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**

Systems Engineering Principles

- **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**

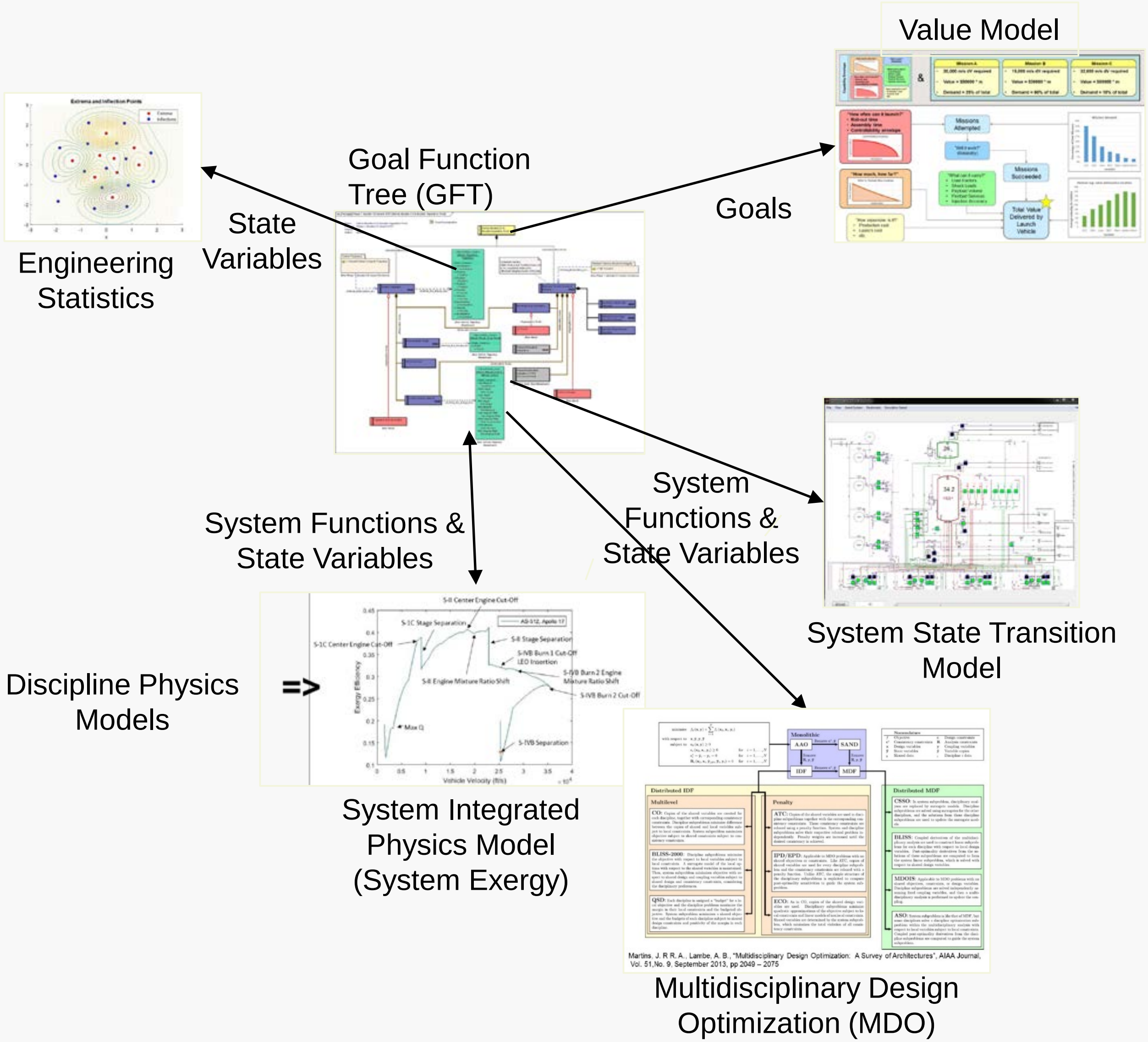
System Engineering Hypotheses

- **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

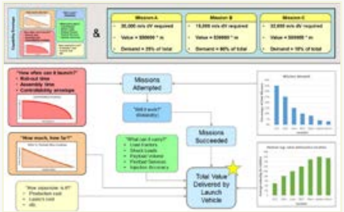
System Value

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

System Value Model

- **A System Value Model is a mathematical representation of Stakeholders Preferences (Expectations) for the system**
  - The basic structure is straight forward
  - 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?

	Status	Gradient	Value
Efficiency	90%	150,000	135,000
Weight	700	-130	-91,000
Reliability	1500	2	3,450
Maintainability	7.8	-340	-2,652
Maintenance Cost	500	-1	-250
Support Equipment	12	-15	-180
Manufacturing Cost	700	-1	-700
Design Value			$ 43,668



$$\pi = f_{aircraft}\left(x_1, x_2, \ldots, x_n\right)$$

$$v_e = \sum_{j=1}^{m}\left(\sum_{i=1}^{n}\frac{\partial \pi}{\partial x_i}\cdot\frac{\partial x_i}{\partial y_j}y_j\right)$$

$$v_t = \sum_{k=1}^{p}\left(\sum_{j=1}^{m}\frac{\partial v_e}{\partial y_j}\cdot\frac{\partial y_j}{\partial z_k}z_k\right)$$

Launch Vehicle Value Model

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

$$\dot{C}_T = \sum_i c_{ei}\,\dot{\epsilon}_i + \sum_n \dot{Z}_n$$

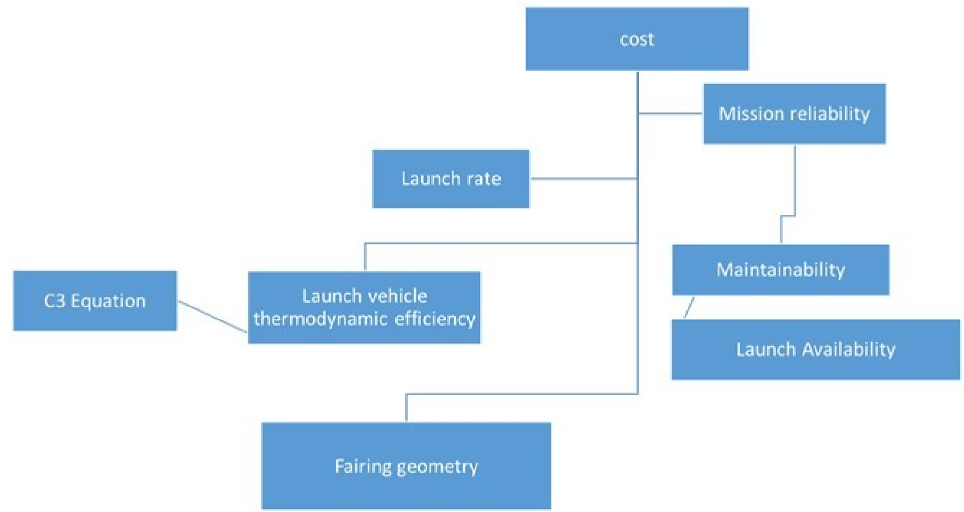
$$c_{ei} = \frac{\frac{\$}{kg}}{J/kg} \rightarrow \left(\frac{propellant\ cost}{exergy}\right) = \$/J$$

$$\dot{\epsilon}_i = \frac{kg}{yr}\left(\frac{J}{kg}\right) \rightarrow \left(\frac{mass}{year}\right) * HHV = \frac{J}{yr}.$$

