The World's Forum for Aerospace Leadership

Electric Aircraft Technologies Symposium (EATS)

System Engineering Principles of Complexity

Session: System Engineering Needs and Challenges Generated by Electrification of Air Vehicles

Systems Engineering Postulates and Hypotheses

- **Postulate 1: <u>Systems Engineering is product and environment specific, and context dependent.</u>**
- **Postulate 2: <u>The Systems Engineering domain consists of subsystems, their interactions among themselves, and their interactions with the system environment</u>**
- **Postulate 3: The function of Systems Engineering is to integrate engineering disciplines in an elegant manner**
- **Postulate 4: <u>Systems engineering influences and is influenced by organizational structure and culture</u>**
- **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: <u>Understanding of the system evolves as the system development or operation progresses</u>**
- **Postulate 7 Corollary: Understanding of the system degrades during operations if system understanding is not maintained.**

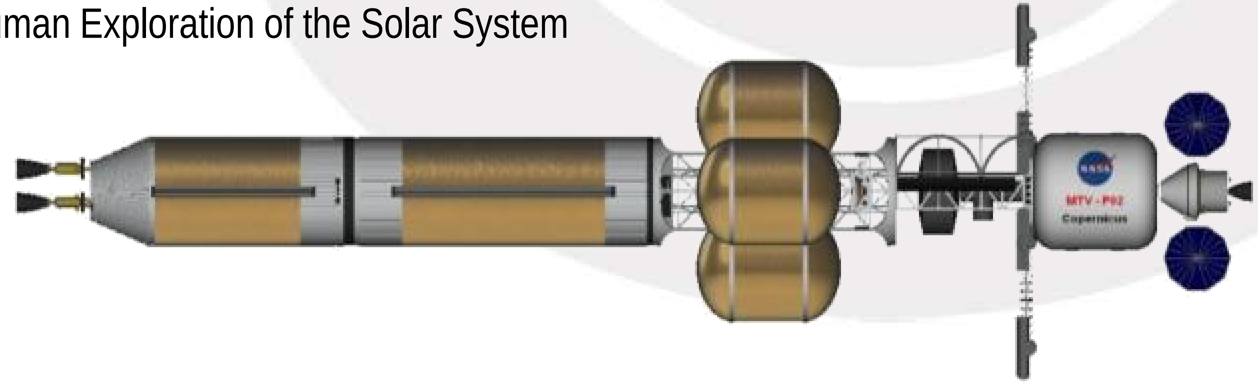
- Hypothesis 1: <u>If a solution exists for a specific context, then there exists at least one ideal Systems Engineering solution for that specific context</u>
  - Hamilton's Principle shows this for a physical system
    - $\int_{t_1}^{t_2}(\delta T - \delta V + \delta W)dt = 0$
- Hypothesis 2: <u>System complexity is greater than or equal to the ideal system complexity necessary to fulfill all system outputs</u>
- Hypothesis 3: Key Stakeholders preferences can be represented mathematically
- Hypothesis 4: The real physical system is the perfect model of the system
  - Kullback-Liebler Information shows this for ideal information representations of systems
    - $I(f,g) = \int f(x)\log(f(x))\,dx - \int f(x)\log(g(x|\theta))\,dx = 0$

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 are specific, agreed to preferences by the developing organization
  - Sub-Principle 3(b): Requirements and design are progressively defined as the development progresses
  - Sub-Principle 3(c): Hierarchical structures are not sufficient to fully model system interactions and couplings
  - Sub-Principle 3(d): A Product Breakdown Structure (PBS) provides a structure to integrate cost and schedule with system functions
- **Principle 4: Systems engineering spans 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 mathematical basis
  - Sub-Principle 5(b): Systems engineering has a physical/logical basis
  - Sub-Principle 5(c): Systems engineering has a sociological basis
- **Principle 6: Systems engineering maps and manages the discipline interactions within the organization**
- **Principle 7: Decision quality depends on the system knowledge represented 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**
- **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**

