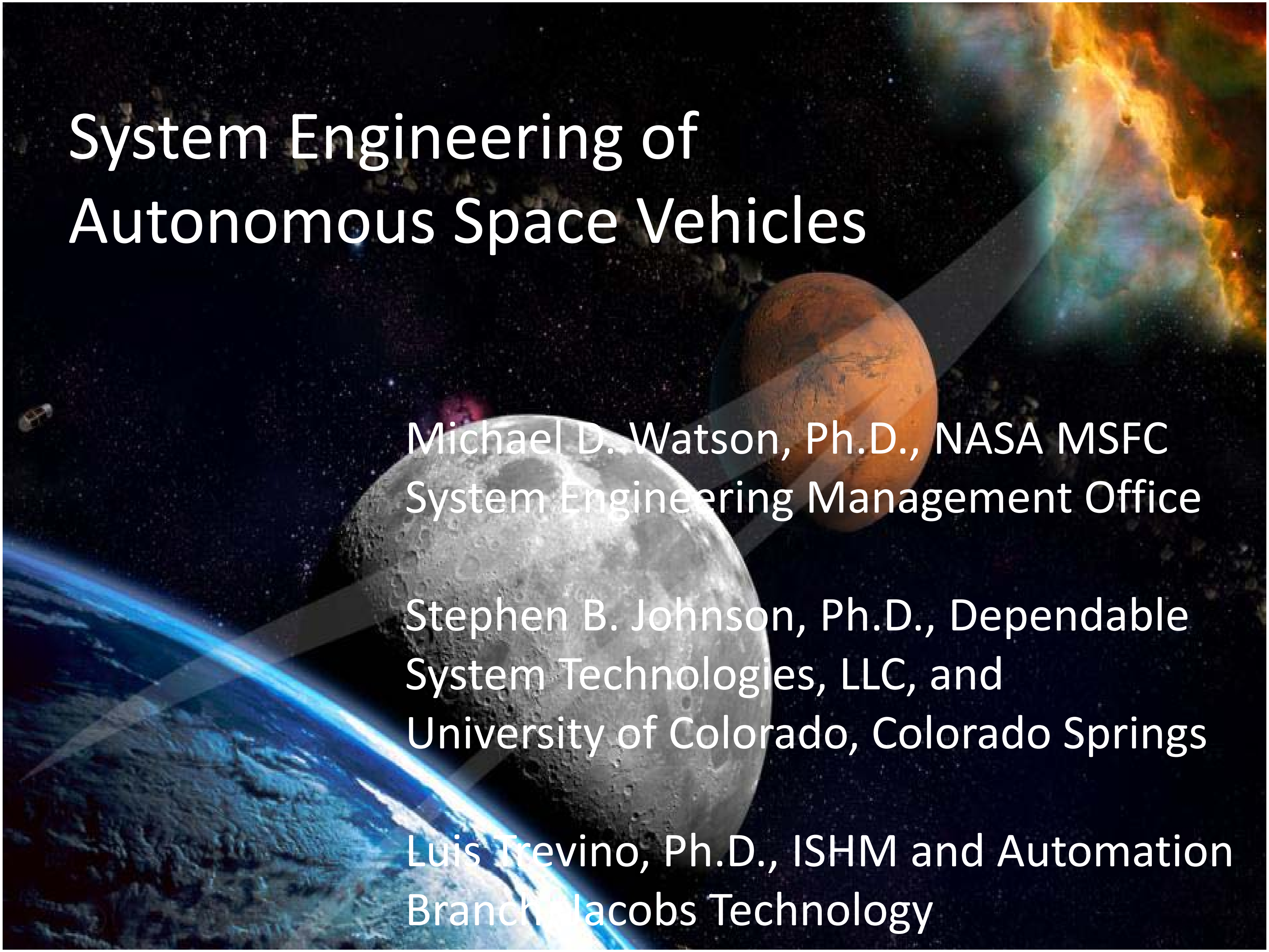

System Engineering of Autonomous Space Vehicles

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Outline

- System Engineering of Autonomous Systems
- Spacecraft Systems Overview
- Spacecraft System State Variables
- Autonomy Stack
- Candidate Autonomous Algorithms for Spacecraft Systems
- Autonomous Algorithm Integration
- Summary

System Engineering of Autonomous Systems

- System Engineering seeks to obtain Elegant Systems which function
  - Effectively in their intended application and environment
  - Most efficiently as compared to options fitting the system context
  - Robustly in application and operation
  - Avoiding Unintended Consequences

