Modular, Intelligent Power Systems for Space Exploration

Invited Presentation

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Abstract:

NASA's new Space Exploration Initiative demands that vehicles, habitats, and rovers achieve unprecedented levels of reliability, safety, effectiveness, and affordability. Modular and intelligent electrical power systems are critical to achieving those goals. Modular electrical power systems naturally increase reliability and safety through built-in fault tolerance. These modular systems also enable standardization across a multitude of systems, thereby greatly increasing affordability of the programs. Various technologies being developed to support this new paradigm for space power systems will be presented. Examples include the use of digital control in power electronics to enable better performance and advanced modularity functions such as distributed, master-less control and series input power conversion. Also, digital control and robust communication enables new levels of power system control, stability, fault detection, and health management. Summary results from recent development efforts are presented along with expected future technology development needs required to support NASA's ambitious space exploration goals.

Modular, Intelligent Power Systems for Space Exploration

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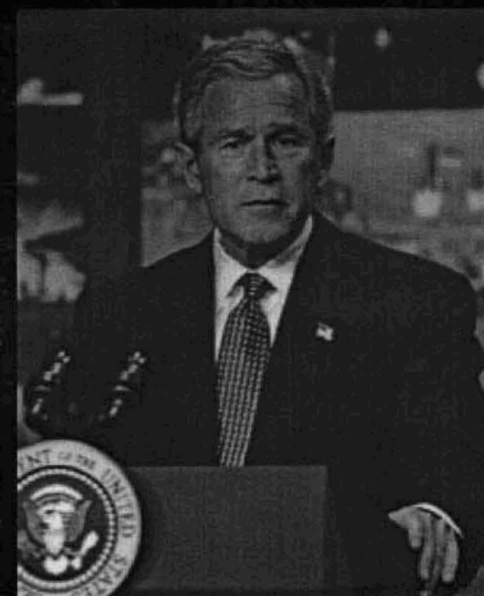
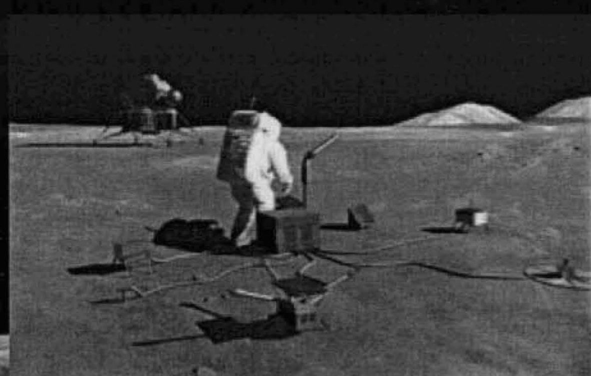
Outline

- Constellation - NASA's Vision for Space Exploration
- Challenges for Electric Power Systems
- Recent Advances
- Future Needs and Plans
- Conclusions

A Bold Vision for Space Exploration

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2014 (goal of 2012)
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration



