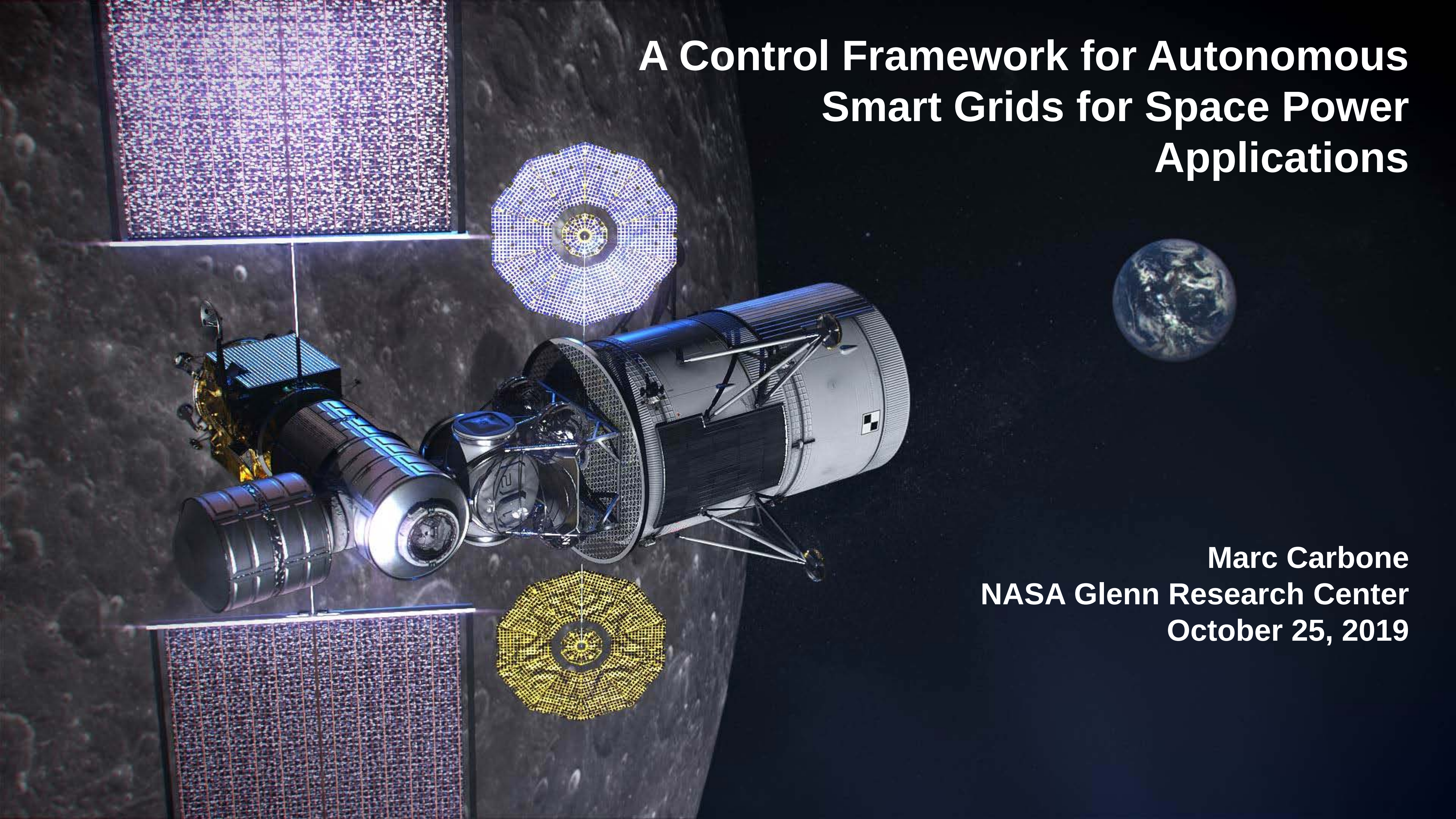
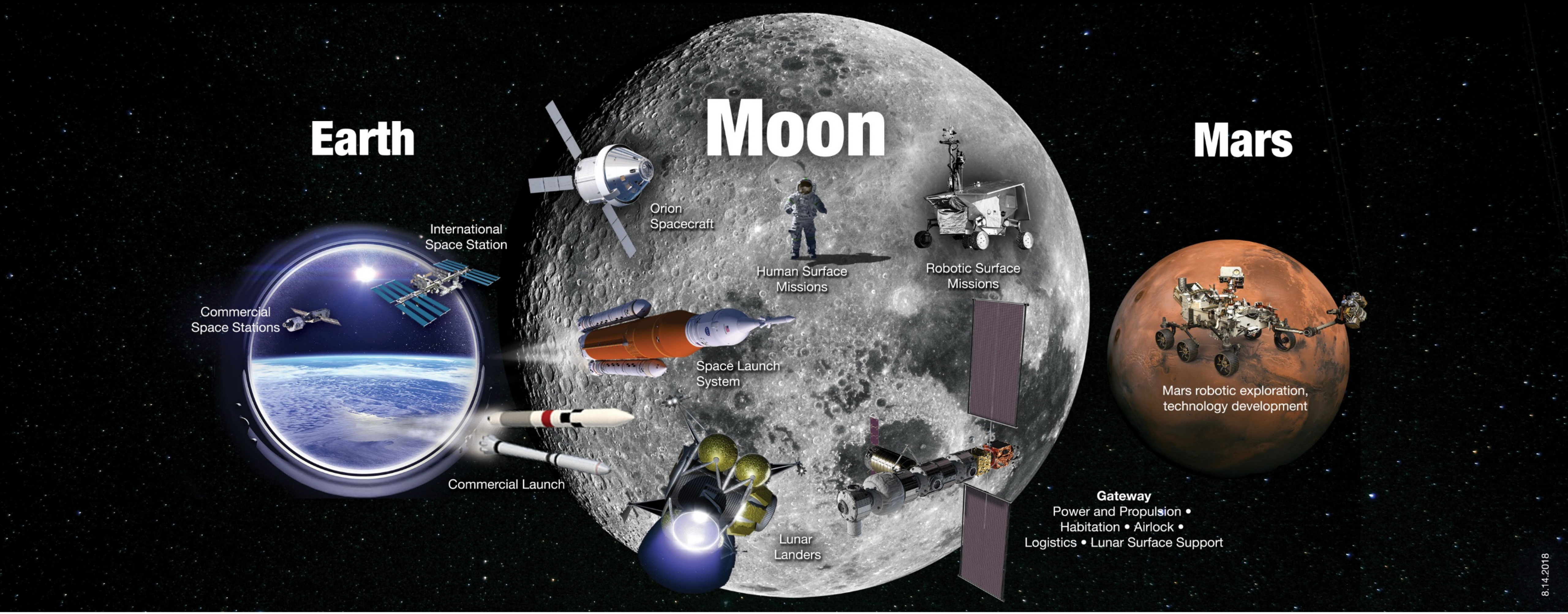


