Intelligent (Autonomous) Power Controller Development for Human Deep Space Exploration

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Discussion Topics

• Overview of NASA’s Deep Space Exploration Vision
• Notional Deep Space Vehicle Power Architecture
• Autonomous Power Control Architecture
• Autonomous Power Control Functions
• Autonomous Controller Evaluation and Test
• Status and Future Plans
• Summary
Evolvable Mars Campaign
A Pathways Approach to Exploration

Earth Dependent
- International Space Station
- Low-Earth Orbit

Proving Ground
- Exploration Augmentation Module
- Asteroid Redirect Vehicle
- Distant Retrograde Lunar Orbit

Earth Independent
- Mars Surface
- Mars Vicinity
- Mars Cargo Pre-Deployment
- Phobos
- Deimos

The Trade Space
Across the Board
- Solar Electric Propulsion
- In-Situ Resource Utilization (ISRU)
- Robotic Precursors
- Human/Robotic Interactions
- Partnership Coordination
- Exploration and Science Activities

Cis-lunar Trades
- Deep-space testing and autonomous operations
- Extensibility to Mars
- Mars system staging/refurbishment point and trajectory analyses

Mars Vicinity Trades
- Split versus monolithic habitat
- Cargo pre-deployment
- Mars Phobos/Deimos activities
- Entry descent and landing concepts
- Transportation technologies/trajectory analyses
What is the Problem?

- Communication and recovery times are longer than any previous experience
- Communications bandwidth is a factor of 100 less than ISS

<table>
<thead>
<tr>
<th>Mission</th>
<th>Communications bandwidth</th>
<th>Communications latency time</th>
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<tbody>
<tr>
<td>Deep Space Vehicle</td>
<td>&lt; 2 Mbps (DSN)</td>
<td>15 to 45 minutes</td>
</tr>
<tr>
<td>Apollo / Orion</td>
<td>&lt; 2 Mbps (DSN)</td>
<td>1-2 seconds</td>
</tr>
<tr>
<td>ISS</td>
<td>300–800 Mbps (TDRS)</td>
<td>Real-time</td>
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- Power Is Most Critical System On Board Vehicle
  - Every system on the vehicle needs power
  - Electric Power System (EPS) will need a high level of availability
  - Electric Power System (EPS) will need to operate autonomously for long periods of time
Multi-junction solar array power
  - 24 kW for user loads
  - 50 – 300+ kW for electric propulsion

Two independent power channels with multi-level cross-strapping

Lithium Ion battery storage
  - 300+ amp*hrs
  - Sized for 1.5 hr eclipses

Distribution
  - 120 V secondary (SAE AS 5698 power quality Spec)
  - 2 kW power transfer between visiting vehicles
Notional Deep Space Vehicle Power Architecture
Autonomous Power Control Architecture
What is Autonomous Power Control?

An Intelligent Power Controller utilizes advanced hardware and control technology and works in conjunction with the ground mission operations and the vehicle manager to autonomously manage and control:

- Distributed power generation and storage assets
- Power distribution networks
- Loads

Exploration Systems

Near Earth Systems
Typical Spacecraft Control Architecture

Mission Operations (Planning and Execution)

- Power
- Thermal
- \ldots
- ECLSS

Spacecraft Control

- Reactive Control
  - Power
  - Thermal
- Reactive Control
- Reactive Control
- Reactive Control
  - ECLSS
Power System Reactive Layer Controller

- S/A Voltage Control
- Switchgear Trip Control
- Secondary Voltage Control
- Battery Charge Control

Diagram showing the interconnection of various components including SSU, DCSU, MBSU, DDCU, and RPC.
Traditional vs Autonomous Spacecraft Controller

Transitioning some traditional ground based control functions to the vehicle

Development of an Autonomously Controlled Spacecraft is consistent with the “Future of Human Space Exploration” roadmap and enables the transition from “Earth Reliant” systems to “Earth Independent Systems”
Mission Operations
- Monitors vehicle operations
- Adjusts long term mission objectives

Vehicle Manager
- Plan vehicle operation to achieve mission objectives
- Coordinate vehicle subsystems

Autonomous Power Controller
- Monitor / control normal mode of operation
- Respond and report faults of the EPS system

EPS Hardware (Reactive Control)
- Provides close-loop control of the EPS hardware
Intelligent Controller Data Flow

Mission Operations

Vehicle Manager

Autonomous Power Controller

- Energy Availability
- Load Profile Evaluation
- EPS Operating State
- ORU State of Health
- Caution/Warning
- Proposed Corrective Action(s)