System Engineering of Autonomous Systems

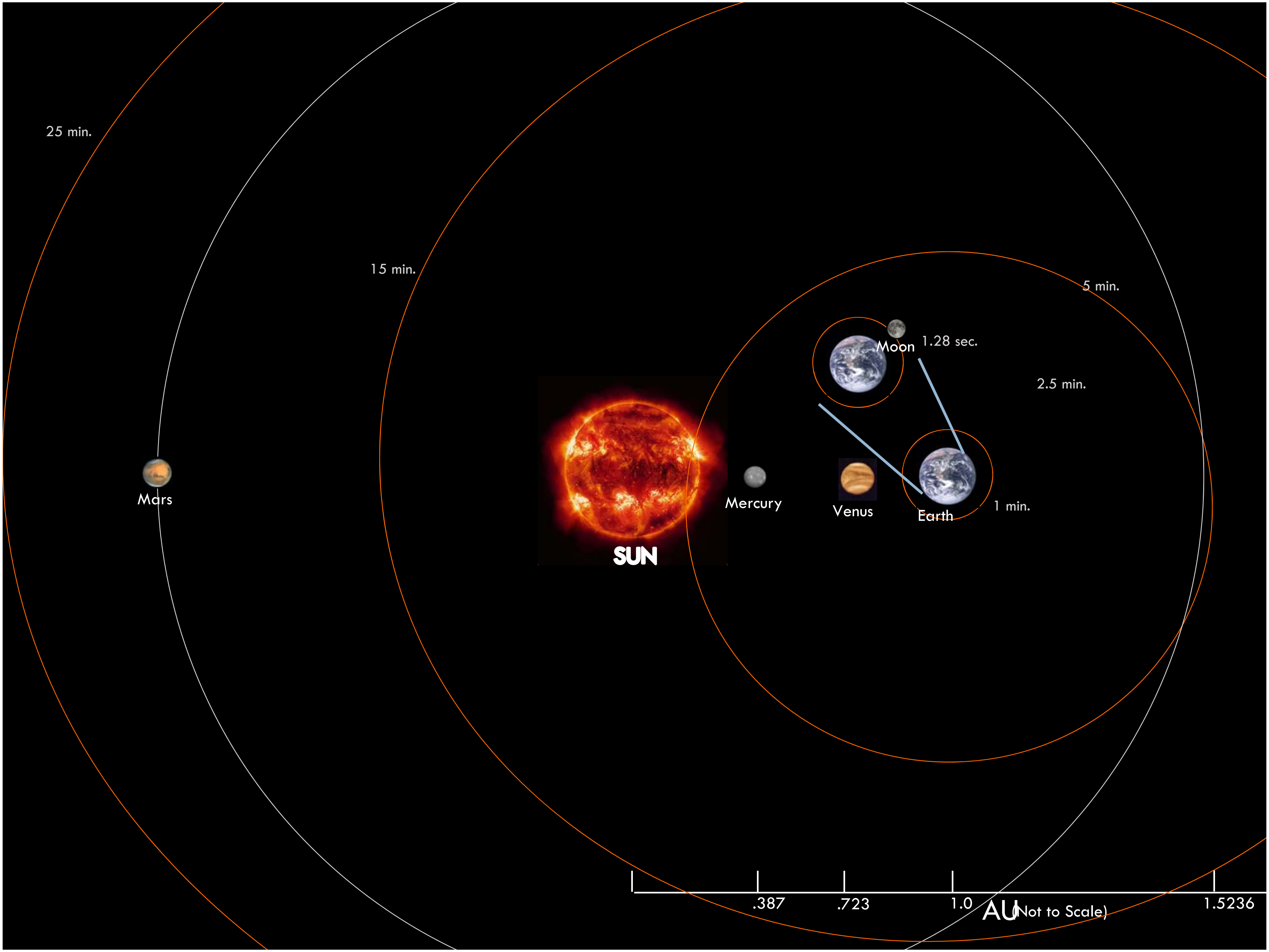
- Elegant System Engineering requires
  - Understanding the Mission Context
    - System Applications
    - System Environments (operational, test, abort, etc.)
  - Understanding the Physics of the System
    - System Interactions with themselves and with their environments are governed by their physics
    - Information Theory provides linkages between physical state representations and actual physical states
  - Managing the organizational influences on system design and the system context influences on the organization
  - Understanding Policy and Law Constraints
    - National Space Policy
    - International Space Treaties and agreements
      - Space Debris, Contamination, Property