A Control Framework for Autonomous Smart Grids for Space Power Applications

Marc Carbone
NASA Glenn Research Center

October 25, 2019

NASA’s Roadmap for Deep Space Exploration



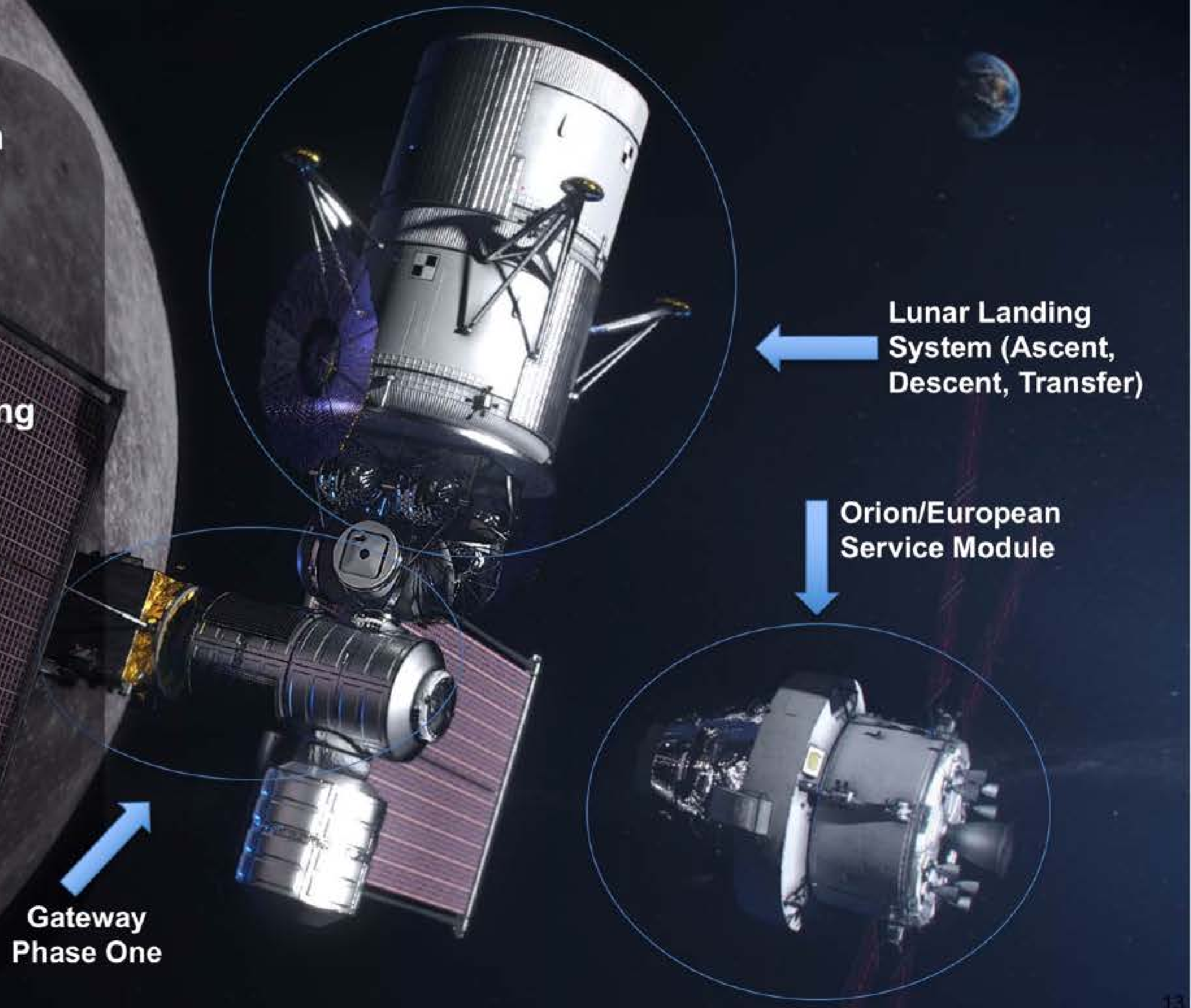
America Will Lead
Fly Astronauts on American Spacecraft
Develop New Commercial Space Stations

America Will Lead
Fly Astronauts Around the Moon
Establish the First Human Outpost Around the Moon
Develop American Landers to Return Humans to the Moon

America Will Lead
Return the First Scientific Collection from Mars
Practice a Round-trip Leading to Humans to Mars

Gateway Phase 1: 2024

- Initial Gateway focuses on the minimum systems required to support a 2024 human lunar landing while also supporting Phase 2
- Provides command center and aggregation point for 2024 human landing
- Establishes strategic presence around the Moon – US in the leadership role
- Creates resilience and robustness in the lunar architecture
- Provides building block for the future, expanded capabilities on and around the Moon



Power System Control Challenges on The Gateway

- Unlike the International Space Station (ISS), Astronauts will only occupy the Gateway occasionally.

- NASA wants to develop autonomous operations for long periods of time (~days) .

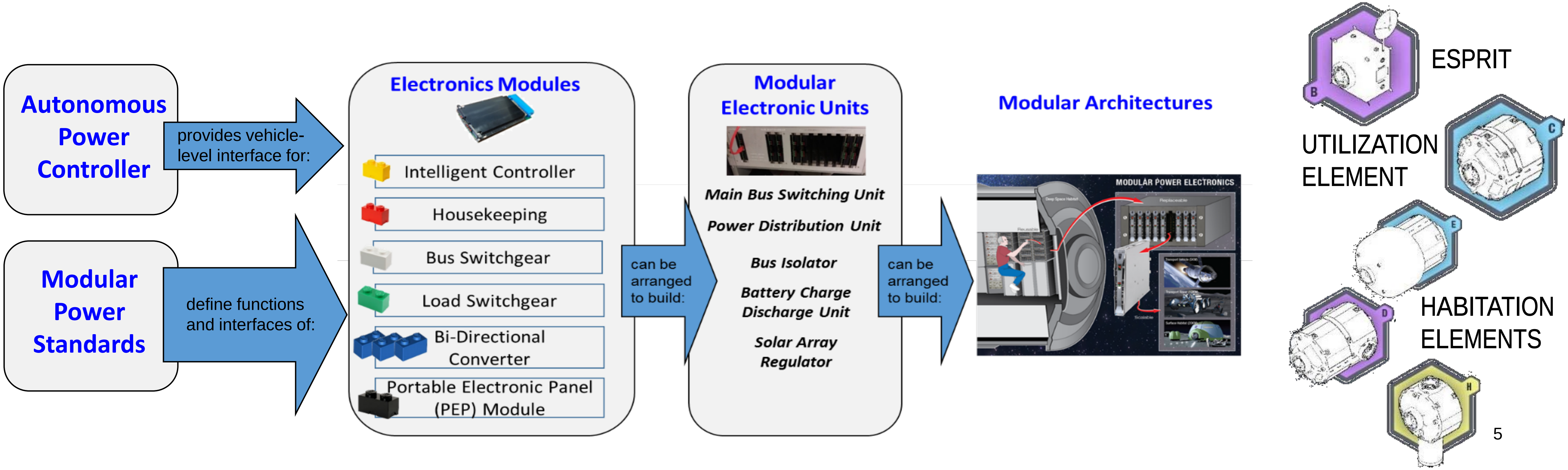
- Due to the availability of the deep space network, there will be periodic communication losses from Earth to the Gateway.

- Therefore, advanced autonomous control strategies will be needed to ensure the reliable delivery of electrical power of the Gateway.