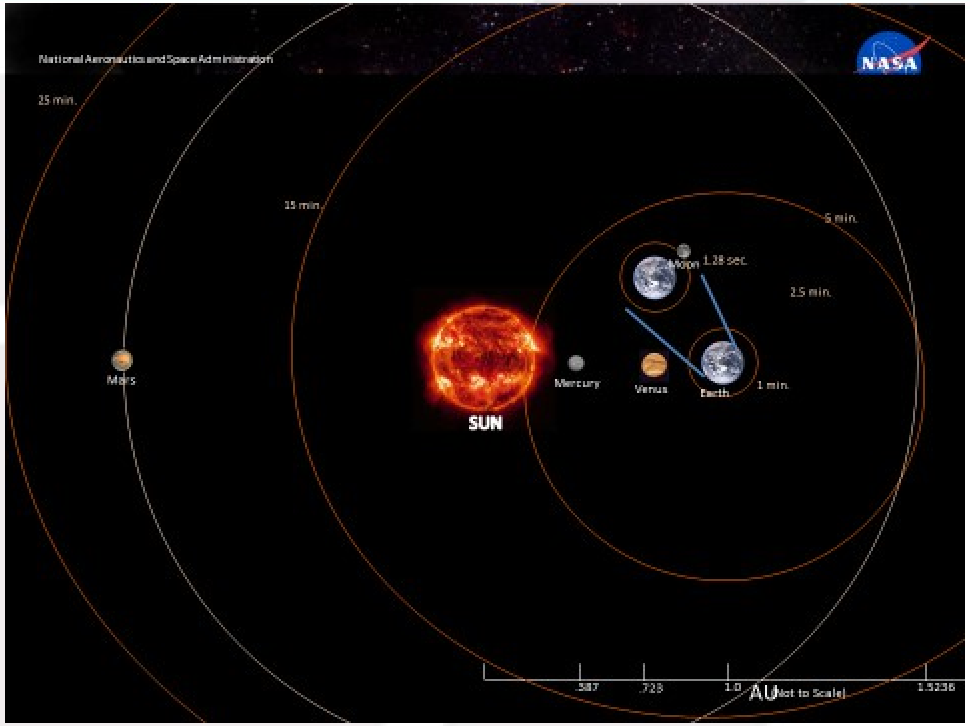
Autonomy in Context: What and Why?

- Spacecraft and Surface System Autonomy is the enabling capability for Human Exploration beyond Lunar Sortie Missions
  - Autonomy is necessary for complex system operations (Hypotheses 1 & 2)
  - Timely response to unplanned or unscheduled events (Principles 7 & 9)
- Propulsion, Structure, Thermal Conditioning, ECLSS, Electrical Power, Avionics, RCS, Communication are all understood sufficiently to allow engineered solutions to be reliably produced (Postulates 1, 2, 7, 7 Corollary, Principles 3, 4a)
  - Challenges do exist in terms of Space Environmental Effects, efficiency, compact size
    - Radiation Hardened computer processors needed
  - Physics and demonstrated solutions are available from which to engineer a vehicle
  - Large organizations involved in defining the vehicle (Postulate 4, Principles 2 & 6)
- Operations are sufficiently understood for terrestrial based execution, not on-board execution (Principle 4a, 4f)
  - Manual operations provide a rich knowledge base of planning and execution processes
  - Manual operations have a generic template (derived from Apollo/Saturn) applied uniquely to each spacecraft
  - Terrestrial based manual operations will not support operations beyond 5 light minutes from Earth
- Autonomous Operations are essential to Human Exploration of the Solar System