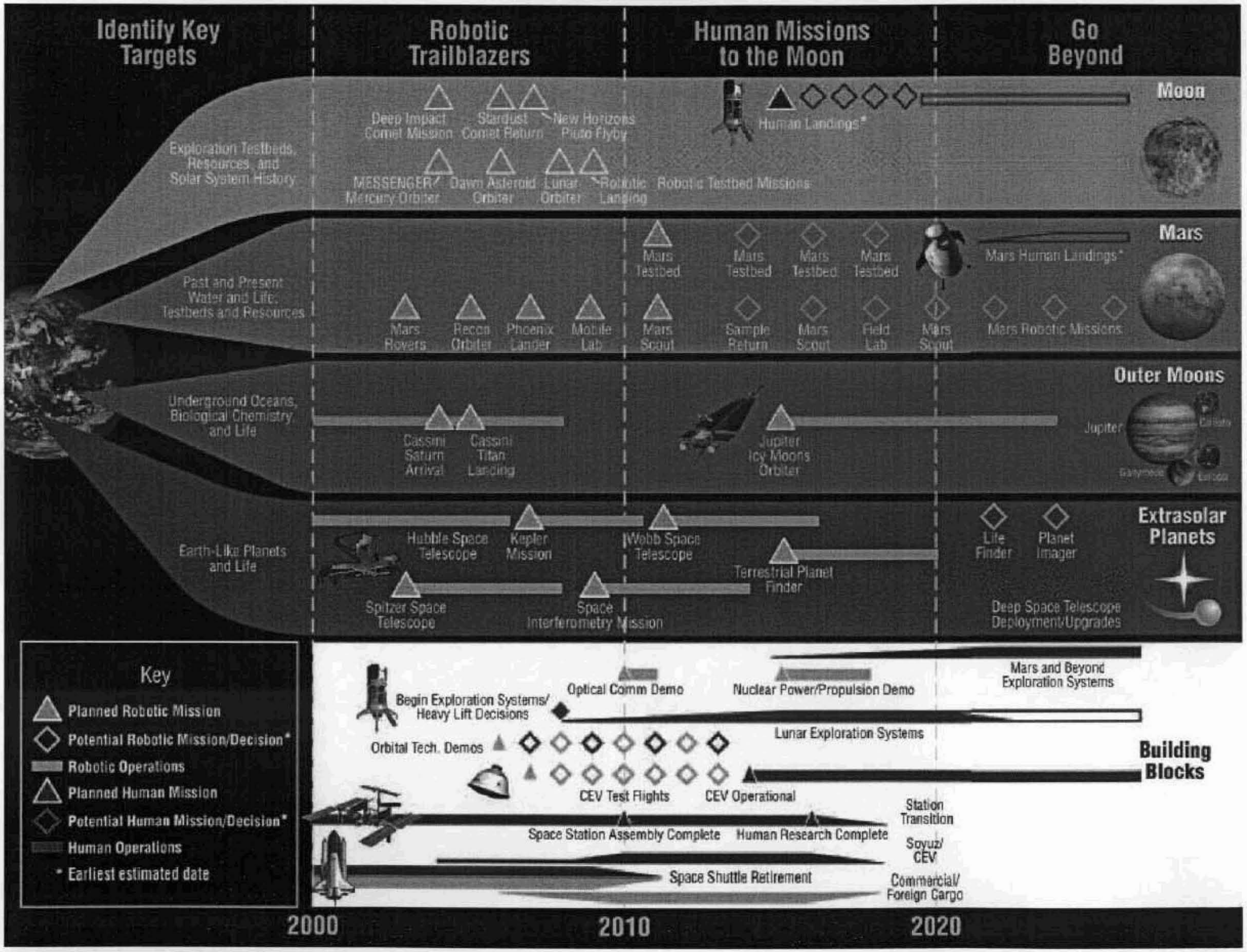


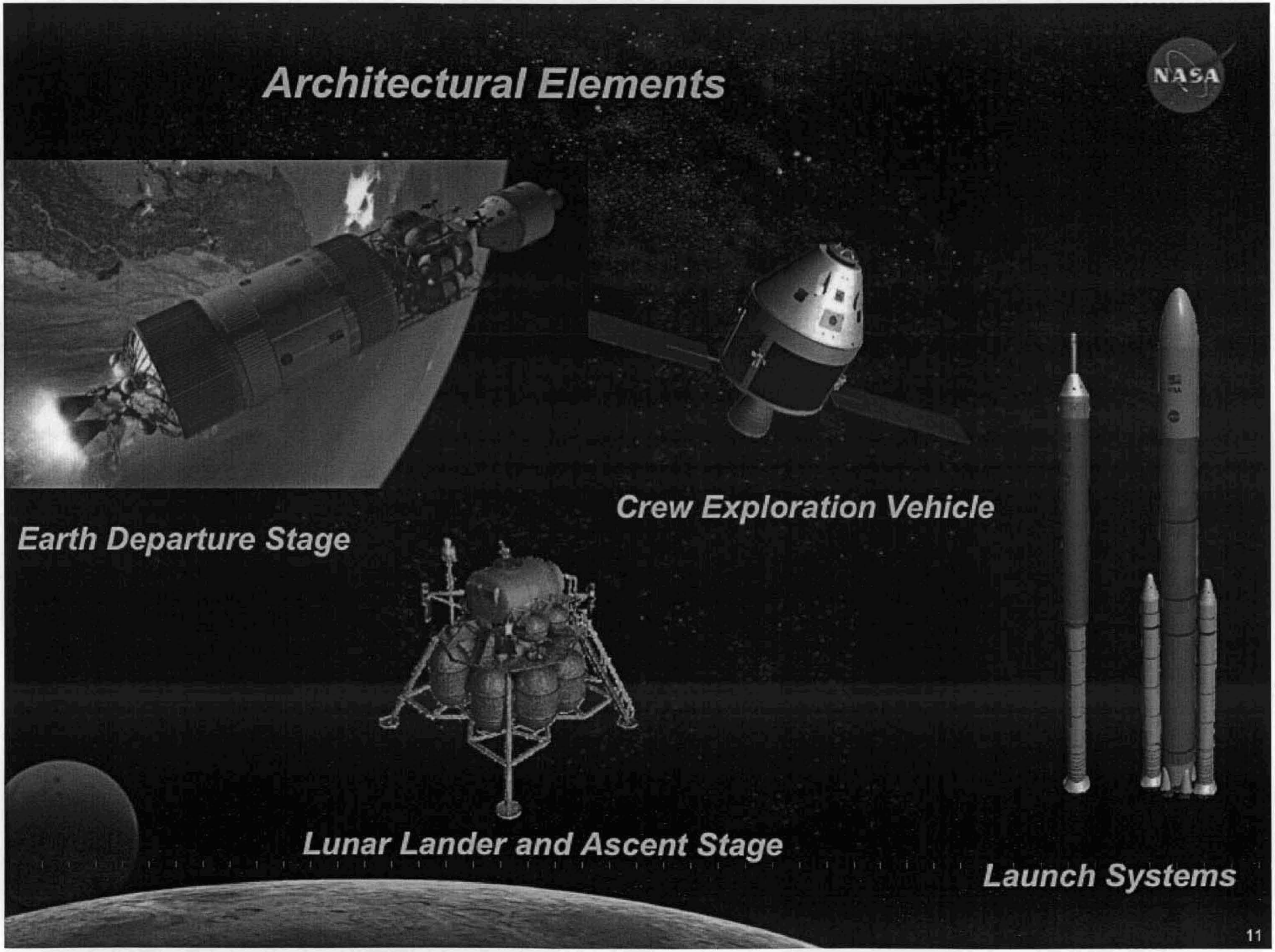
"It is time for America to take the next steps.

Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We'll make steady progress – one mission, one voyage, one landing at a time"

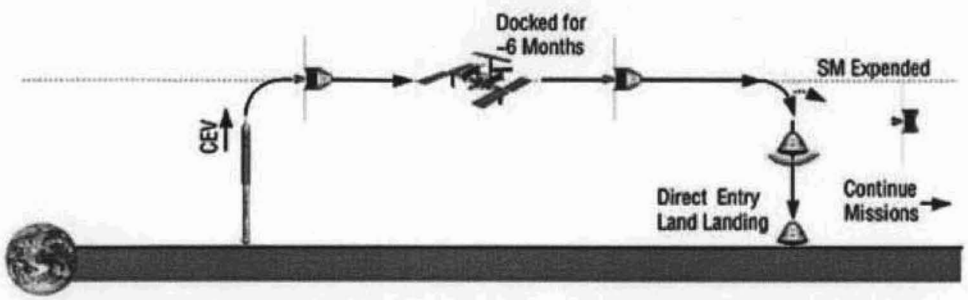
President George W. Bush – January 14, 2004

NASA's Space Exploration Timeline (2004)

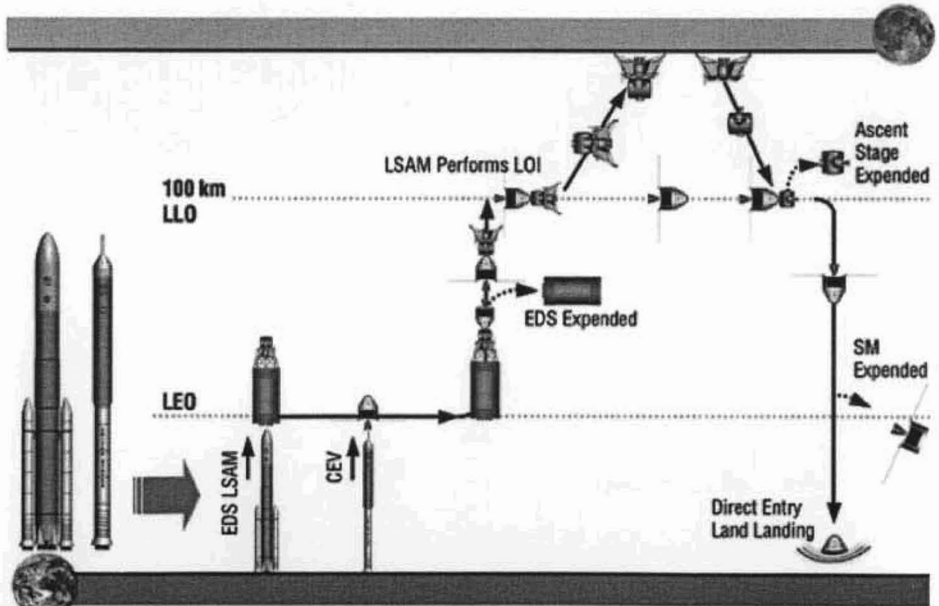



Architectural Elements
Earth Departure Stage
Crew Exploration Vehicle
Lunar Lander and Ascent Stage
Launch Systems