Advanced Modular Power Systems (AMPS) – Glenn Research Center

- **Modular power system architectures help minimize maintenance operations, improve power availability, and reduce the number of unique spare parts.**

- **This project matures modular power system technologies, inclusive of modular power standards, modular power electronics, regenerative fuel cells, and <u>autonomous power controls</u>, in support of NASA's cis-lunar Gateway.**



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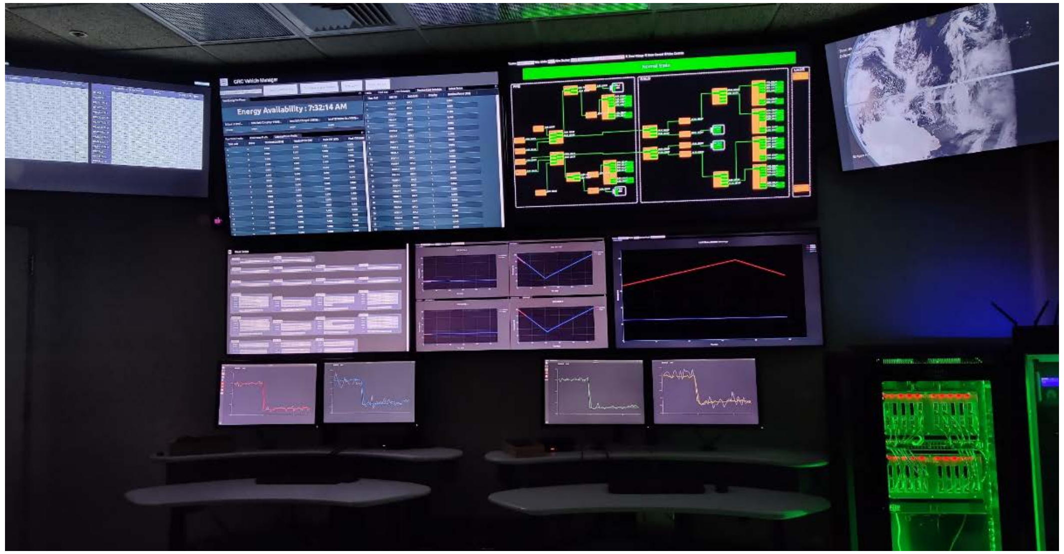
Autonomous Power Control Functions

- **Without direct communication from mission control, an Autonomous Power Controller is needed to deliver safe and reliable power.**

- **Electrical power systems in space are subject to many of the same challenges as on Earth**
  - Load scheduling
  - Energy storage balancing
  - Generation control
  - Fault detection, diagnosis, and restoration

- **Many of the same concepts and technologies found in terrestrial power systems can be applied to space applications**
  - Hierarchical control paradigm
  - Optimal load scheduling
  - State Estimation
  - Power Flow

- **Re-architecting these concepts to be used in an autonomous power control scheme results in a more robust and resilient power system**

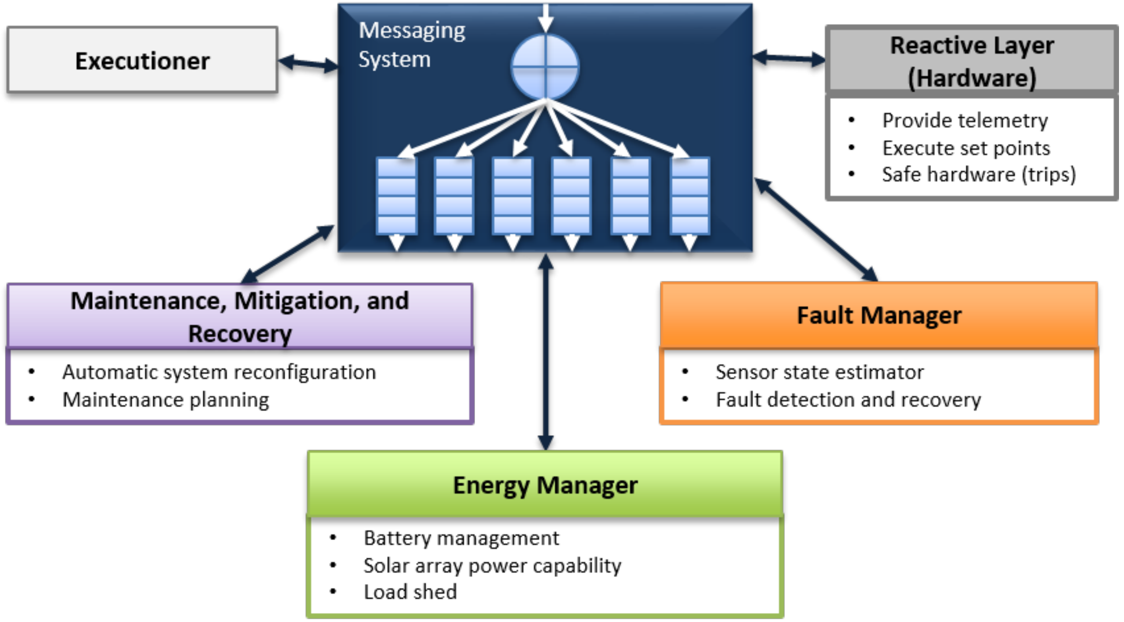


Autonomous power control lab, NASA Glenn Research Center

AMPS Autonomous Power Control team is advancing the ability to manage electrical power systems without human intervention.

Energy Management

- Accurately forecast the power and energy available to the loads in the future
- Deliver power to as many as possible high priority loads as possible.
- Ensure power system constraints are not violated, including energy storage assets.
- Ability to shed loads to protect power system constraints.



Fault Management

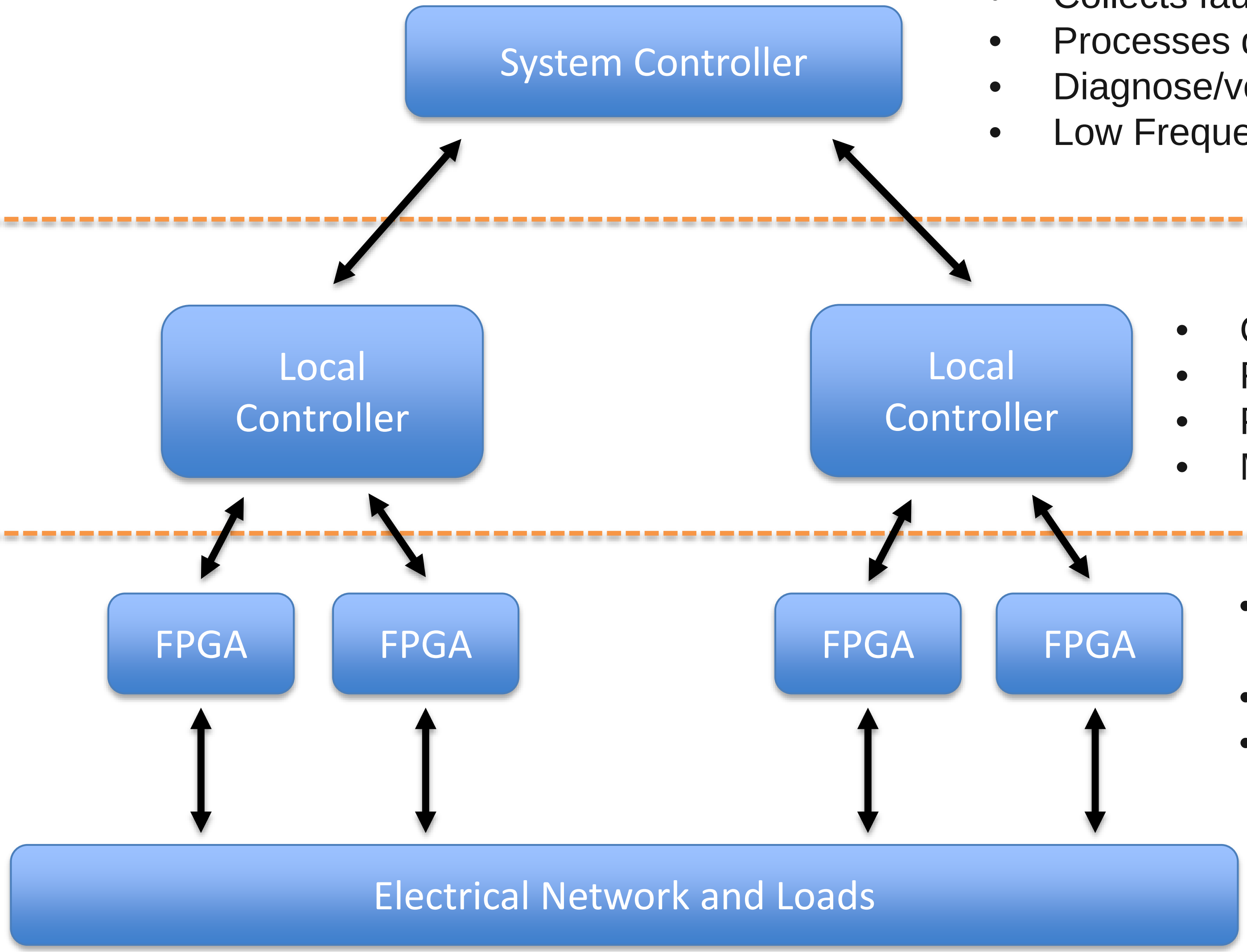
- Detect, isolate, and recover from faults without a human operator in the loop.
- Protect the subsystems and vehicle from hard failures (short to ground) and detect soft failures (sensor failures).
- Rely on both model-based and rules-based fault management techniques.