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
  - Timely response to unplanned or unscheduled events
- Propulsion, Structure, Thermal Conditioning, ECLSS, Electrical Power, Avionics, RCS, Communication are all understood sufficiently to allow engineered solutions to be reliably produced
  - 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
- Operations are sufficiently understood for terrestrial based execution, not on-board execution
  - 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
  - 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


25 min.
15 min.
5 min.
Moon
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2.5 min.
Mars
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Mercury
Venus
Earth
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1.0
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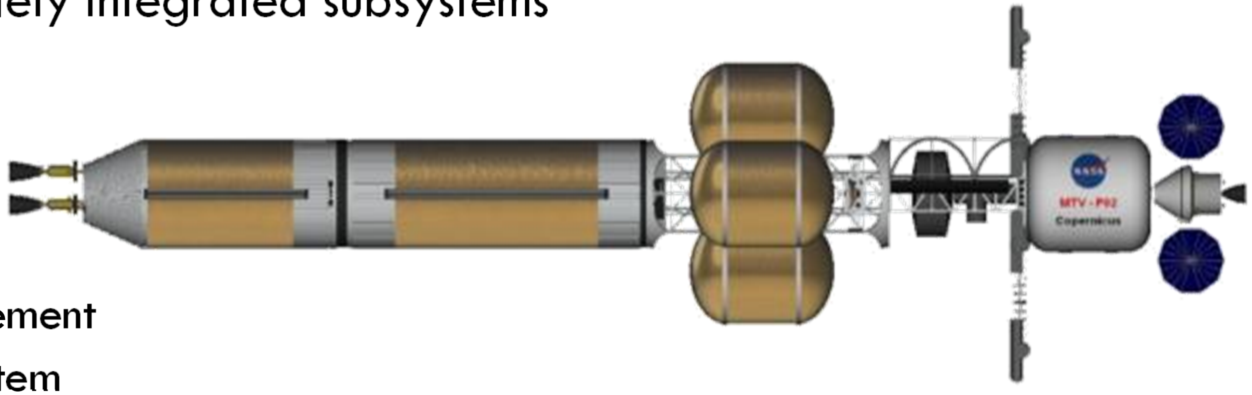
(Not to Scale)
1.5236

Spacecraft Systems Overview

- Beyond Earth Orbit (BEO) crew transport vehicle are comprised of several unique and intricately integrated subsystems
  - Propulsion
  - Structure
  - Electrical Power
  - Avionics
  - Thermal Management
  - Flight control system
  - Communication and Tracking
  - Vehicle Management (Guidance, Navigation and Control (GN&C) and Mission and Fault Management (M&FM))
  - Environmental Control and Life Support Systems (ECLSS)

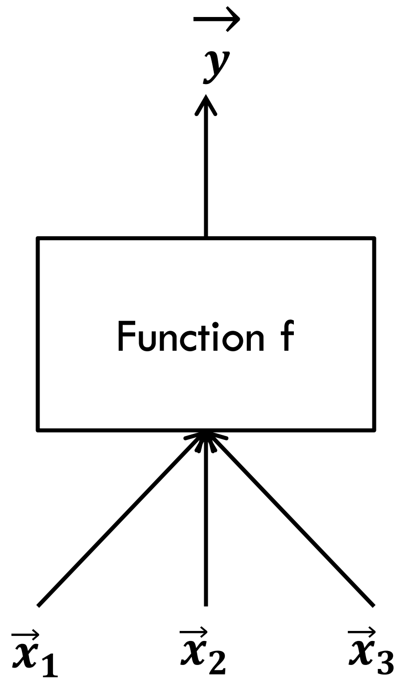


- Each of these subsystems are driven by unique physics and information theory relationships
- Control Theory governs the control of each subsystem both independently and at the vehicle level