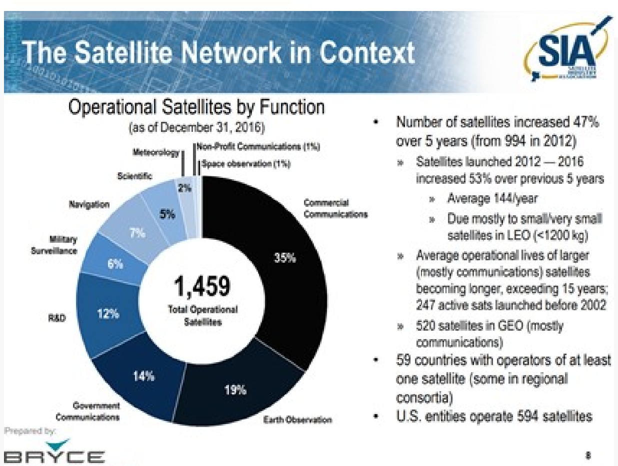
$$\dot{Z}_n = L_R * unit\ cost + \frac{manufactoring\ base\ cost}{yr}$$

Mission Reliability is an important value

$$R_{mission}\ (R_m) = R_{launch} * A_O * R_{flight}$$



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



Δdiameter:	diameter:	Satellite Benefit (value of payload)	$ Value (Billions)
	4	Commerical Communications:	$45.69
1	5	Optical Sensing:	$24.80
3	8	Interplanetary Missions:	$6.53
2	10	Astronomical Telescope:	$1.31

Human Exploration:		(measured by using % of US GDP)		$ Value:
National Renown:		0.06	=	$ 1,116,000,000,000.00
Extended Science		0.1	=	$ 1,860,000,000,000.00
Technological Gains:		0.056	=	$ 1,041,600,000,000.00
Medical Advances:		0.1	=	$ 1,860,000,000,000.00

Launch Vehicle Value Model

- **Launch Vehicle Value based on 3 factors (currently)**
  - Value is not cost!!!! It includes cost.
  - Industry Value

Launch Vehicle Value	=	Benefit -Ct
Value to Scientific Uses	=	$63,008,431,752.36
Value to Commerical Services	=	$20,584,576,252.36
Value to Resource Mining	=	($2,252,876,665.31)
Value to Human Exploration	=	$ 2,936,540,961,752.35
Total Value	=	$3,017,881,093,091.75

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

    + Unit Cost + Satellite Cost

V2(Commerical 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

Value Lost from Failed Mission		
V(L)(Commerical Communication	=	$7,995,274,012.95
V(L)(Optical Sensing	=	$6,538,291,607.03
V(L)(Interplanetary)	=	$3,732,182,001.85
V(L)(Astronomical Telescope)	=	$2,930,436,400.37
total Value Lost	=	$21,196,184,022.20

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

Satellite Benefit ($B)	4 meters	5 meters	8 meters	10 meters
Commerical Communications:	$45.69	$45.69	$45.69	$45.69
Optical Sensing:	$12.40	$24.80	$24.80	$24.80
Interplanetary Missions:	$2.61	$5.87	$6.53	$6.53
Astronomical Telescope:	$0.00	$0.00	$0.13	$1.31
Total:	$60.70	$76.36	$77.15	$78.32

Launch Vehicle Value	Value
Revenue Value (V1)	$3,017,881,093,091.75
Mission Reliability Value (V2)	$66,294,779,977.80
Payload Size Value (10m Fairiing) (V3)	$78,320,964,000.00

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

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

$$= \left(M_{vehicle,final} \frac{V_{vehicle,final}^2}{2} - M_{vehicle,initial} \frac{V_{vehicle,initial}^2}{2} \right)$$

$$+ \left(\frac{G M_E M_{vehicle,initial}}{r_{altitude,initial}} - \frac{G M_E M_{vehicle,final}}{r_{altitude,final}} \right)$$

$$\eta_{ex} = 1 - \frac{X_{des}}{X_{expended}}$$

.

Crew Module Exergy Balance

$$\Delta X_{ECLSS} = \Delta X_{ACS} + \Delta X_{AR} + \Delta X_{THC} + \Delta X_{WRM} + \Delta X_{WM}$$

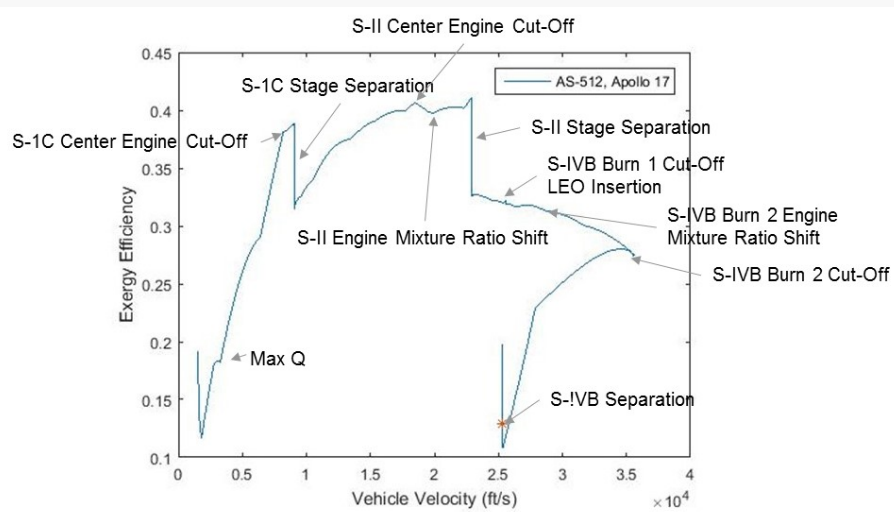
$$\sum_{process} \boldsymbol{m_{fluid}} \left((\boldsymbol{h_{final}} - \boldsymbol{h_{cabin}}) - T_{cabin}(\boldsymbol{s_{final}} - \boldsymbol{s_{cabin}}) + \left(\frac{\boldsymbol{V_{final}^2}}{\boldsymbol{2}} \right) \right)$$