Automatic Reconfiguration

- Ability to automatically reconfigure the power distribution system to deliver power to the loads.
- Use a shortest path first algorithm (Dijkstra's algorithm) to determine most efficient routing.

Hierarchical Control Scheme

Hardware Hierarchy



Fault Detection and Diagnosis Capability

Level 3

- Collects fault messages from local controllers
- Processes data through dynamic state estimator
- Diagnose/verify faults
- Low Frequency (1-10Hz)

Level 2

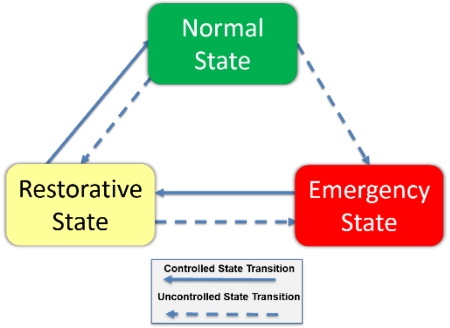
- Collects FPGA flags
- Rules-based fault detection
- Processes transient fault data
- Medium Frequency (20-100Hz)

Level 1

- Checks for status (over current, over/under voltage, trip)
- Collects measurements from sensors
- High frequency (~1MHz)

Fault Detection and Diagnosis

- **Without constant human supervision, the fault detection and diagnosis strategies onboard the Gateway will need to be robust and autonomous so they can:**
  - Quickly safe the system
  - Accurately identify the cause and location of the failure
  - Apply appropriate corrective actions (reconfiguration)

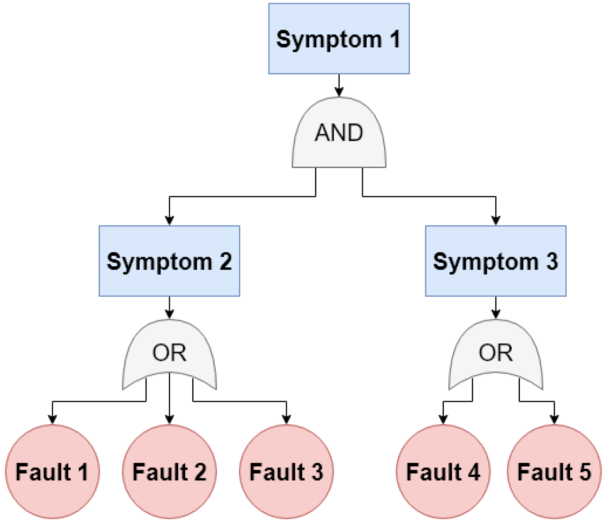


- **In the last few decades, theoretical and experimental research has shown new ways to detect and diagnose faults.**
- **To utilize the strengths of each approach, a hybridization of multiple common techniques can be used to create the best overall solution**
  - Automatic protection
  - Monitoring (rules-based detection)
  - State estimation
  - Machine learning
  - Expert system

Fault Types	
Line Faults Hard short High impedance short	**Switch Faults** Stuck open Stuck closed
Sensor Faults Offset Noisy Stuck	**Communication Faults** FPGA to local controller Local controller to central APC
Converter faults	**Power Supply Failure**
Load Faults	**Solar Array Failure**

Hybrid Fault Management Approach

- **Current State of the Art**
  - Much of the research in fault detection and diagnosis (FDD) considers only a single type of algorithm.
  - Because each method has strengths and weaknesses, multiple algorithms can be coordinated to capture the strengths of each method.
  - In general, the current research lacks the integration of automatic hardware protection into the FDD control scheme.
  - Most existing flight systems heavily rely on humans-in-the-loop for diagnostics.
- **Using both Expert System and Model-Based techniques, an autonomous fault management scheme can be created that can diagnose faults quickly, and accurately.**



Expert system with rules-based fault detection

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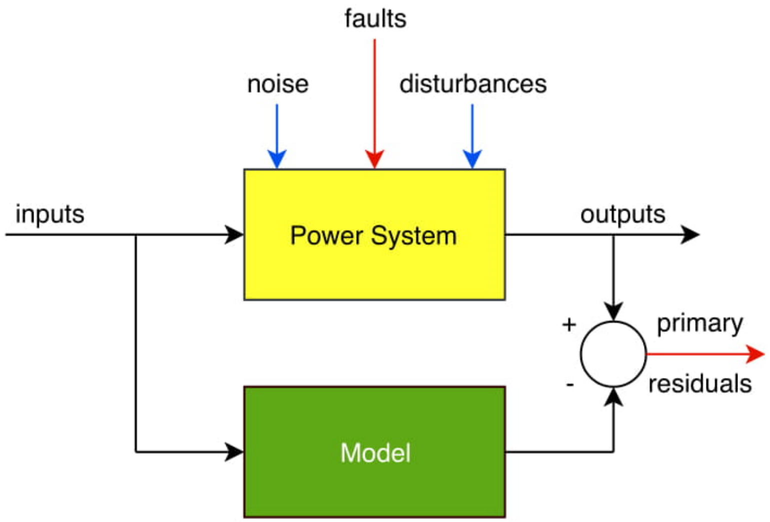
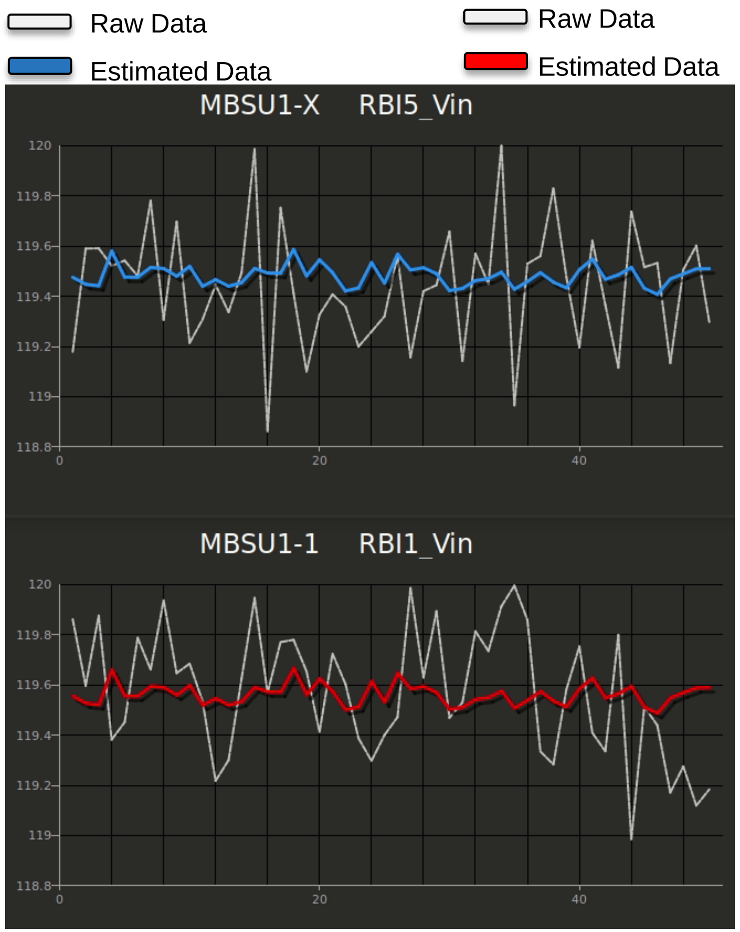