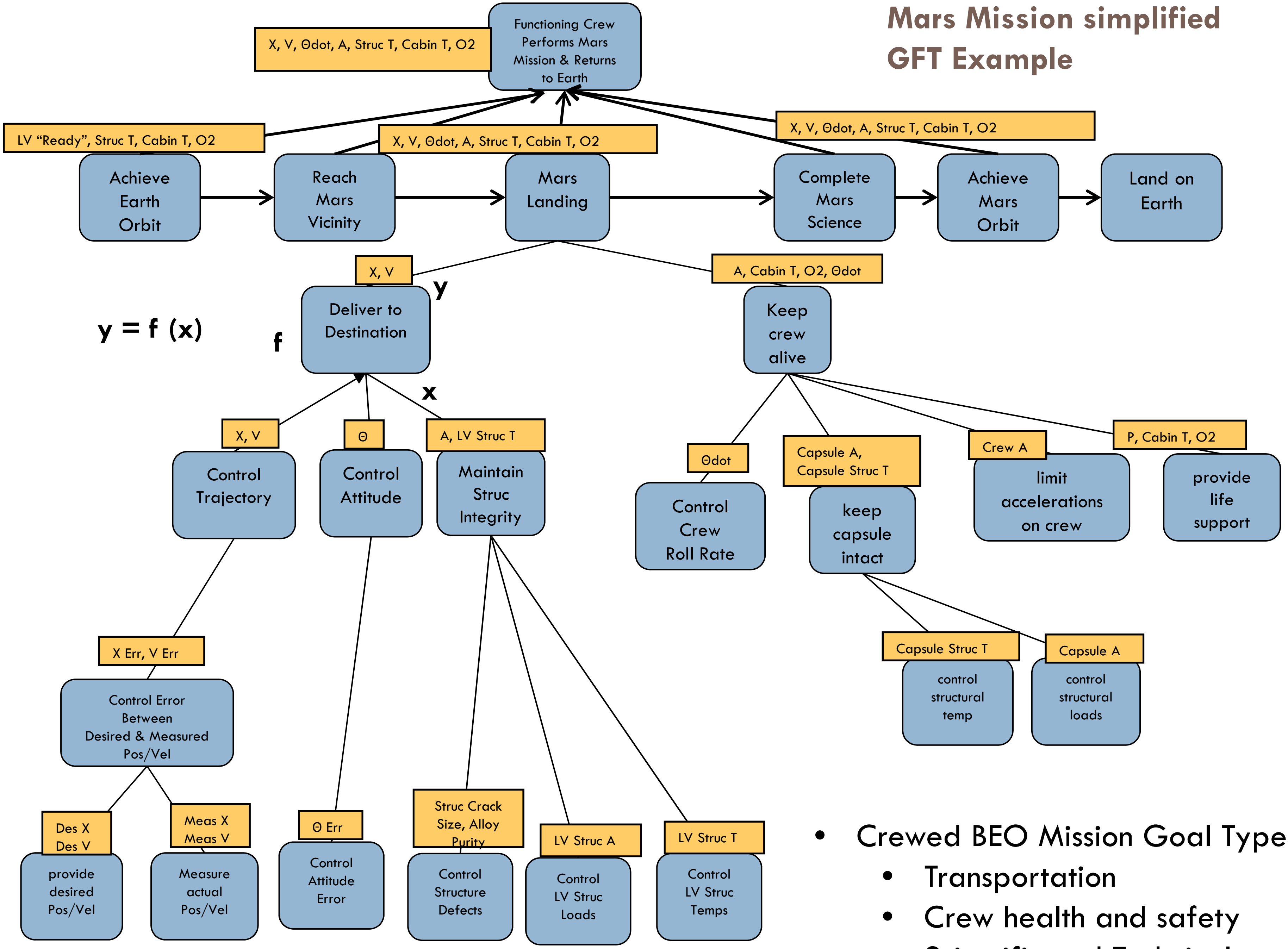
State Variable Methodology

- Goal/Function Tree
  - State Variable to define System Performance
    - State variables are defined as inputs and outputs to functions: y=f(x)
      - x = inputs to the functions f
      - f transforms the inputs into the outputs y
    - Goals = Requirements => define intended range of the output state variables y
    - Failure = state (value) of output state variable y is out of intended range
    - State variables enforce strong connection of the functional decomposition to the system's physical laws and causation
    - The state variables are the connection between function and design—exist in both function and design representations
  - Allows system to be analyzed in each mission phase and goals which can have different ranges and values for each state variable
    - Allowed leak rates vary inversely with time from Earth Return date

$R_l \le \vec{y} \le R_h$ ➔ G



Mars Mission simplified GFT Example



- Crewed BEO Mission Goal Types
  - Transportation
  - Crew health and safety
  - Scientific and Technical

Transportation Goals

- Position, Velocity, Acceleration
- Earth Departure, Mars Departure
  - Propulsion System
  - Flight Control System
- Interplanetary Coast
  - Propulsion System
  - Flight Control System
- Planetary Orbital Insertion
  - Propulsive
  - Aero Braking
- Surface Descent
  - Propulsive
  - Aero Surfaces
- Planetary Mobility
  - Drive force
  - Control System