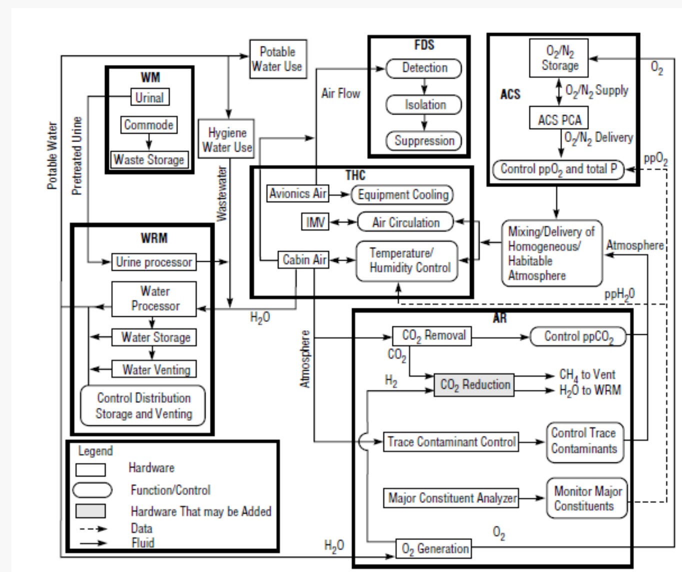
$$- \sum_{process} \boldsymbol{m_{fluid}} \left((\boldsymbol{h_{initial}} - \boldsymbol{h_{cabin}}) - T_{cabin}(\boldsymbol{s_{initial}} - \boldsymbol{s_{cabin}}) + \left(\frac{\boldsymbol{V_{initial}^2}}{\boldsymbol{2}} \right) \right)$$

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

$$- \boldsymbol{P_{cabin}}(\boldsymbol{Vol_{final}} - \boldsymbol{Vol_{initial}})$$

$$+ \boldsymbol{m_{in}} \left[\sum (\boldsymbol{h_{in}} - \boldsymbol{h_{cabin}}) - T_{cabin}(\boldsymbol{s_{in}} - \boldsymbol{s_{cabin}}) + \left(\frac{\boldsymbol{V_{in}^2}}{\boldsymbol{2}} \right) \right.$$





Spacecraft Exergy Balance and Optical Transfer Function

Spacecraft Exergy Balance

$$\Delta \boldsymbol{m}_{\boldsymbol{propellant,engine}}\left(\boldsymbol{h}_{\boldsymbol{prop,engine}}+\frac{\boldsymbol{V}_{\boldsymbol{e,engine}}^{2}}{\mathbf{2}}\right)$$
$$+\Delta \boldsymbol{m}_{\boldsymbol{propellant,thruster}}\left(\boldsymbol{h}_{\boldsymbol{prop,thruster}}+\frac{\boldsymbol{V}_{\boldsymbol{e,thruster}}^{2}}{\mathbf{2}}\right)$$
$$+\sum_{t}\left(\sigma A e\left(T_{radiator}^{4}-T_{space}^{4}\right)+\boldsymbol{V}_{\boldsymbol{bus}}\boldsymbol{I}_{\boldsymbol{bus}}\cos(\theta)\right)\boldsymbol{\Delta t}-\boldsymbol{X}_{\boldsymbol{des}}$$
$$=\left(\boldsymbol{M}_{\boldsymbol{vehicle,final}}\left(\frac{I_{c,final}\,\omega_{vehicle,final}^{2}}{\mathbf{2}}+\frac{\boldsymbol{V}_{\boldsymbol{vehicle,final}}^{2}}{\mathbf{2}}\right)\right.$$

Optical Transfer Function

$$\iint_{-\infty}^{\infty}\psi_{obj}s_{f}dxdy$$
$$=\iint_{-\infty}^{\infty}\psi_{obj}(x_0+\boldsymbol{\epsilon}x,y_0+\boldsymbol{\epsilon}y)e^{j\left(\frac{k_0}{2f_1}\right)(x^2+y^2)}\mathrm{circ}(x+\Delta x+\delta x,y+\Delta y+\delta y)dxdy$$

Where

$$\epsilon x=1.22\lambda_0\left(\frac{f_1}{d_0+\epsilon z+\omega_y\Delta t}\right)+v_x\Delta t+\omega_y\Delta t$$
$$\epsilon y=1.22\lambda_0\left(\frac{f_1}{d_0+\epsilon z+\omega_x\Delta t}\right)+v_y\Delta t+\omega_x\Delta t$$

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

$$\Delta x=\alpha x\Delta T$$
$$\Delta y=\alpha y\Delta T$$

$C^2>\boldsymbol{4Mk}$ Over Damped

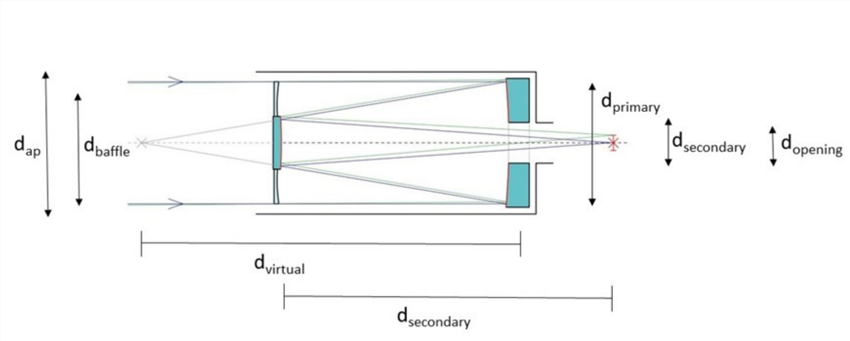
$$\delta x=c_1e^{-\left(\frac{C}{2M}-\frac{1}{2M}\sqrt{C^2-4Mk}\right)t}+c_2e^{-\left(\frac{C}{2M}+\frac{1}{2M}\sqrt{C^2-4Mk}\right)t}$$

$C^2=\boldsymbol{4Mk}$ Critically Damped

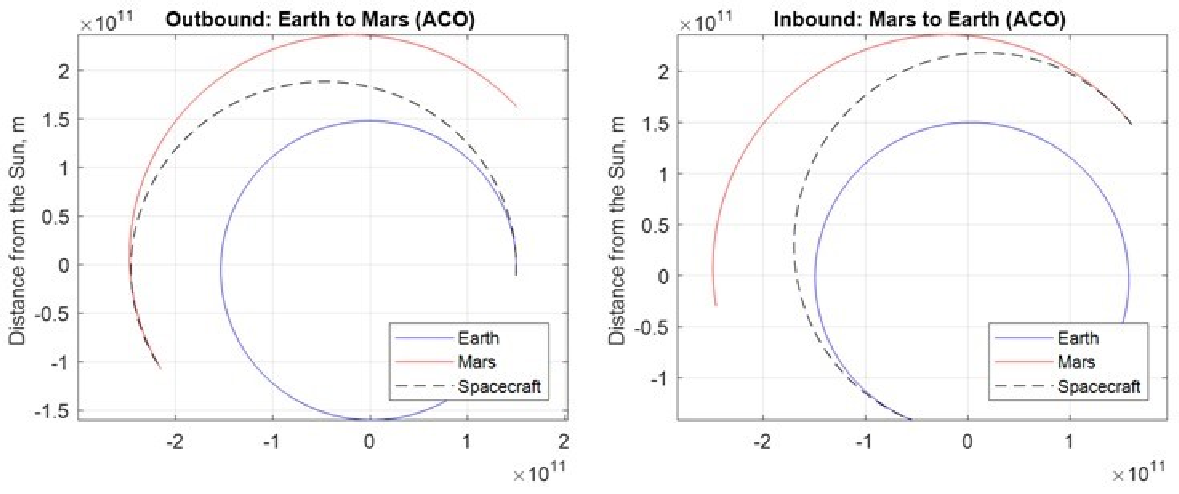
$$\delta x=(c_1+c_2)e^{-\left(\frac{C}{2M}\right)t}$$