Model-based fault detection and diagnosis

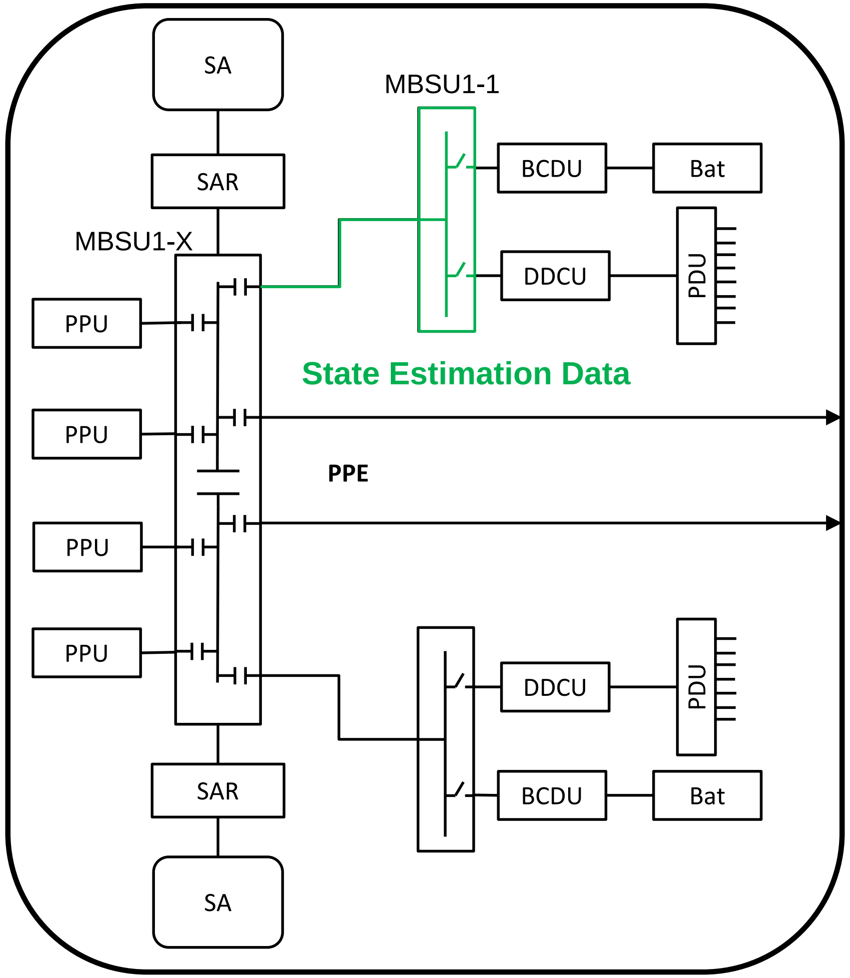
Communication Faults

- The APC can detect missing packets and stale data using time stamped messages
- State estimation can be used to replace data lost due to communication faults and faulty sensors

- Communication Fault Diagnosis:
    1. The local controller on Main Bus Switching Unit (MBSU) 1-1 detects stale data by observing time stamps from the reactive layer.
    2. A communication fault alarm is sent to the system level fault manager.
    3. The fault manager then performs state estimation without the measurements from MBSU1-1, and backfills the missing data.
    4. With valid state estimates, the fault manager confirms the communication fault and continues processing data until the fault is removed.



Voltage signals and estimates from two different Main Bus Switching Units (MBSU)



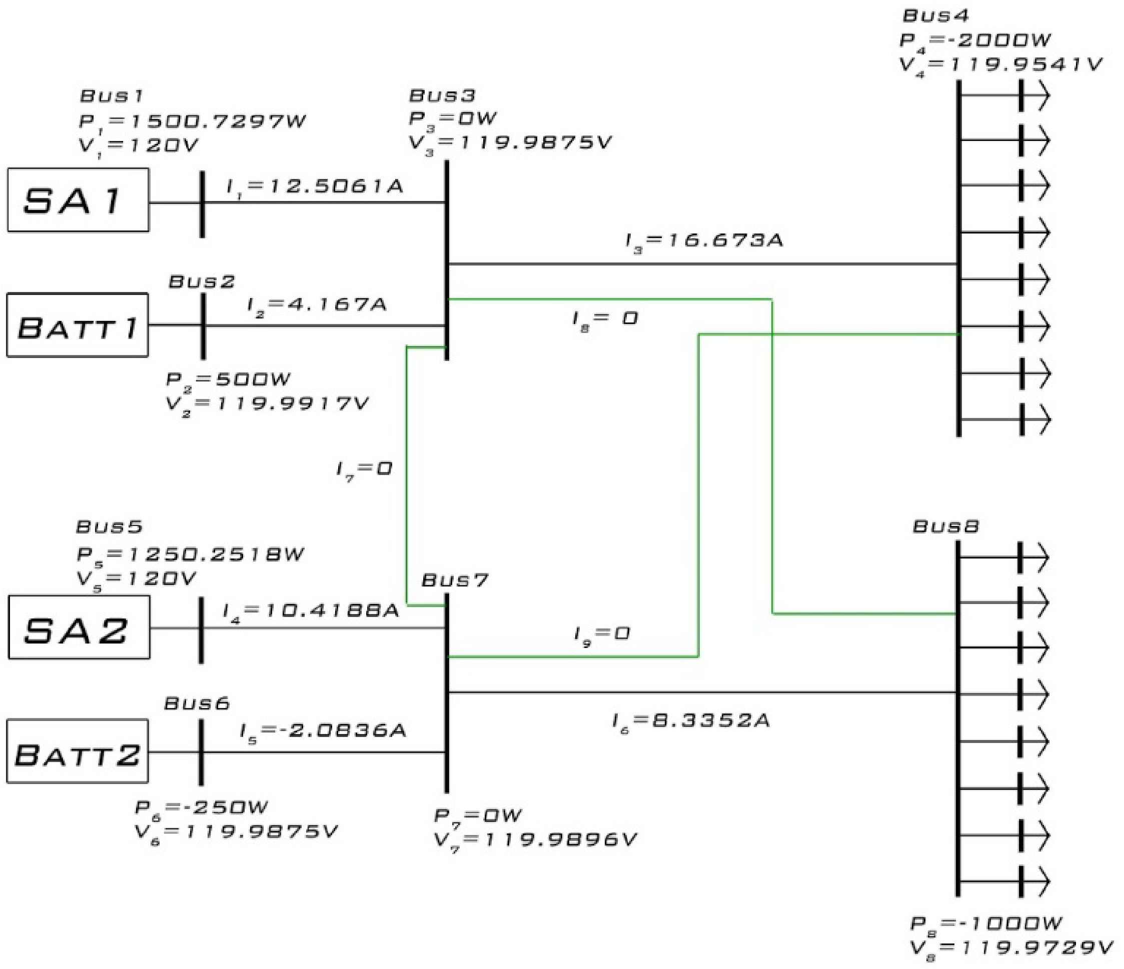
Conceptual power architecture of the Power and Propulsion Element (PPE)