Crew Health and Safety Goals

- Provides link between human health and System Performance
  - Biological
  - Psychological
- Biological State Variables are linked directly with System State Variables
  - Biological
    - Heart rate
    - Respiration rate
    - Food intake
    - Water intake
    - Solid and Liquid waste production rate
  - Spacecraft Systems
    - Breathable air (oxygen concentration, carbon dioxide concentration, atmospheric pressure)
      - Oxygen can be stored as LOX and converted to gas as needed
    - Drinkable water (mass)
    - Consumable food (mass)
    - Solid and Liquid waste processing/disposal (mass)
    - Vehicle acceleration rates (linear and rotational accelerations)
    - Crew Cabin/Suit temperature (temperature and humidity)
    - Activity (work and exercise) and sleep times (hours or minutes / crew day)
    - Communication System (family communications (email, video, audio), entertainment, etc.)
- Ranges vary with mission phases

Science and Technology Goals

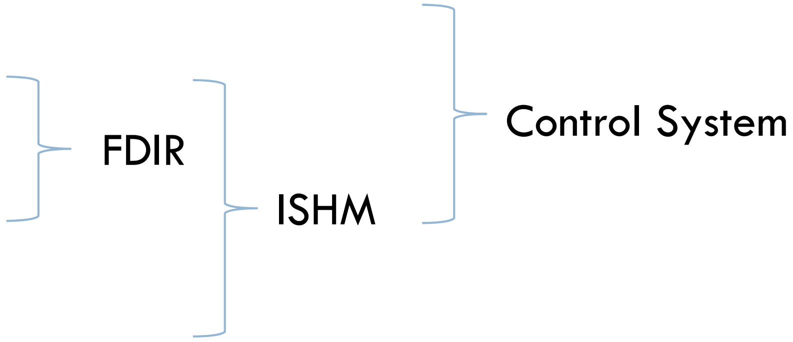
- Information Return
  - Communication systems
    - Transmission rates
      - radiated power
      - signal strength
      - beam width
- Sample Return
  - Containment System (mass, pressure, leakage rate)
  - Samples (mass)

Autonomy Stack

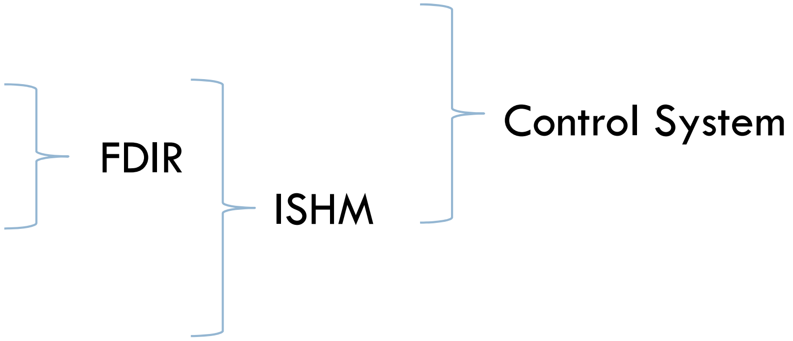
- Autonomy must operate consistent with the physical control laws of the vehicle systems
- Multiple subsystems exist within the vehicle
  - Management algorithms must match subsystem physical control laws
- Vehicle level integration is a unique set of relationships dependent on the subsystem types chosen
  - Type of Propulsion
  - Type of Flight Control System(s)
  - Type of ECLSS
  - Type of Electrical Power Generation
  - Etc.