$C^2<\boldsymbol{4Mk}$ Under Damped

$$\delta x=c_3e^{-\left(\frac{C}{2M}\right)t}cos\left(\sqrt{4Mk-C^2}t-\varphi\right)$$
$$\tan(\varphi)=\frac{x'(0)}{x(0)\sqrt{\frac{k}{M}}}$$
$$c_3{}^2=\sqrt{x(0)^2+\frac{M}{k}x'(0)^2}$$



Mars Interplanetary Exergy Analysis



$$e_{transfer} = 1 - \frac{r_{periapsis}}{a_{transfer}}$$

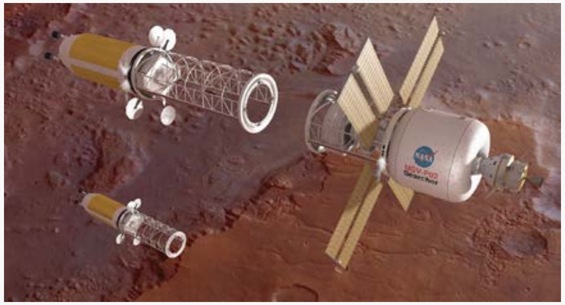
$$V_{periapsis,transfer} = \sqrt{\mu_{planet}\left(\frac{2}{r_{periapsis}} - \frac{1}{a_{transfer}}\right)}$$

$$V_{periapsis,parking} = V_{periapsis,transfer} - \Delta V$$

$$a_{parking} = 1/\left(\left(\frac{2}{r_{periapsis}}\right) - \left(\frac{V_{periapsis,parking}^2}{\mu_{planet}}\right)\right)$$

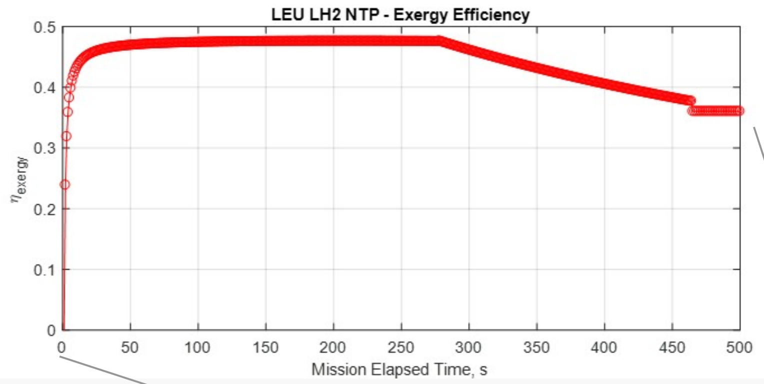
$$e_{parking} = 1 - \frac{r_{periapsis,parking}}{a}$$

$$r_{apoapsis} = r_{periapsis}\left(\frac{1 + e_{parking}}{1 - e_{parking}}\right)$$

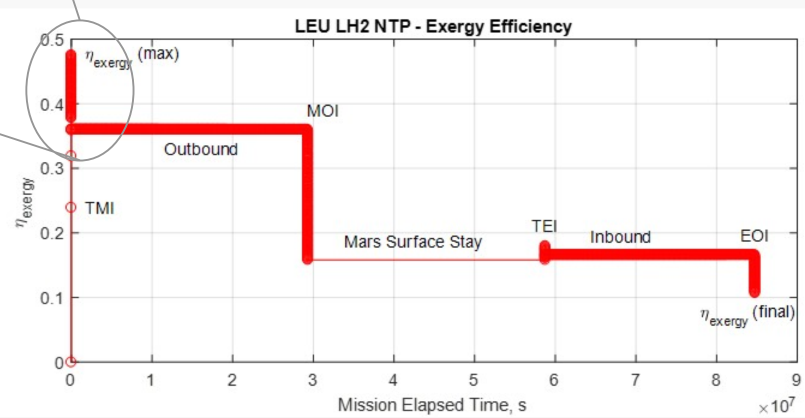


Mars Interplanetary Exergy Analysis

- $$\sum_{stages}\left[\Delta m_{propellant}\left(h_{prop}+\frac{v_e^2}{2}\right)\right]-X_{des}=$$
$$\sum_{stages}\left[\left(M_{vehicle,final}\frac{v^2_{vehicle,final}}{2}-M_{vehicle,initial}\frac{v^2_{vehicle,initial}}{2}\right)+\left(\frac{GM_EM_{vehicle,initial}}{r_{altitude,initial}}-\frac{GM_EM_{vehicle,final}}{r_{altitude,final}}\right)\right]$$