Security Analysis

- **Once a reconfiguration plan is proposed a *Power Flow* is analyzed using the current load schedule to predict component rating violations such as**
  - Line over current
  - Bus over/under voltage
  - Battery charge/discharge limits

- **If the proposed reconfiguration meets all of the requirements it can be enabled, otherwise a new plan must be created.**

- **Power flow can also be used to ensure that the current load demand can be met after a fault, thus ensuring *n-1* security to the power system**

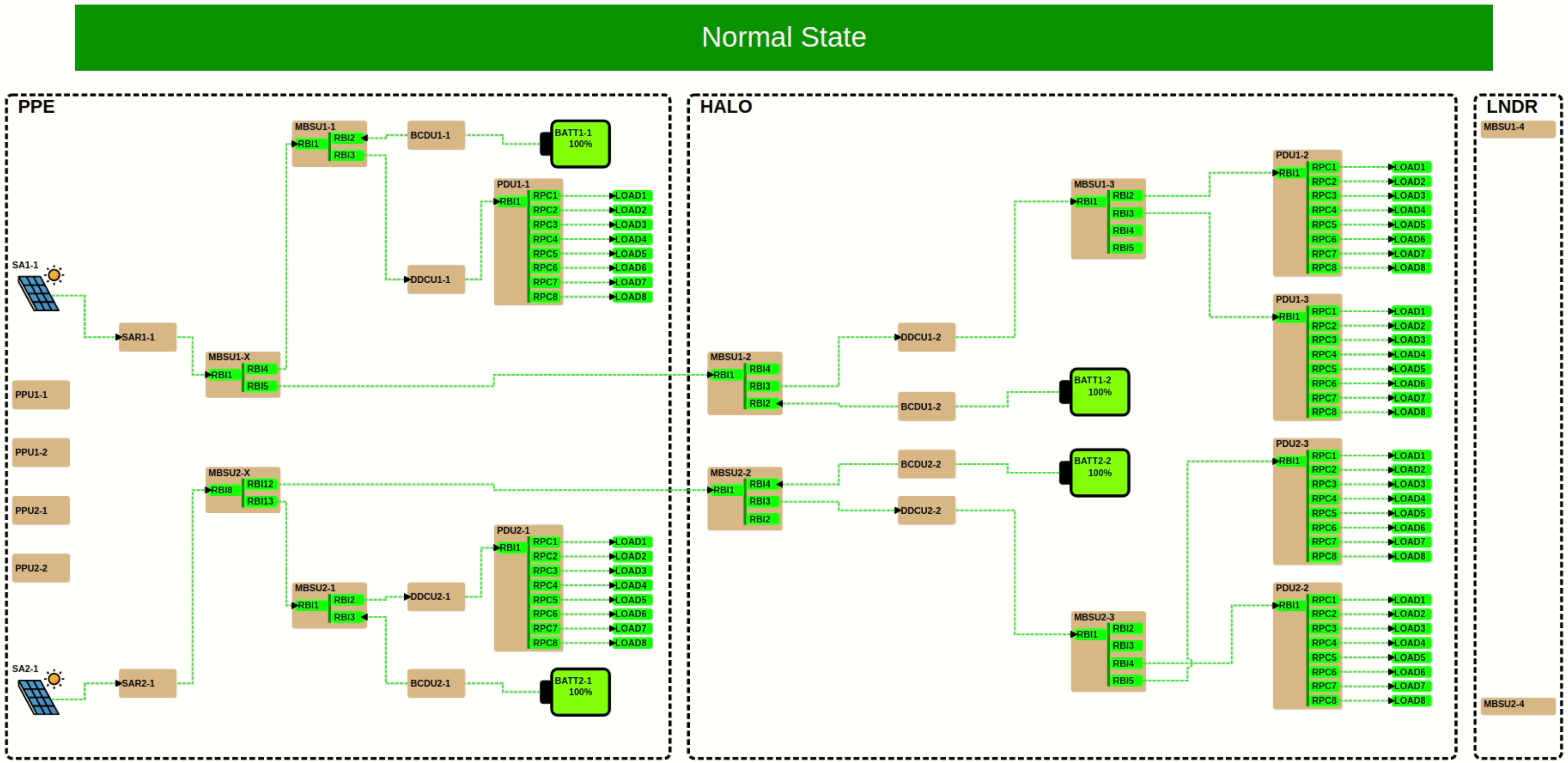


Results from a sample power flow algorithm

Autonomous Network Reconfiguration

- **After a fault, this service sets the electrical network based on a modified Dijkstra's shortest path algorithm**
  - Finds a near optimal topology based on the given fault information
  - Computes quickly (<100ms) to minimize load outages
- **Implements load shedding based on available generation capability**

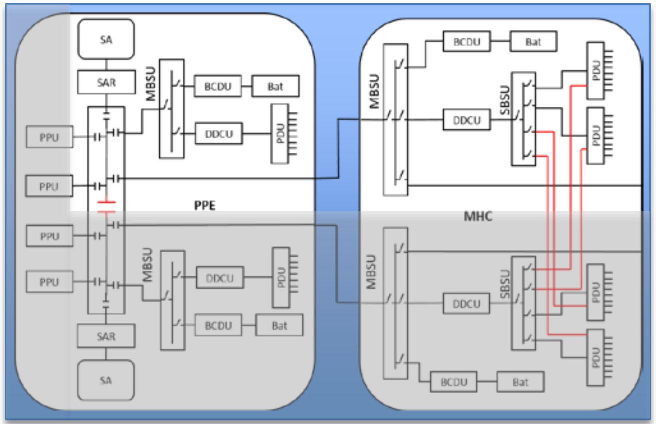
- **Example: Battery Fault**
  - A line has shorted casing the circuit breaker in switch RBI2 of Main Bus Switching Unit (MBSU) 1-2 to open (**Emergency State**).
  - The network reconfigures and sheds all non-critical loads.
  - A new load schedule is proposed designed for the loss of battery (BATT) 1-2 (**Restorative State**).
  - The fault is repaired and the original load schedule is implemented (**Normal State**)