Design Reference Missions



Initial CLV/CEV mission to the International Space Station - 2014



Initial Lunar return mission - 2018-2020

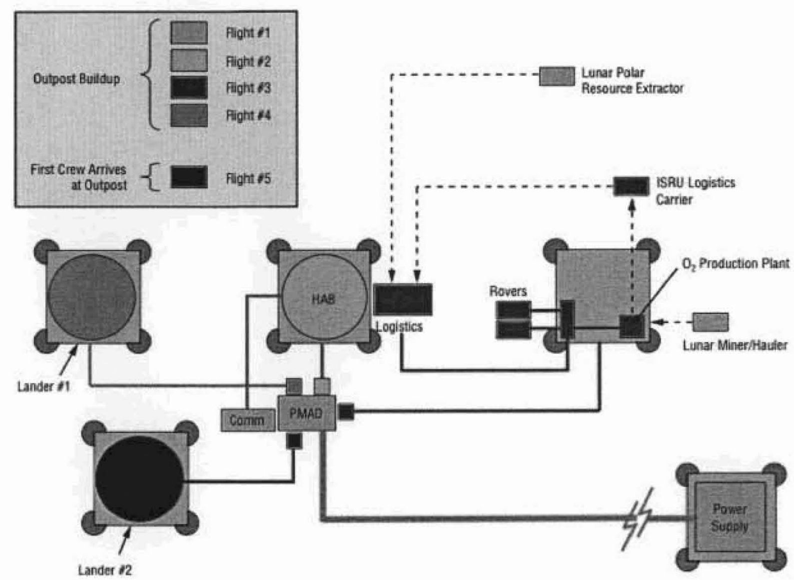


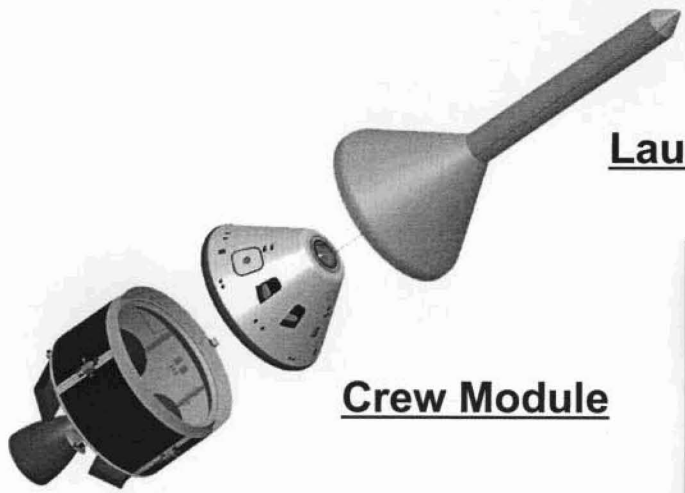
Figure 4-44. Core Outpost Schematic

Permanent Lunar Base Concept

Power System Challenges for Exploration

- High Energy Density
  - High generation and storage capacity, low launch mass
- High Fault Tolerance and Reliability
  - "Two-fault tolerant" requirement
    - Fail op, fail safe? OR Fail op, fail op, fail safe?
  - Modularity - limit impact of single faults
- Low Cost
  - Maximize use of current technology
  - Use common components within and between elements
  - Autonomy - reduce ground operations
- Interoperability
  - Power sharing between connected elements
    - CEV - Service Module, Crew Module, Launch Abort System
    - CEV&ISS, EDS&LSAM, CEV&LSAM