Autonomy Stack

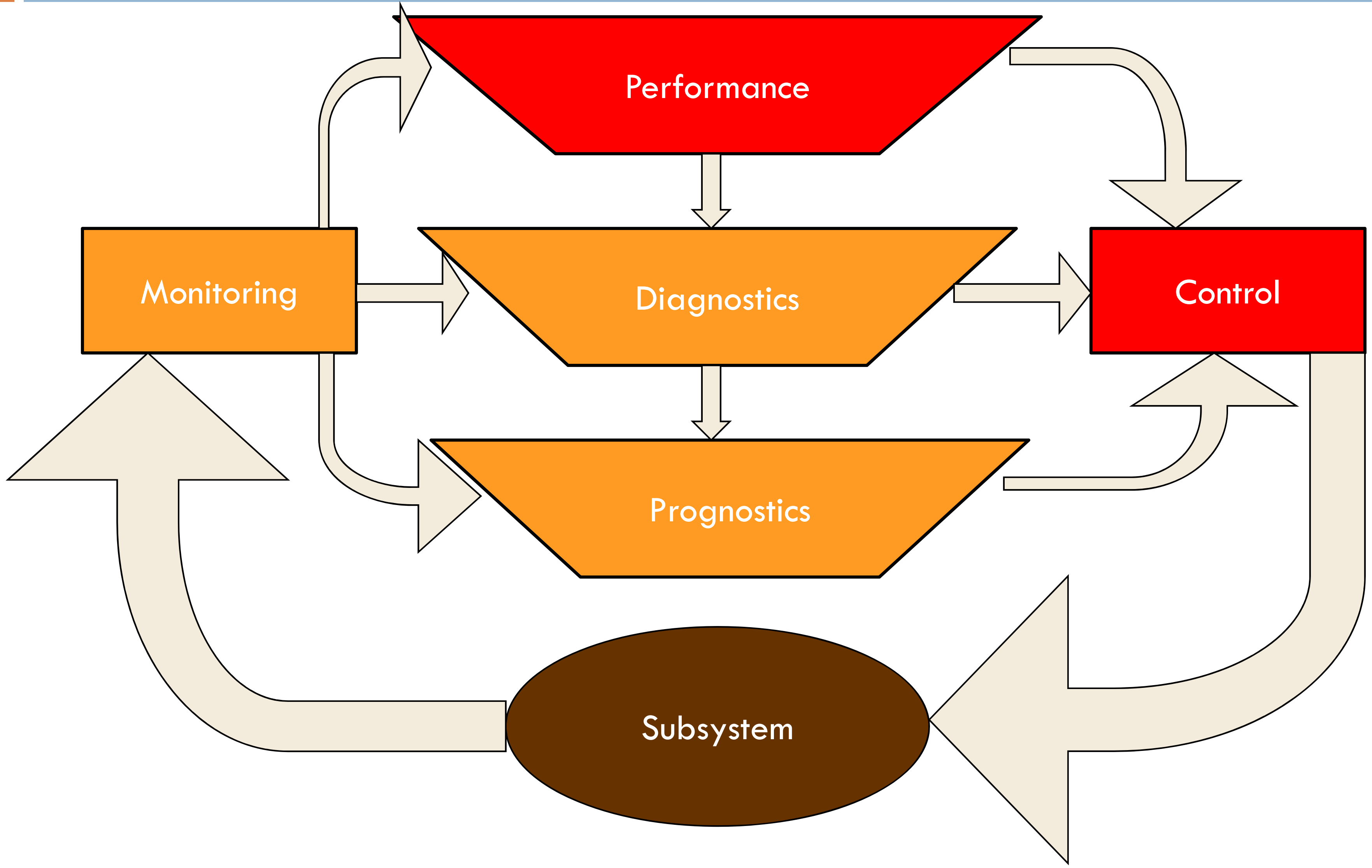
- Vehicle Autonomy has 5 distinct functions
  - Control
  - Monitoring (sensing)
  - Performance Determination
  - Diagnostics
  - Prognostics