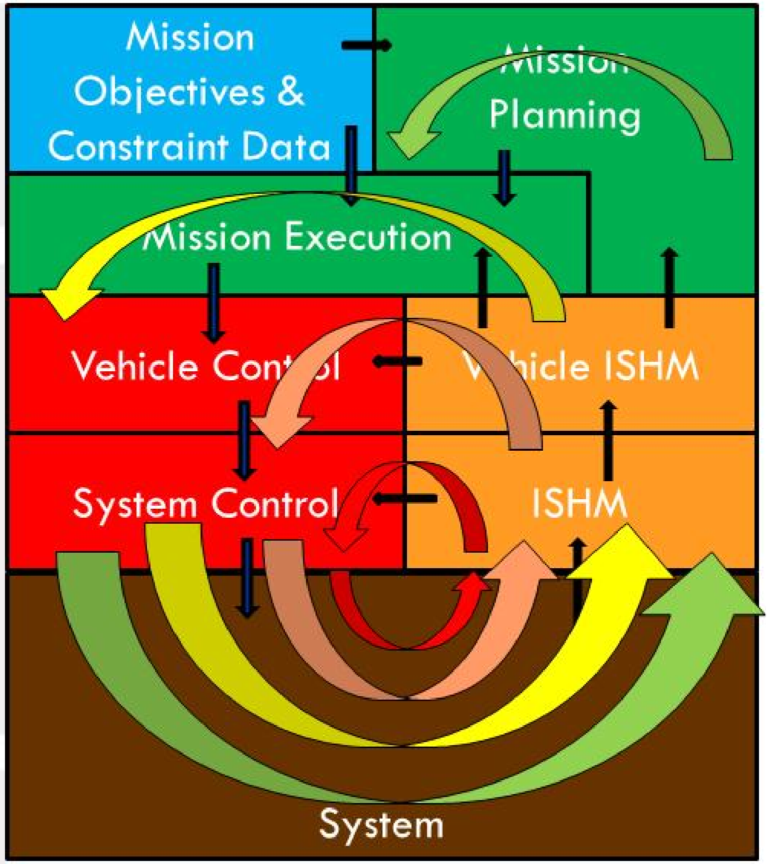
Operations Concept Drivers

- Small Crew Size (4-6)
  - 1 crew member per shift available for vehicle operations
  - Limited systems experts
- Complex Systems
  - Nuclear Power and Propulsion Systems (Principle 8)
  - Life Support and Environmental Protection
  - USN Attack Submarines are similar complexity systems but have 134 crew members
  - ~525 high level functions to manage an interplanetary crewed spacecraft.
- Abort Scenarios
  - Unambiguous determination
  - Extremely low latency
  - Fully autonomous/automated (crew incapacitated conditions)
  - Vehicle reconfiguration necessary
- Long Communication Latency/Blockages
  - 15 minutes one way, 30 minutes round trip to Mars
    - Ground based intelligence not responsive to maintain crew safety
  - 1 hour blockage by Moon each Lunar orbit
- Harsh Environment
  - Solar flare radiation
  - Meteorites



Autonomous Algorithm Integration

- 3 Levels
  - Mission Execution and Planning
  - Vehicle Management
    - Subsystem Integration Based
    - Physics form basis of subsystem interactions
      - » Form basis of normal or failed states
  - Subsystem Level
    - Physics based



Summary

- Human exploration outside of the Earth planetary system (beyond Earth orbit) requires autonomous operation of the vehicle
  - Communication Latencies
  - Crew size Limits
  - Vehicle Complexity
- A fully autonomous vehicle of this complexity will require multiple autonomous algorithms working cooperatively within a set of mission objectives and system constraints
  - The understanding of the physics of the systems, system interactions, and environmental interactions is essential to the system engineering of this complex system
- Algorithms at the vehicle level will need to handle future projected states to enable safe mission execution and planning.
- Verification and validation approaches will need to be defined for these algorithms, both individually and as an integrated set (Principles 10 and 11)
  - V&V will also need to borrow from Formal Methods (e.g., model checkers)
- Applications looking at autonomous system cooperation will be essential to the development of human rated spacecraft operated away from the Earth planetary system