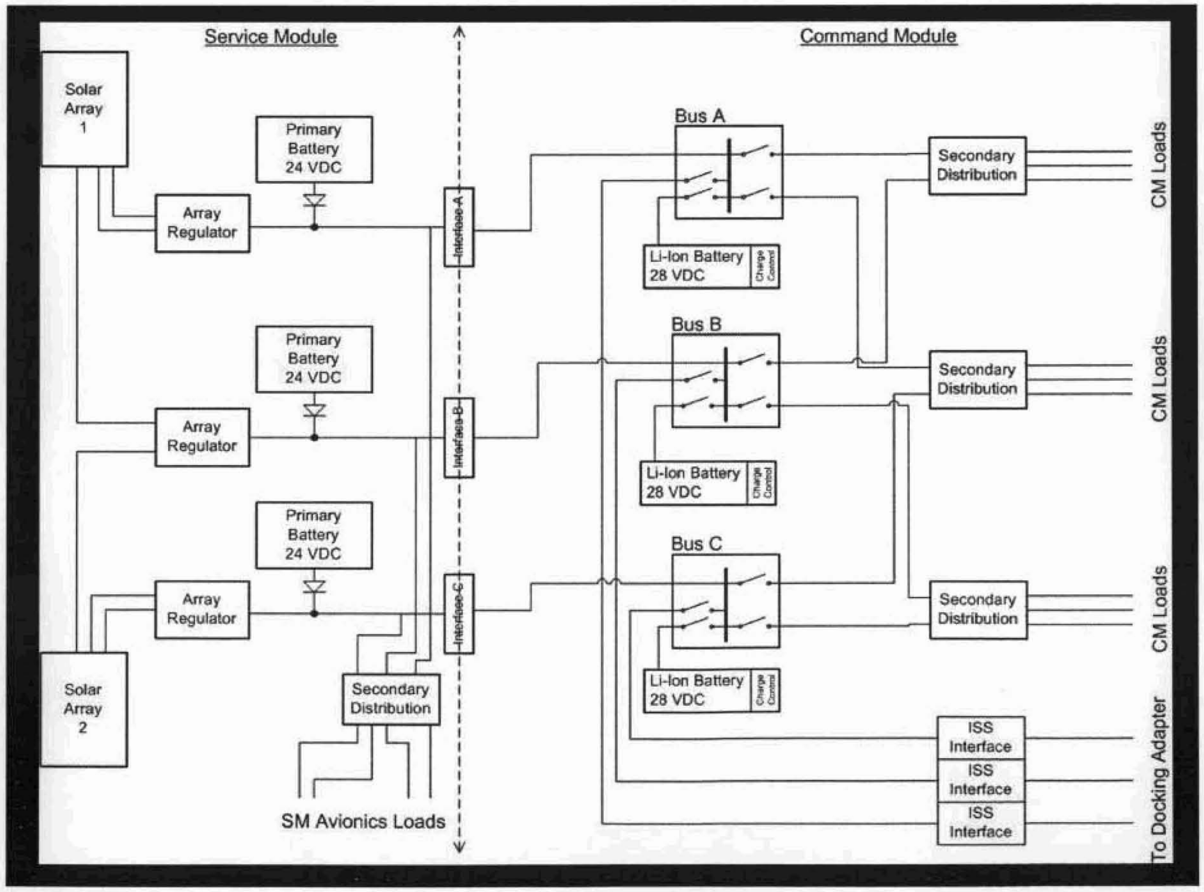
Example CEV Power System



Launch Abort System

Crew Module

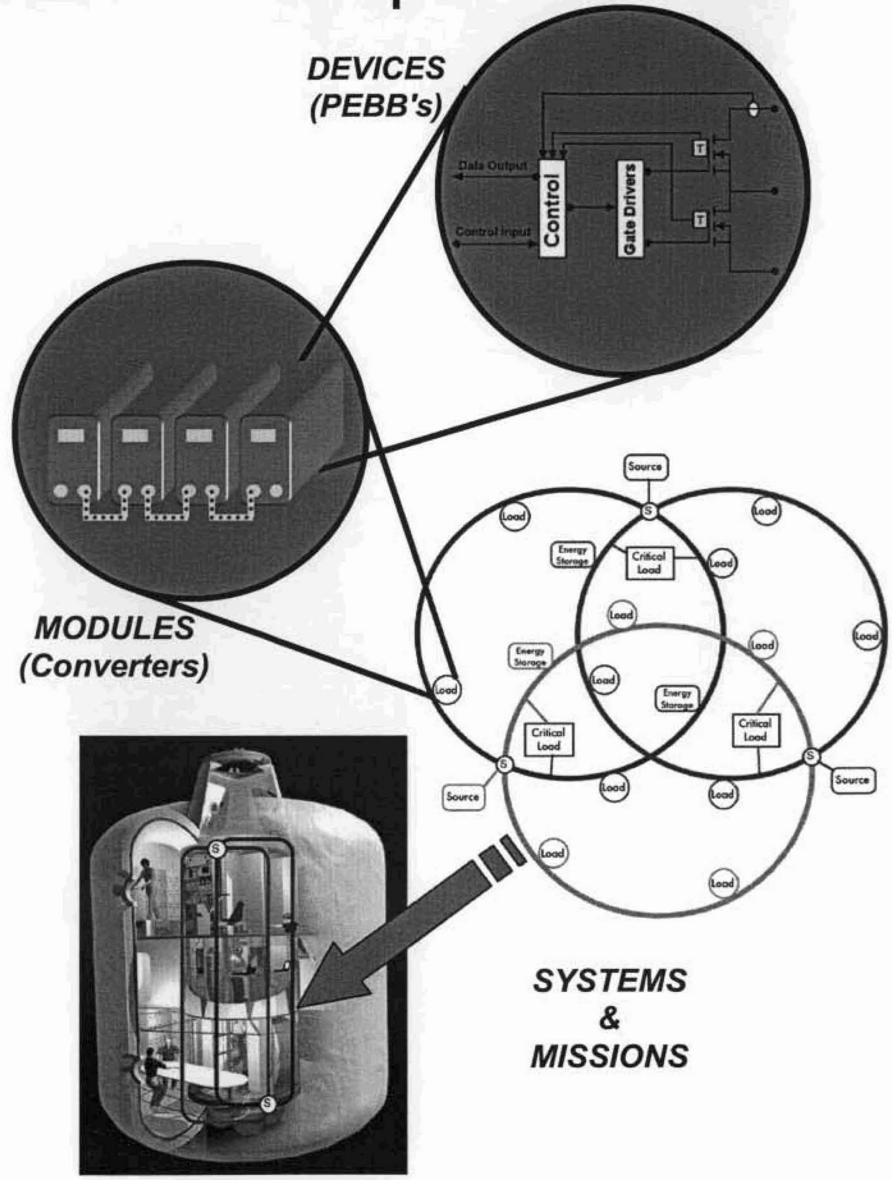
Service Module



Modular, Intelligent Power Systems Concepts and Benefits

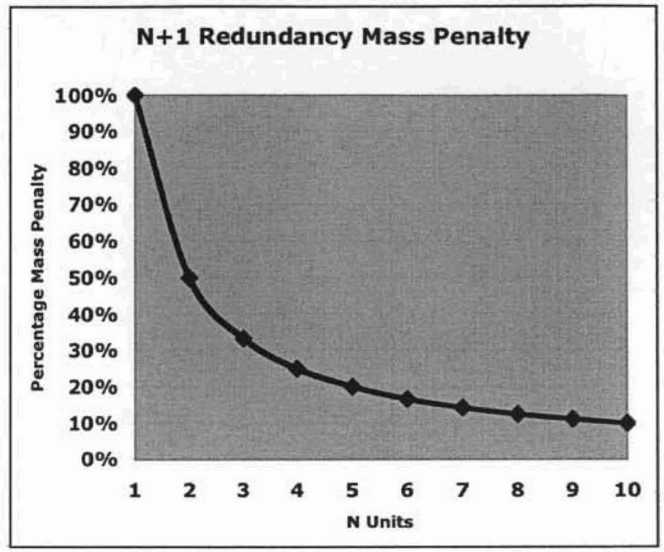
Modular Power System Concepts

- Combine power processing and information technology.
- "Monolithic" power system components are replaced by collections of common "smart modules".
- The power system can be "modularized" at various levels.
  - Device Level
    - Uses common power switching devices integrated with an intelligent controller.
    - Power Electronic Building Blocks (PEBB's).
  - Functional Module Level
    - Functional modules utilize PEBB's to build converters and switchgear collaborating with each other.
  - System Level
    - Integrate modules into sub-systems with power generation, storage, distribution, regulation, protection, and control.



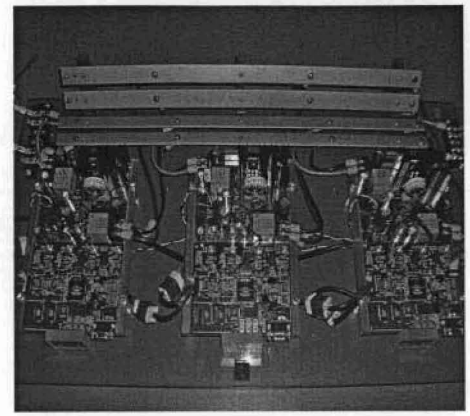