Reactive Layer

- Array Voltage
- Battery Current
- Main Bus Current / Voltage
- Secondary Bus Voltage / Current
- Switch States

EPS Hardware

- Array Pointing Vectors
- Array Voltage S.P.
- Battery Charge/Discharge SP.
- Switchgear Positions

- Navigation Vectors
- Traffic / Array Pointing Constraints
- Spacecraft (other subsystems) State
- Proposed load profile

- Energy Availability
- Load Profile Evaluation
- EPS Operating State
- ORU State of Health
- Caution/Warning
- Proposed Corrective Action(s)
Autonomous Control State Diagram

Assess / Manage Power System State

- **Normal State** -- Normal operation, system operating on plan, continue indefinitely without interruption
- **Abnormal State** -- No faults in hardware but system is not performing as planned
- **Emergency State** -- Fault occurs – relieve system stress and prevent further deterioration
- **Restorative State** -- System is degraded but safe – restore power flow to all loads in a safe manner in minimum time
Autonomous Power Functions
Normal / Power Controller
- Provides the Vehicle Manager with power availability
- Coordinates with Vehicle Manager to develop a workable load schedule
- Executes Vehicle Manager load schedule
- Coordinate re-planning in Abnormal Mode when schedule is “broken”
- Optimizes energy utilization
- Optimizes distribution system utilization
- Maintain power quality within the distribution system
- Send configuration information to the reactive layer control
Fault Mode Control Functions

Emergency / Restoration States
- “Safes the System”
- Reports “Emergency State to the Vehicle Manager C&W System
- Identifies the fault
  - Hard Faults
  - Soft Faults
- Develops a restoration plan to restore the system to Normal State
- Coordinates restoration plan with the vehicle manager
- Executes the restoration plan through the Reactive Layer Control
Autonomous Controller Evaluation and Test
Test and Evaluation Approach

Autonomous Power Controller

Deep Space Vehicle Power System Test Bed

Real Time Simulation
Dynamic Electric Power System Modeling

• Currently leveraging the Air Force INVENT Program approach to develop common Electrical Power System (EPS) elements to be used within space electrical power system simulations.
  – Library of elements can be used on any number of configurations and used to simulate various power system Simulink applications

• Simulation characteristics include the following:
  – Provides real time, dynamic simulation of multiple connected power systems such as multiple channels of ISS or Deep Space architectures
  – Average value modeling of power electronics
  – Faster, accurate circuit simulation for switching elements based on state equation approach
  – Features a communication infrastructure to synchronize simulations running on multiple processors.

• Validation of the EPS elements was achieved by simulation of interconnecting channels of ISS and comparison to available ISS power system Saber hardware model data.
Electrical Power System (EPS) Simulation Development

EPS Model Library:
- PV Cells
- Isolating Converter
- Battery Cells

Units and Assemblies:
- Smart S/A
  - Solar Panels
  - SAR
- Interface Reg.
  - Isolating Converter
- Smart Battery
  - Batt. Reg

Systems:
- Deep Space Habitat
- ISS
- ISS Primary Grid
- ISS Secondary Grid
Autonomous Power System Test Bed

• Evolving into a platform to evaluate the performance of the autonomous control with real hardware
• Contains
  • Solar simulators / regulators
  • Batteries / simulators
  • Power Distribution Equipment
    • MBSU’s
    • PDU’s
  • Multiple Load Types
Autonomous Control T&V Configuration

Real-time Power System Simulation

Data Base

Controller Internal GUI

Vehicle Manager

Operator GUI

Simulation Internal GUI

Test Bed Power Hardware
Accomplishments:
• Defined initial autonomous vehicle control architecture
• Implemented distributed facility to develop and test the Autonomous Power Controller (APC), Vehicle Manager, and test bed hardware
• Developed a real-time simulation of the Deep Space Habitat power system
• Developed prototype of an Autonomous Power Controller (APC) for Normal Modes capable of long-term energy management
• Demonstrated APC controller with remote hardware at JSC
• Defined, implemented, demonstrated the interface between APC and Vehicle Manager

Future Plans
• Develop capability to identify power system faults
• Develop contingency options to accommodate faults
• Integrate GRC power system test bed for hardware in the loop evaluation
• Intelligent Power Systems are key for long term missions and operations far from earth.

• Development of an Autonomously Controlled Spacecraft is consistent with the “Future of Human Space Exploration” roadmap and enables the transition from “Earth Reliant” systems to “Earth Independent Systems”.

• Verification of developmental space EPS autonomous power controllers will be achieved through real-time EPS simulations, hardware in the loop and power system test bed validation efforts.


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Questions???