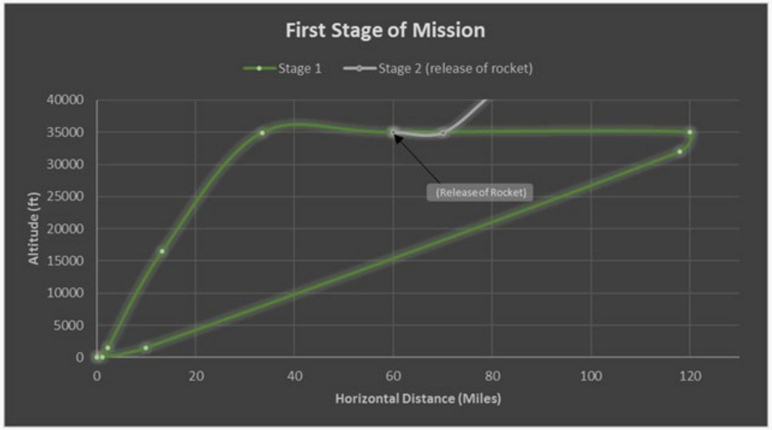


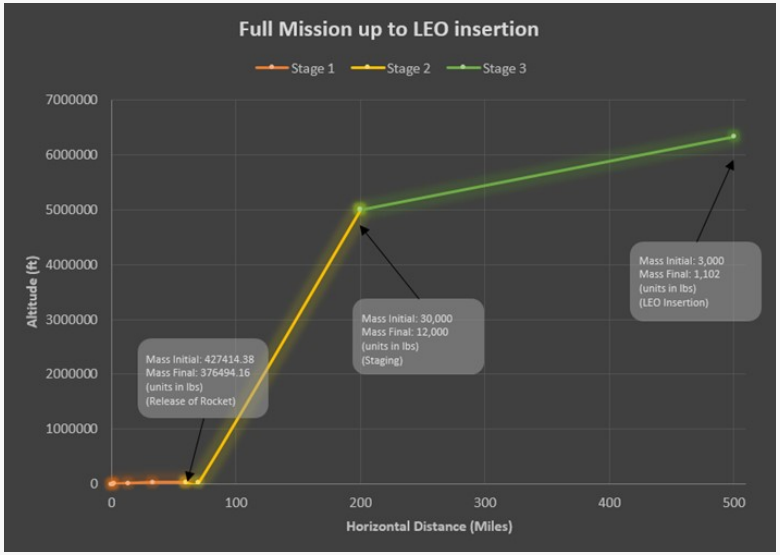
Mass	Velocity	ΔKE_{step}	Distance	ΔPE_{step}
$M_f = M_i$	$V_f > V_i$	+	$r_f > r_i$	+
$M_f = M_i$	$V_f < V_i$	−	$r_f < r_i$	−
$\begin{cases} M_f > M_i \\ M_f = XM_i \end{cases}$	$\begin{cases} V_f > V_i \\ V_f = ZV_i \end{cases}$	+	$\begin{cases} r_f > r_i \\ r_f = Yr_i \end{cases}$	$\begin{cases} + \ (Y > X) \\ - \ (Y < X) \end{cases}$
$\begin{cases} M_f > M_i \\ M_f = XM_i \end{cases}$	$\begin{cases} V_f < V_i \\ V_i = ZV_f \end{cases}$	$\begin{cases} - \ (Z^2 > X) \\ + \ (Z^2 < X) \end{cases}$	$\begin{cases} r_f < r_i \\ r_i = Yr_f \end{cases}$	−
$\begin{cases} M_f < M_i \\ M_i = XM_f \end{cases}$	$\begin{cases} V_f > V_i \\ V_f = ZV_i \end{cases}$	$\begin{cases} + \ (Z^2 > X) \\ - \ (Z^2 < X) \end{cases}$	$\begin{cases} r_f > r_i \\ r_f = Yr_i \end{cases}$	+
$\begin{cases} M_f < M_i \\ M_i = XM_f \end{cases}$	$\begin{cases} V_f < V_i \\ V_i = ZV_f \end{cases}$	−	$\begin{cases} r_f < r_i \\ r_i = Yr_f \end{cases}$	$\begin{cases} - \ (Y > X) \\ + \ (Y < X) \end{cases}$



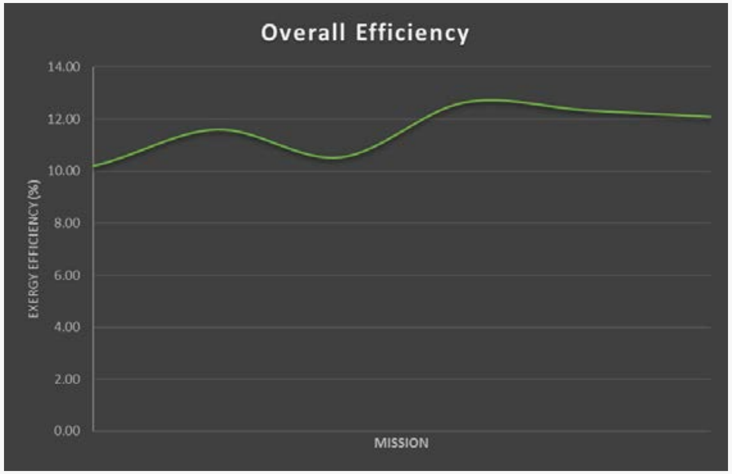
Air Launched Rocket Exergy Analysis

747-400 lifting a 2 stage rocket to launch altitude and velocity





- $\Delta m_{propellant,aircraft} H_{total,aircraft} + \sum_{stages}\left[\Delta m_{propellant}\left(h_{prop} + \frac{V_e^2}{2}\right)\right] - X_{des} = \sum_{stages}\left[\left(M_{vehicle,final}\frac{V_{vehicle,final}^2}{2} - \right.\right.$



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

- **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

SLS SE&I MANAGEMENT STRUCTURE

June 9, 2014 version

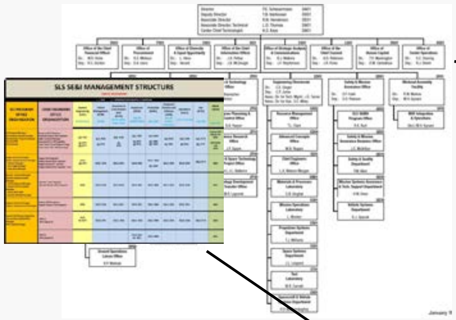
( ) = OPR [ ] = ORGANIZATIONS MAPPED TO DISCIPLINE

SLS PROGRAM OFFICE ORGANIZATION	CHIEF ENGINEERS OFFICE ORGANIZATION	Systems Engineering (EV01) [EV70, EE12]	Vehicle Management (EV40) [EV40]	Structures & Environments (StE) (EV30) [EV30, ER40, ES21, ES22]	Propulsion (ER01) [ALL ER EXCEPT ER40]	Production (EM01) [ALL EM]	Integrated Avionics and Software (ES01) [ALL ES EXCEPT ES21,ES22]	Operations (EO01) [ALL EO, ES10]	Test (ET01) [ALL ET]	S&MA (QD01) [ALL QD]
SLS Program Manager SLS Program Deputy Manager SLS Associate Program Manager Assistant PM Procurement	Program Chief Engineer Program Deputy Chief Engineer SE&I Technical Manager Assistant CE for Affordability Tech. Assist. Cross Program Integ. Tech. Assist. Ext. Interface Integ.	LSE: EV01 Alt: EV70 Alt: EV73	DLE: EV40 Alt: EV40	DLE: EV30 Alt: EV30	DLE: ER01 Alt: ER51 Alt: ER24	DLE: EM03 Alt: EM03 Alt: EM03	DLE: ES30 Alt: ES01	DLE: EO04 Alt: EO04	DLE: ET10 Alt: ET10	Program CSO Deputy CSO QD02 SE&I S&MA Lead QD35
Stages Element Manager Stages Deputy Element Manager - Avionics Manager - Core Stage Manager - Integration Manager	Stages Chief Engineer Stages Deputy Chief Engineer Stages Deputy CE - Avionics Stages Deputy Chief Engineer - Test	EV70 Alt: EV71	EDLE: EV41	EDLE: EV34	EDLE: ER22	EDLE: EM03 Alt: EM32	EDLE: ES12	EDLE: EO40	EDLE: ET10	QD33
Booster Element Manager Booster Deputy Element Manager - Control Systems Manager - Assem & Struct Systems Manager - Motor/BSM ASM - Booster CEI/Interface Mgr	Booster Chief Engineer Booster Deputy Chief Engineer	ER50	EDLE: EV40	EDLE: ER40	EDLE: ER51	EDLE: EM03	EDLE: ES12	EDLE: EO40		QD31
Engines Element Manager Engines Deputy Element Manager	Engines Chief Engineer Engines Deputy Chief Engineer	ER20	EDLE: EV43	EDLE: ER41	EDLE: ER21	EDLE: EM03	EDLE: ES12	EDLE: ER21		QD32
Spacecraft/Payload Integration and Evolution (SPIE) Office Manager SPIE Deputy Manager	SPIE CE SPIE Deputy CE	EV70 Alt: EV70	EDLE: EV41	EDLE: EV30	EDLE: ER23	EDLE: EM03	EDLE: ES10	EDLE: EO40	EDLE: ET30	QD22
	SPIE CE SPIE Deputy CE				EDLE: ER01 Alt: ER21	EDLE: EM03				QD31