Modular Power System - Benefits

- Increase reliability for less mass
  - N+X redundancy = on-line spares.
  - Large mass penalty if N is a low number.
- Reduction in off-line “spares”.
  - Important for long duration, "serviceable" applications.
  - Fewer unique “boxes” mean less “spares” to bring along.
- Lower hardware costs
  - Multiple functions met by using common modules.
  - Less “boxes” to develop and qualify.
  - Cost savings mainly a function of non-recurring/recurring cost ratio.

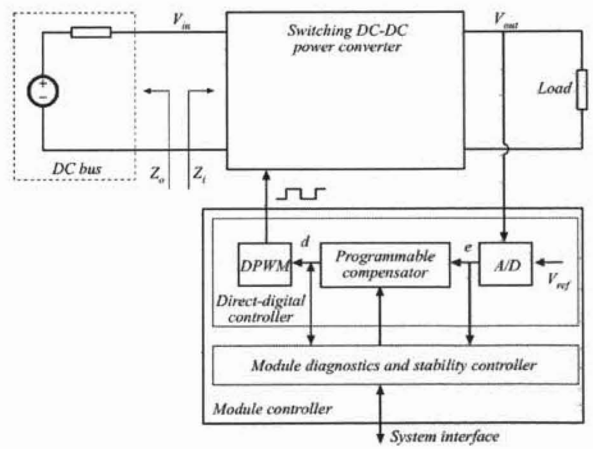


Modular Power System - Other Benefits

- Multi-module collaboration can increase performance
  - Higher efficiency - active module balancing
  - Lower noise (less filter mass) - phase staggered switching

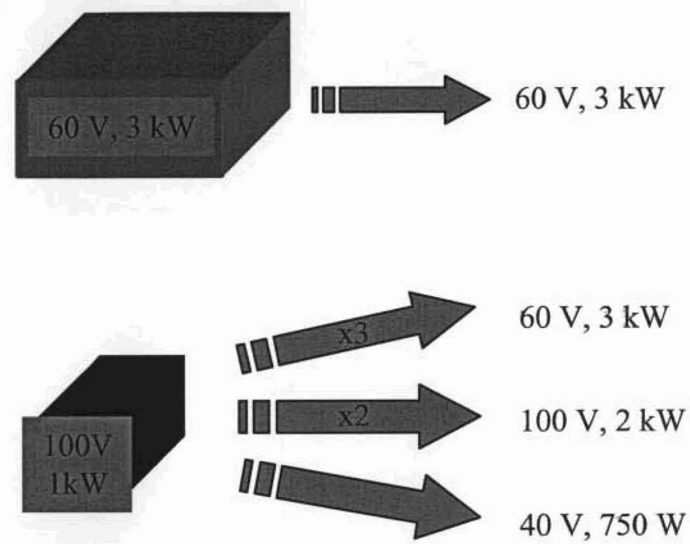


- Digital control + communications enables
  - Active stability control.
  - Active control optimization.
  - Health management (component and system)
  - Distributed topologies