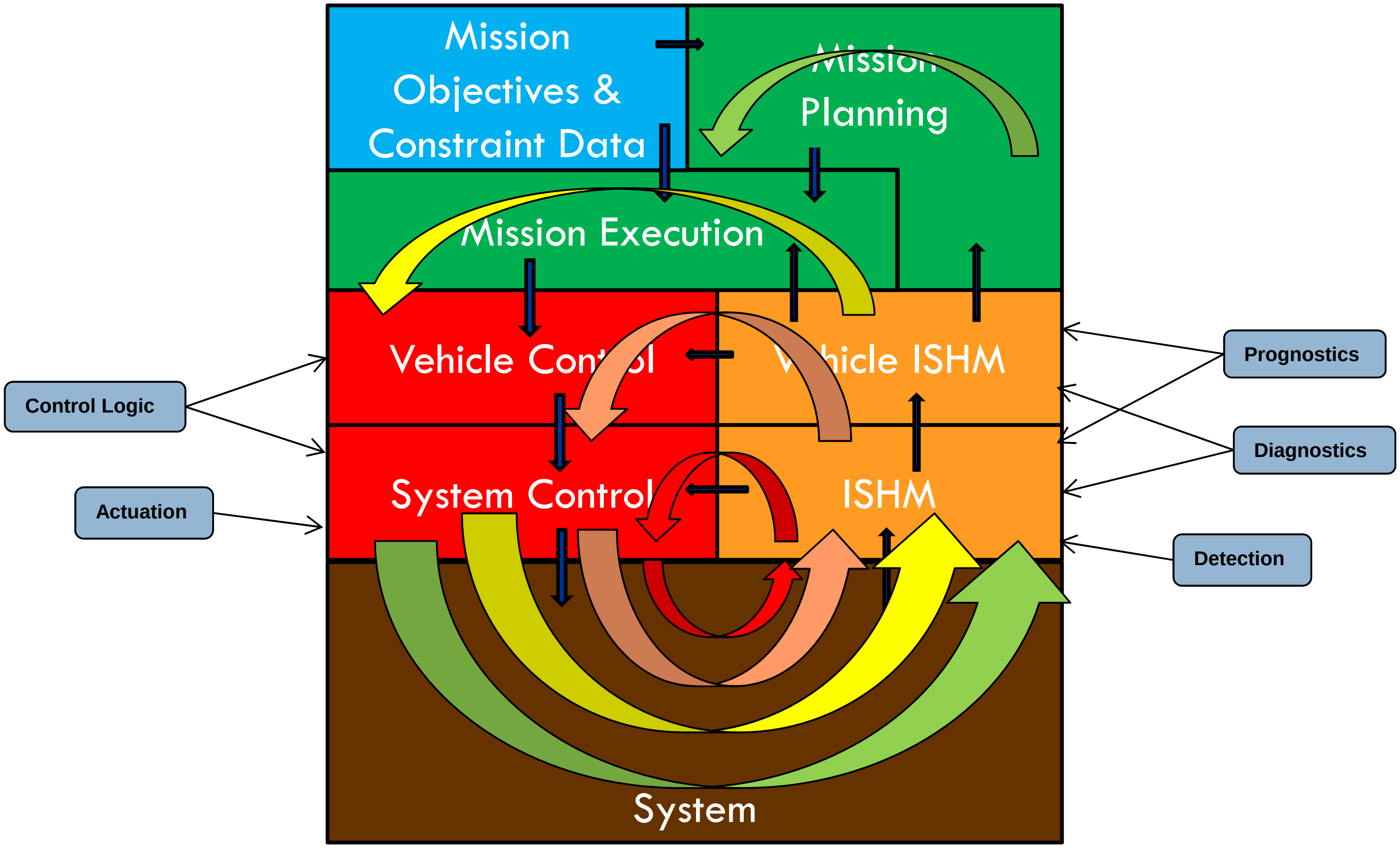
- Subsystems Autonomy has the same 5 distinct functions
  - Control
  - Monitoring (sensing)
  - Performance Determination
  - Diagnostics
  - Prognostics



Subsystem Management Functions for System Control



Autonomy System Stack



Candidate Autonomous Algorithms for Spacecraft Systems

- Several classes of Autonomous Algorithms
  - Expert Systems
  - Neural Networks
  - Bayesian Belief Networks
  - Model Based Reasoning
  - Fuzzy Logic
- Demonstrated in marine, space, industrial, and aviation applications
- Verification and Validation (V&V) approaches will need to be defined for these algorithms, both individually and as an integrated set
  - Formal V&V Methods (e.g., model checkers) need to be properly applied
  - Non-deterministic V&V methods need definition

Candidate Autonomous Algorithms for Spacecraft Systems

- Expert Systems
  - Expert rules establish decision structure
  - Knowledge base contains rules and relationships
  - Serves well as a central authority where rules/relationships are clearly established
  - Can be processing intensive with high data storage requirements depending on rules and rule relationship complexities
  - Well suited for:
    - Mission Planning, Crew and Mission Constraint Management
    - Subsystems with clear cut physical equations and well understood interrelationships

Candidate Autonomous Algorithms for Spacecraft Systems

- Neural Networks
  - Gradient Descent Methods
    - Deterministic due to the underlying mathematics
    - Ideal for nonlinear and interpolative applications/situation
  - Static Networks
    - Learning during training operations only
    - Quality of application based on quality of training cases
  - Dynamic Networks
    - Learning during real time operation
    - Validation and predictability
  - Implementation
    - Hardware (fast)
    - Software
    - Complexity can be difficult to verify and may require specialized chips (e.g., ASIC)
  - Ideal for
    - Control of highly nonlinear subsystems
      - Propulsion, Flight Control System transients
    - Interpolation
      - Good where there is limited knowledge of complex physical interactions
      - Real time adaptation in the event of spacecraft subsystem reconfiguration (failure response)