- **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**

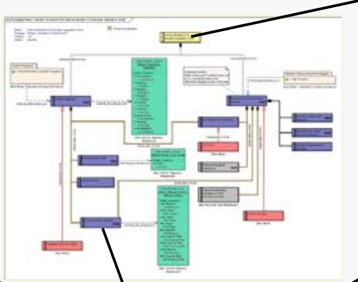
Discipline Integration Models



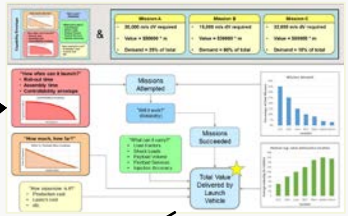
Organizational Structure & Mapping

Organizational Values

Goal Function Tree (GFT)



Value Model

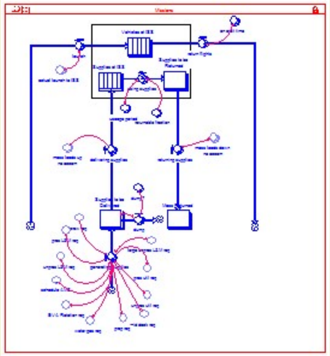


Goals

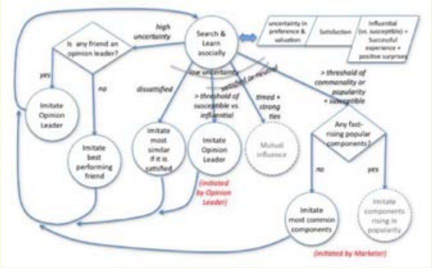
Value Attributes

System Functions

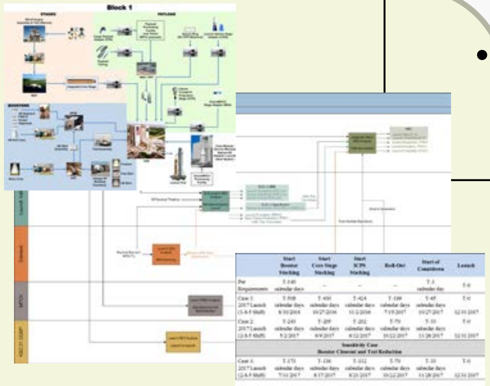
- Allow systems engineers to:
  - Understand information flow through the development and/or operations organization
  - Integrate discipline information into a system level design
  - Analyze information flow, gaps, and blind spots at the System level



System Dynamics Model



Agent Based Model (ABM)



Discrete Event Simulation

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

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: Theory of Systems Engineering”
  - “Engineering Elegant Systems: The Practice of Systems Engineering”

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

Backup

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

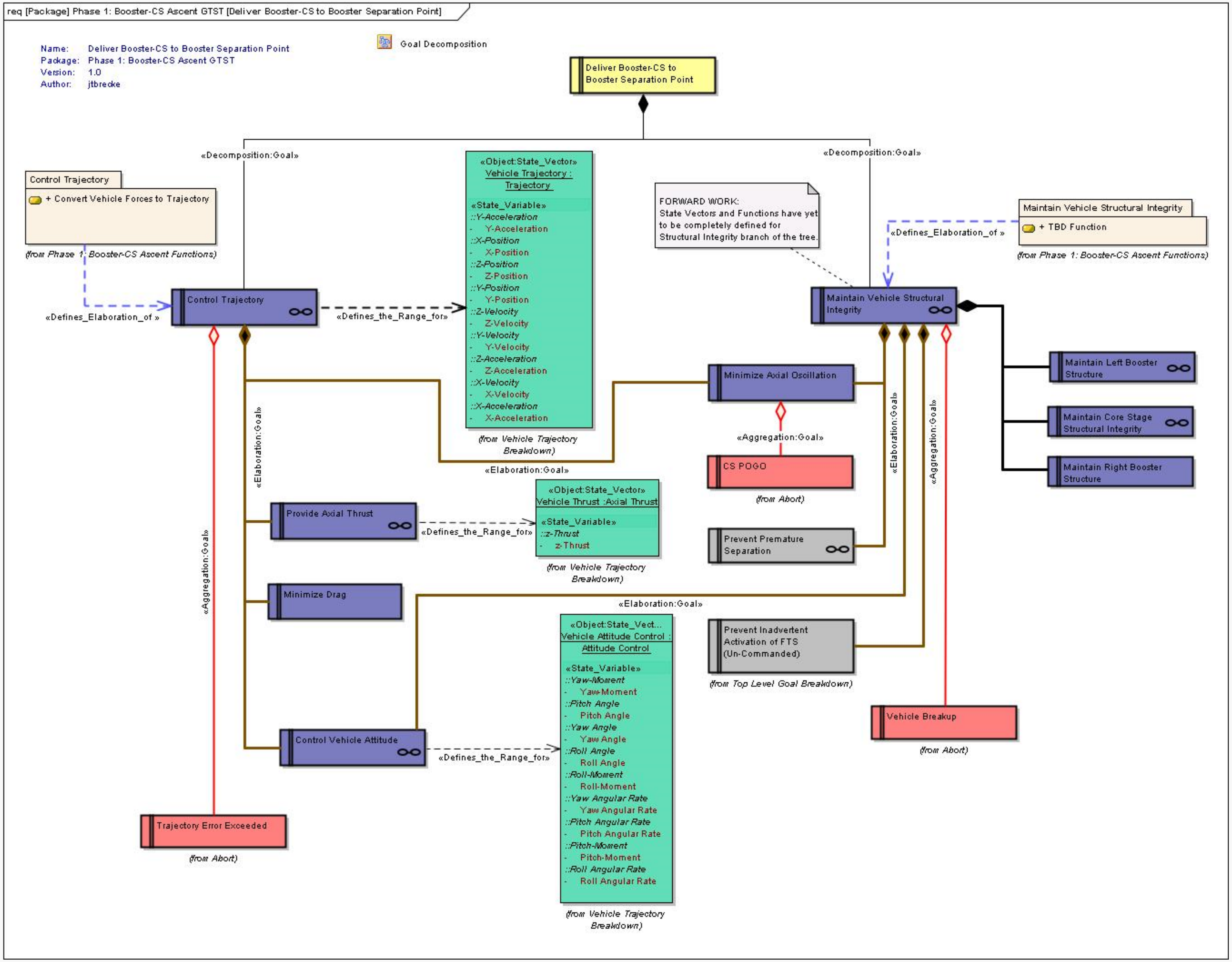
- **System Stage Models represent the system as a whole in terms of the hardware and software states that the system transitions through during operation**