Modular Power System - Disadvantages

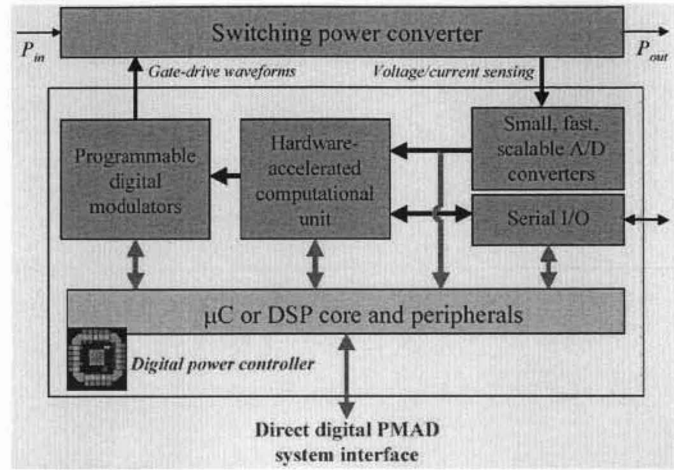
- Modular designs are non-optimal
  - Designed for more than one application.
    - Extra packaging = Increased system mass.
    - Use of over-specified devices.
      - Semiconductors - lower efficiency
      - Capacitors - higher volume
      - Magnetics - higher mass
  - Digital control introduces software headaches to power electronics
    - Version control, verification, etc.

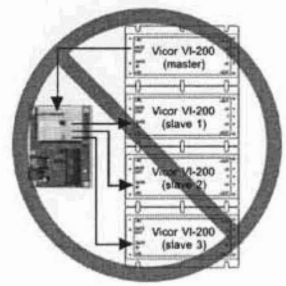


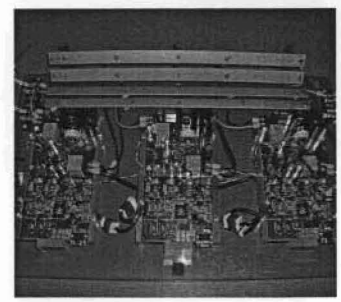
- Non-recurring costs could be higher?
  - Additional capabilities, wider range of requirements.
  - Additional software development.

Intelligent Power Systems

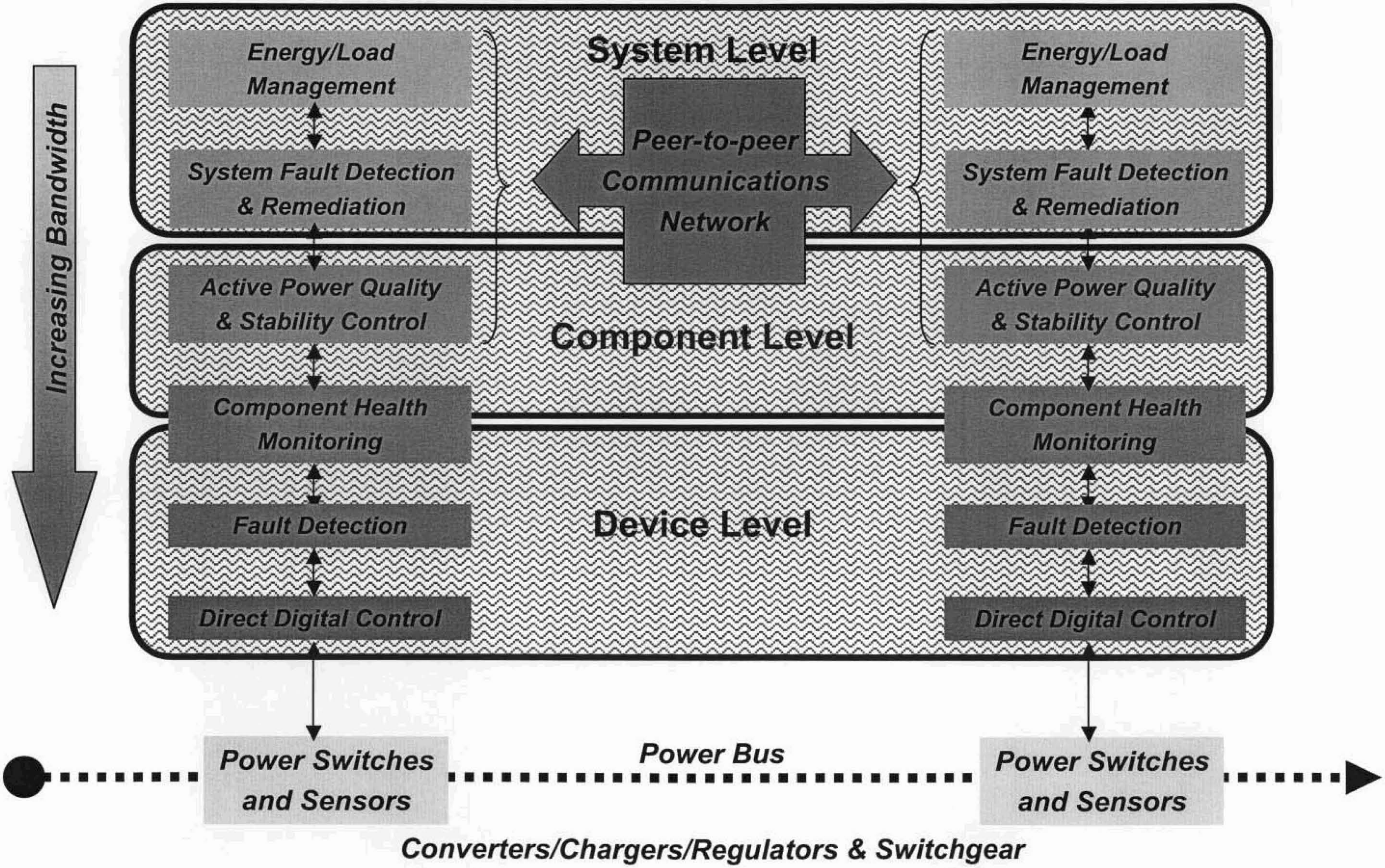
- Maximizes use of digital control
  - Increased information processing capability
  - Increased adaptability and flexibility.
- Communications
  - Peer-to-peer communication
  - Distributed algorithms
  - High level system communication
- Advanced control algorithms
  - Non-linear, adaptive control
  - "Masterless" collaboration
  - Active system stability control
  - Component and System Health Management
  - Autonomous energy management and fault reconfiguration.