Candidate Autonomous Algorithms for Spacecraft Systems

- Bayesian Belief Networks
  - Applies Bayes Rule to Determine System State
    - Prior States
    - Current Belief probability
  - Best employed as an information source for other subsystem or vehicle autonomous algorithms
    - Helps clarify/validate uncertainty
    - Aids inference and reasoning (e.g., augments Expert Systems)
  - Well Suited for:
    - Performance Determination
      - Vehicle
      - Subsystem

Candidate Autonomous Algorithms for Spacecraft Systems

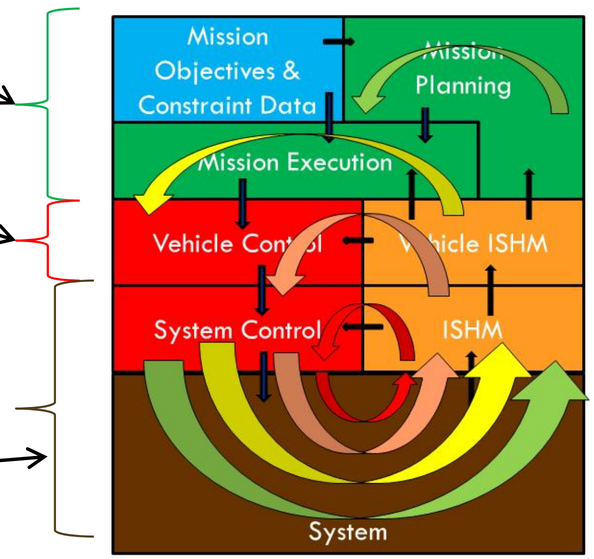
- Model Based Reasoning
  - Models based on extensive domain knowledge
    - Can leverage design models
    - Uncertainty based on fidelity of model implemented
  - Software architecture must address
    - Efficient Programming Language
    - Operating System capable of dealing with
      - Conflict resolution
      - Efficient processing
      - Embedded systems for mission critical applications (i.e., software health management)
  - Well Suited for:
    - Vehicle and Subsystem Diagnostics
    - GN&C (Kalman Filter)

Candidate Autonomous Algorithms for Spacecraft Systems

- Fuzzy Logic
  - Classical Mathematical Set Theory
  - Requires deep knowledge of subsystem physical rules and interactions to properly train
  - Provides support to Reasoning Systems (e.g., Model Based Reasoning)
  - Well Suited for:
    - Flight Control Systems

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



Autonomous Algorithm Integration

- Subsystem Level Autonomy
  - Keys:
    - Understanding the physics of the system
    - Selecting an autonomous algorithm that can
      - effectively manage the system physics(take the necessary actions based on all interactions)
      - and responsively manage the system physics (take the necessary action in a timely manner)
  - System physics are driven by the internal system processes, interactions with other systems, and interactions with the environment, all of which must be managed by the algorithm
  - System-level algorithm matching involves knowledge of the system transfer functions which include external system and environment interactions
    - Control Theory is important in implementation.
      - The physics will define the poles and zeros of the control system and the relative proximity of the system response to these locations.
      - System Transfer Functions must be defined and matched with the characteristics of the autonomous algorithms

Autonomous Algorithm Integration

- Vehicle Level Autonomy
  - Keys:
    - Integration of the systems autonomous algorithms into a cohesive and response management system
    - Algorithms taking proper responses to planned and unplanned conditions
      - Managing the subsystem physics effects on the vehicle are essential
    - Manage interactions between systems
      - Vehicle must manage cooperative vs. competitive subsystem responses such that subsystems do not counter each other's actions leaving the vehicle in a failed state

Autonomous Algorithm Integration

- Mission Execution and Planning
  - Keys:
    - Mission Execution
      - Manages the total execution of the all mission aspects from a vehicle stand point
        - Proper knowledge of the current vehicle states
        - Progress toward specific mission objectives
      - Mitigates subsystem interaction effects through adjustment to system control parameters in response to specific physical events.
    - Mission Planning
      - Based on
        - Proper knowledge of the current vehicle states
        - Progress toward specific mission objectives
      - Conducts Re-planning (with crew approval) to ensure future vehicle states will stay within mission objectives and constraints
      - Three Levels
        - Strategic: Earth-based controls will also be involved
        - Tactical: Crew input and approval
        - Emergency: Automated to prevent loss of mission, crew, or compromise of crew safety

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
  - The Goal-Function Tree methodology provides a system engineering approach to define the vehicle state variables and their interactions.
- 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
  - 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