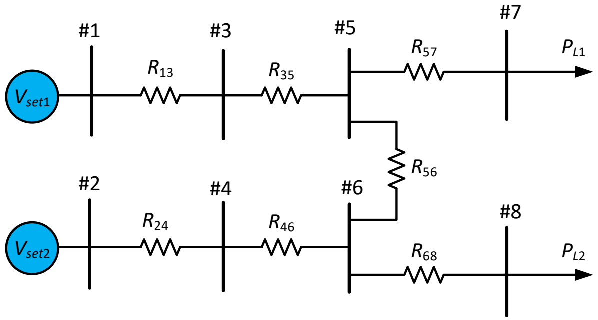


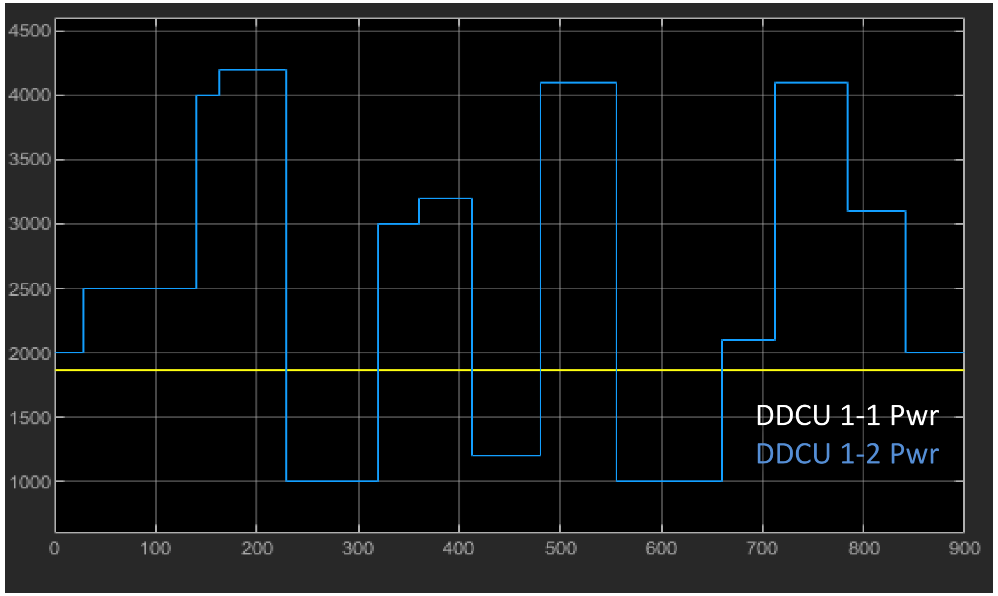
The power system simulation of a conceptual Phase I Gateway

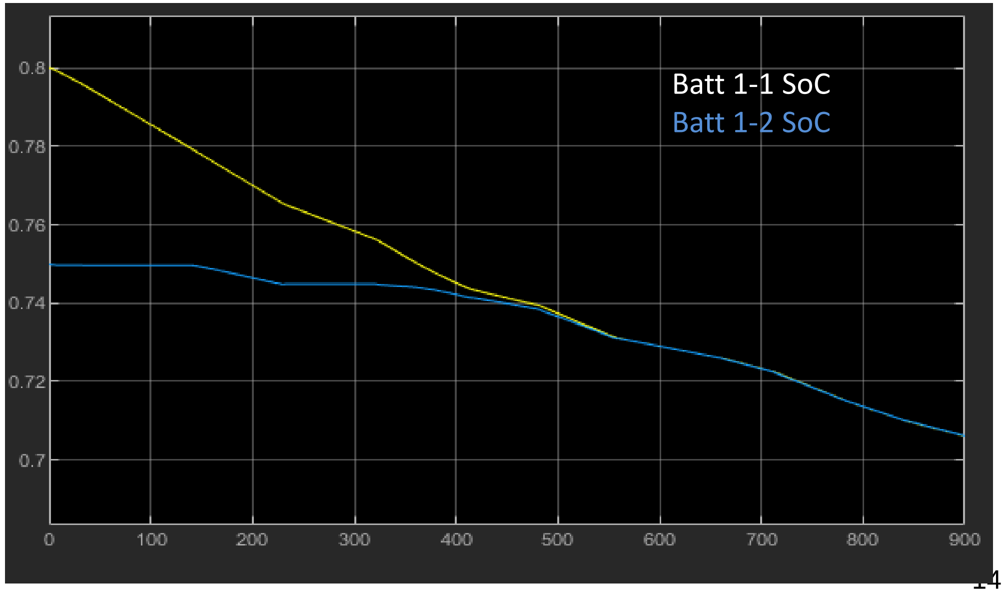
Optimal Battery Management

- **Uniformly discharge the distributed batteries in the power system**
  - Maximizes peak power availability during eclipse.
- **Three-level control solution**
  - Reactive layer controls (BCDU)
    - Droop control
  - Secondary control (central APC)
    - Load sharing of distributed batteries
  - Tertiary control (central APC)
    - Optimal battery management
    - Control load sharing based on battery SoC









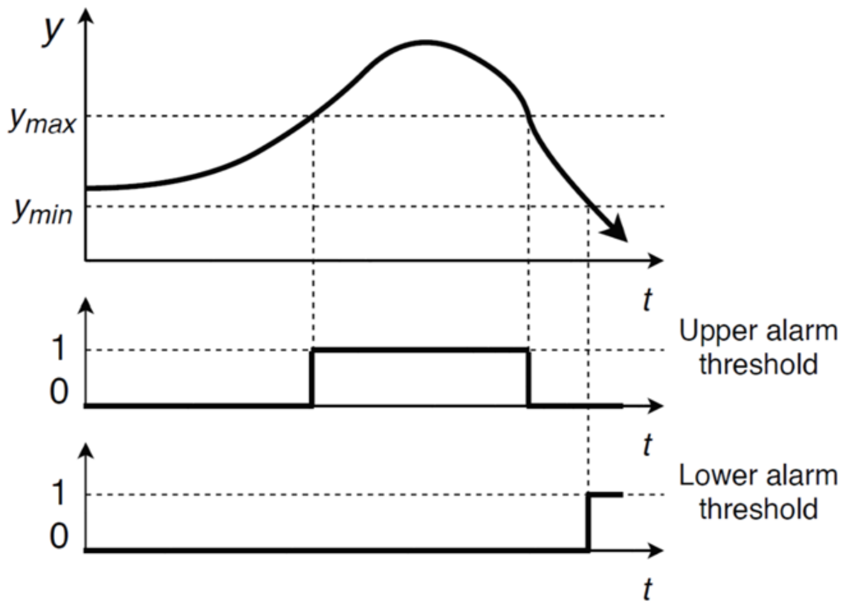
Back-Up Slides

Concept rendering of a lunar lander headed toward the moon

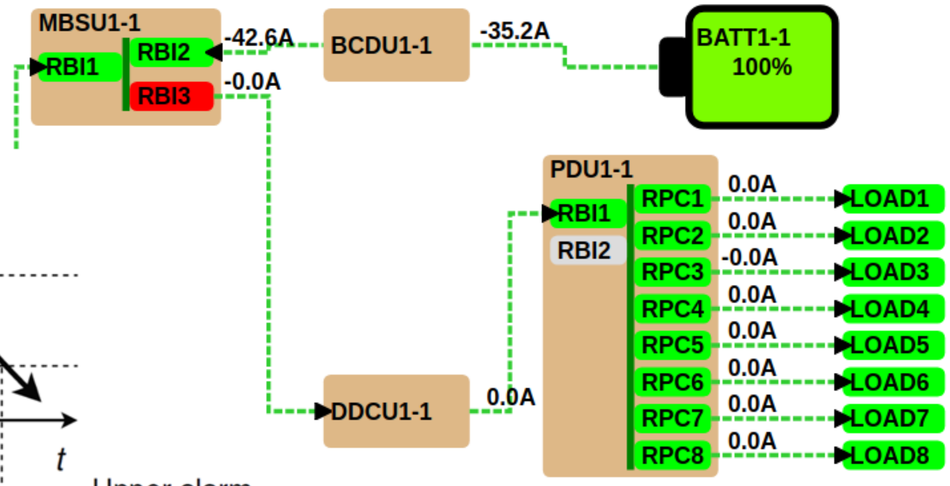
Rules-based Fault Detection

- **At the local controller level, simple physics-based rules are implemented to detect faults.**
- **After a fault has been detected, it is sent to the system controller level, where the fault can be fully vetted.**
- **This helps to reduce complexity at the system controller level and increase time to detection for critical fault cases.**