- **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

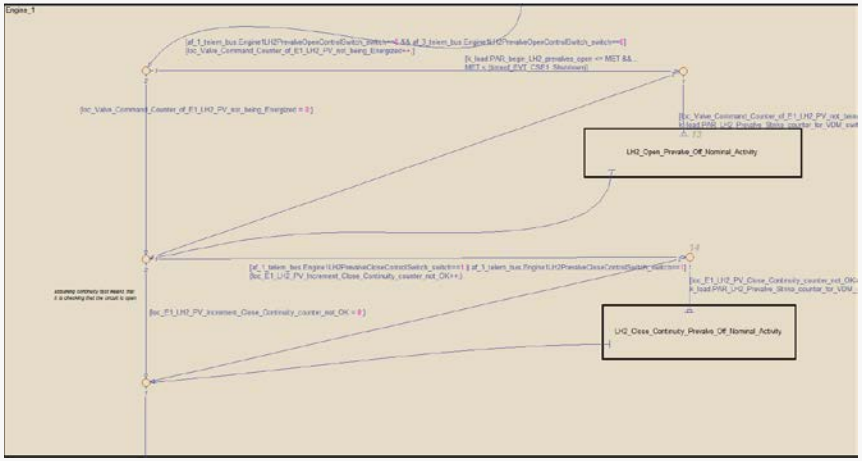
Booster – CS Ascent GFT

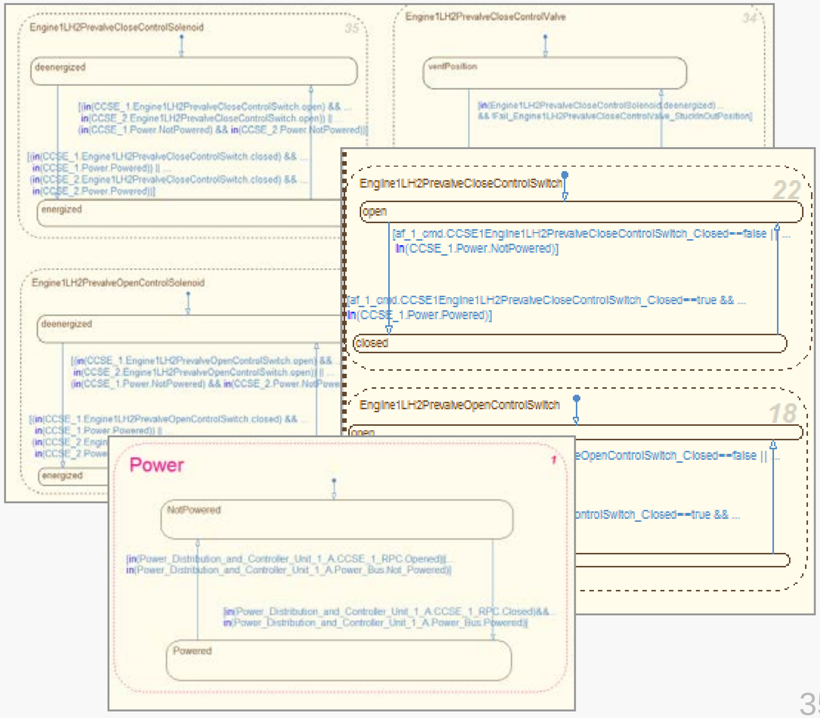
System Works



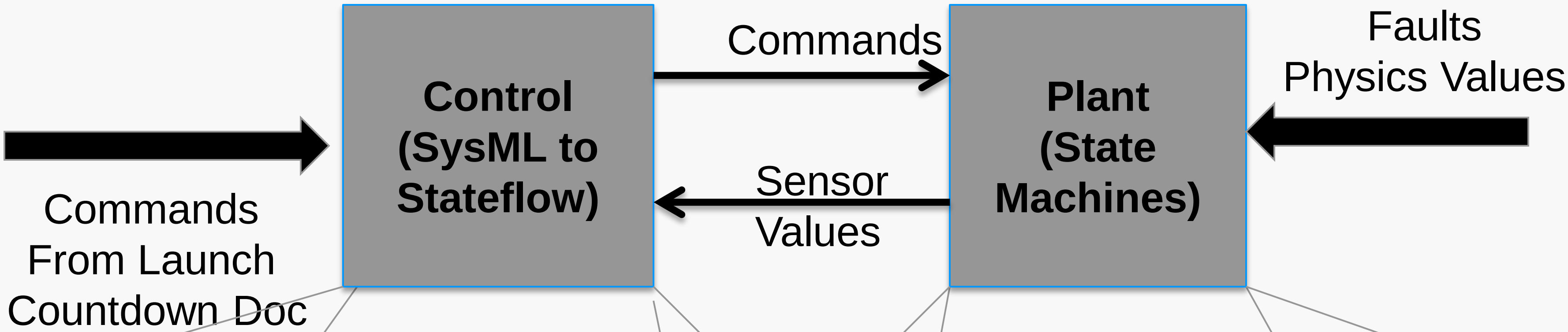
System State Machine Model

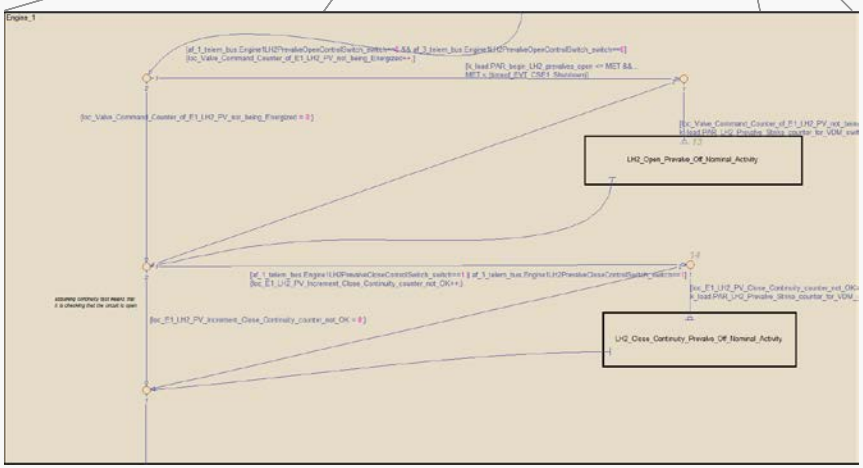
- **The state analysis model is split into two main components:**
  - Manager software model
  - System Plant
- **Modeled using MATLAB Stateflow**
  - Allows the software model to look like the SysML Activity Diagrams
  - Allows the System Plant to be modeled as State Machines
  - Allows those two models to interact with each other within the MATLAB environment
    - Facilitates the ability to generate custom analysis tools
- **Reads in command sequence to execute model**