- **Example: Switch Stuck Open**
  - In the example on the right, a normally stuck closed switch has failed open.
  - The local controller of Main Bus Switching Unit (MBSU) 1-1 uses a rules-based algorithm to detect that a large voltage differential across the switch RBI3.
  - Finally, the fault is sent to the system level fault manager for vetting.



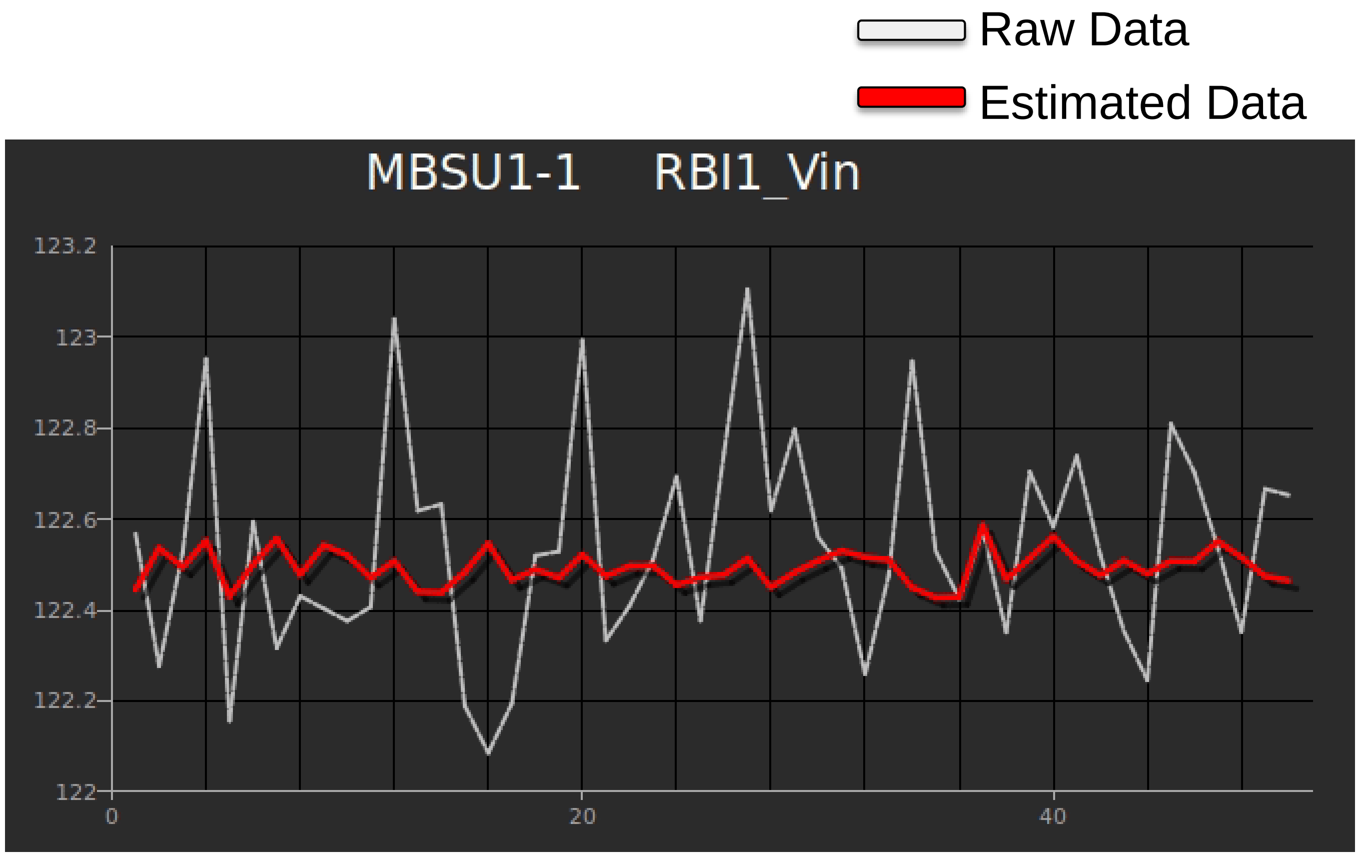
Example of rules-based fault detection.



A distribution branch of a power system after a switch has failed open

Sensor Faults

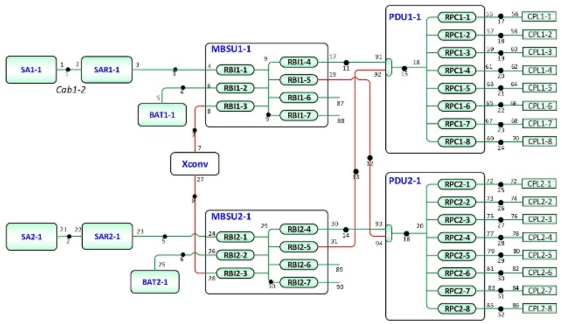
- Electrical power measurement devices (e.g. voltage, current, power, and thermal sensors) are subject to a number of failure modes such as signal bias, excessive noise, and stuck data.
- A dynamic state estimator is able to identify bad with the use of a mathematical model of the power system.
- The state estimator examines the difference between the raw data and the estimated value (i.e. the *residual*) for each sensor.
- If the residual exceeds a certain threshold (based on the statistical properties of the system) a sensor bias can be diagnosed.
- Excessive sensor noise and stuck data can be identified by observing the variance of the residuals.



Voltage signals and estimates from a Main Bus Switching Unit (MBSU) before, during, and after a sensor bias fault

Power System Software Configurability

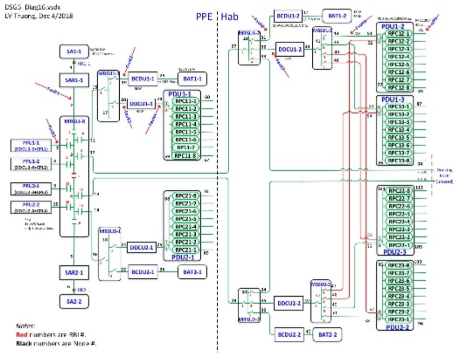
- **The Autonomous Power Controller (APC) uses a single configuration file that fully describes the electrical power system (EPS) topology.**
- **Changing this file allows the APC to function with nearly any spacecraft comprised of the AMPS hardware.**



EAM Power System

EAM configuration file

Autonomous Power Controller (APC)



Gateway Power System (concept)

Gateway configuration file

The AMPS Autonomous Power Control Team

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Thank You!!

Questions???