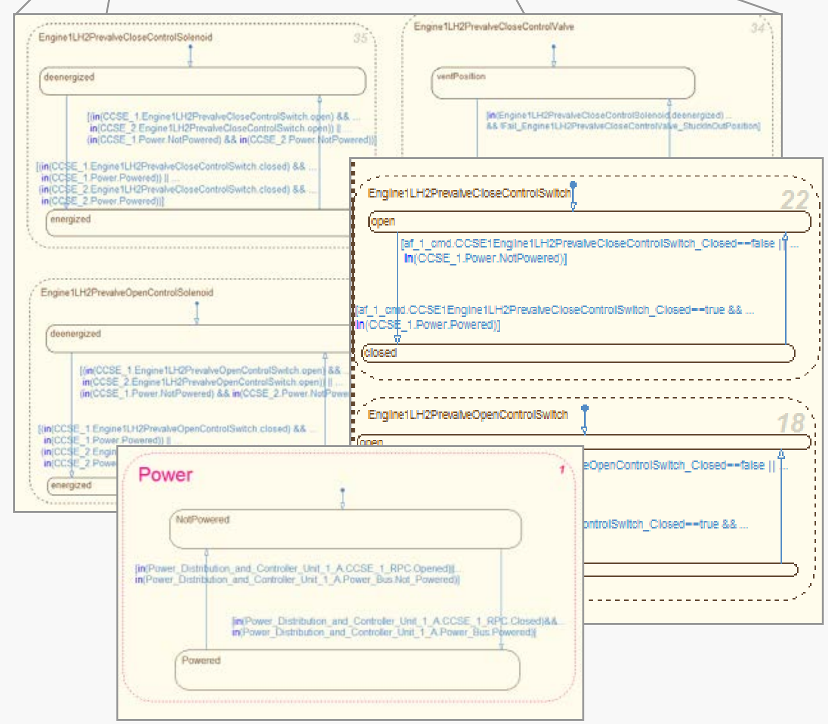




State Analysis Model for SLS M&FM





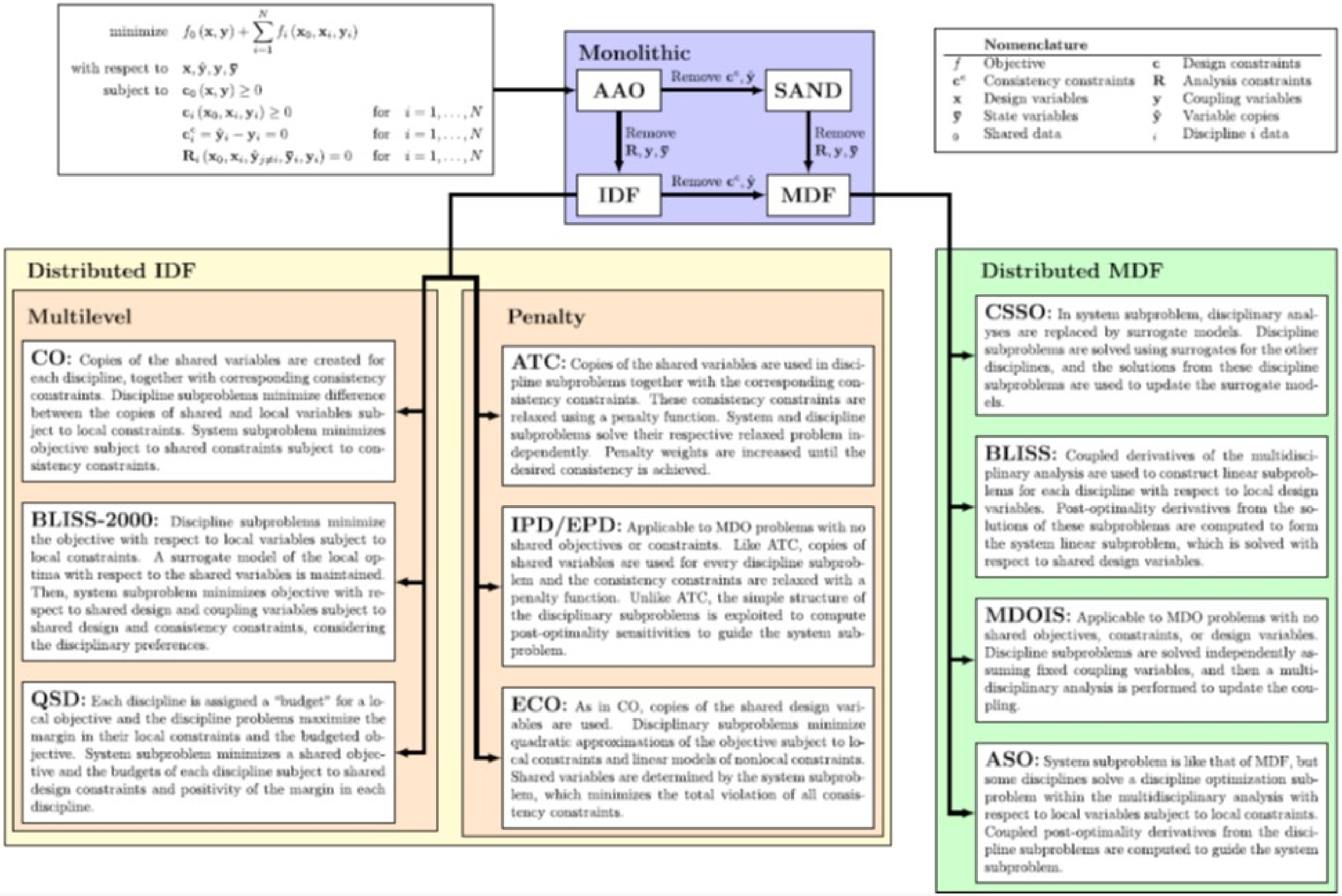


- 14% of R12 modeled
- Over 7,200 Transitions in the Vehicle and Software
- Over 3,500 States in the Vehicle

System Design and Optimization

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

Multidisciplinary Design Optimization



Martins, J. R R. A., Lambe, A. B., "Multidisciplinary Design Optimization: A Survey of Architectures", AIAA Journal, Vol. 51,No. 9, September 2013, pp 2049 – 2075

Engineering Statistics

Goal: Utilize statistical methods to understand system uncertainties and sensitivities

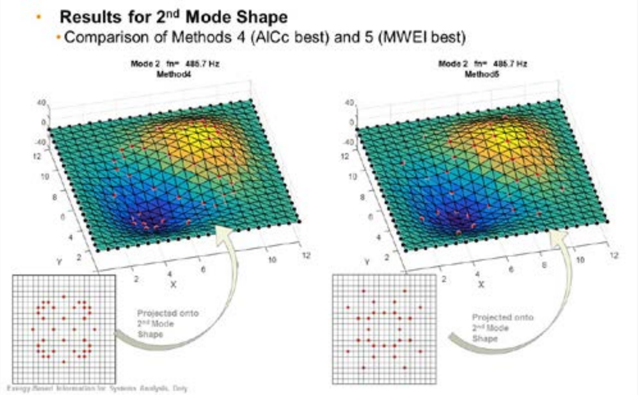
Systems Engineering makes use of Frequentist Approaches, Bayesian Approaches, Information Theoretic Approaches as appropriate

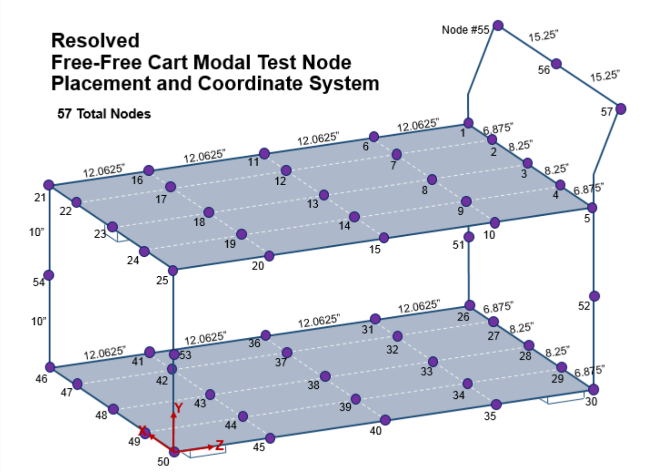
Optimal Sensor Information Configuration

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

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

- **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