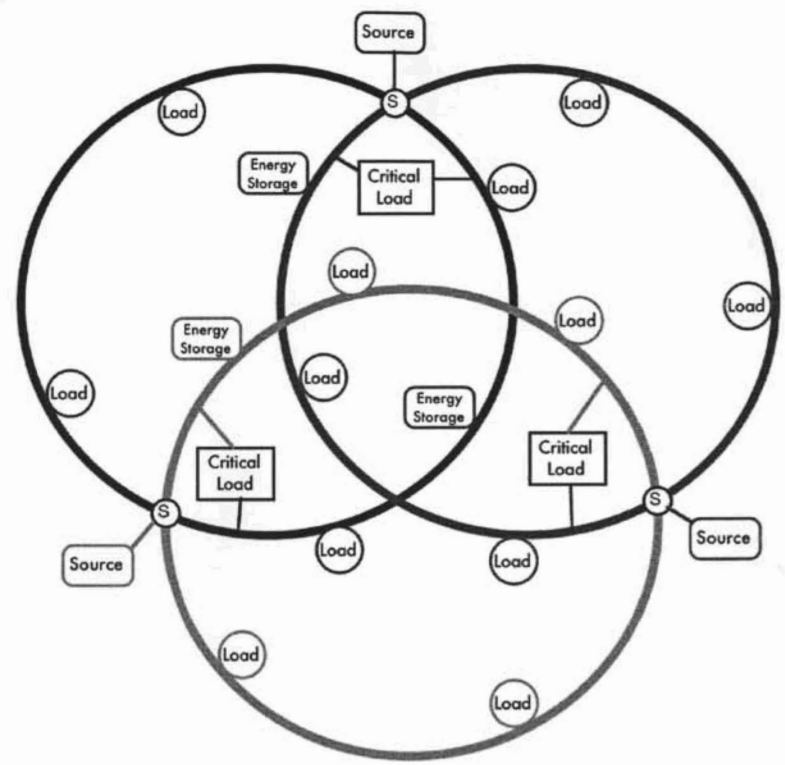


Intelligent PMAD Hierarchy



System Intelligence

- Automated Fault Recovery
  - Centralized agent collects data from all PMAD devices.
  - Detects failures and anomalies
  - Solves optimal solution and reconfigures system.
    - Solution pre-calculated?
- Energy Management
  - Agent analyzes power source capabilities, load demands.
  - Compares against mission priorities
  - Automatically optimizes energy use
- System Health Monitoring
  - Component health aggregated.

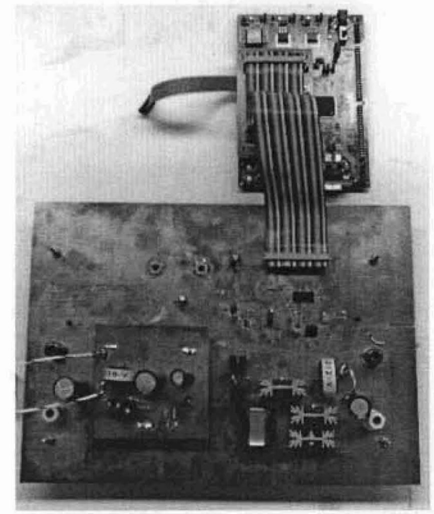


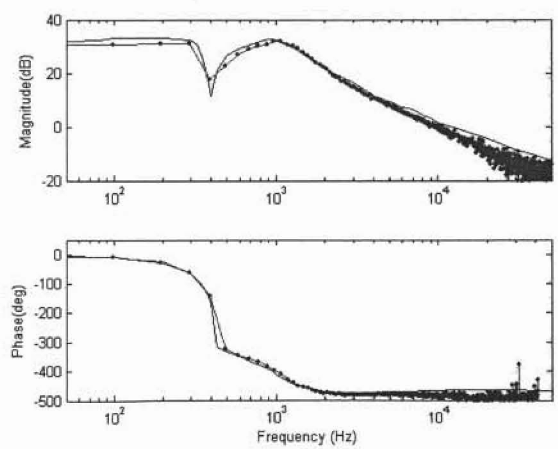
Multi-ring bus distribution architecture

Recent Accomplishments

Intelligent PMAD System Accomplishments

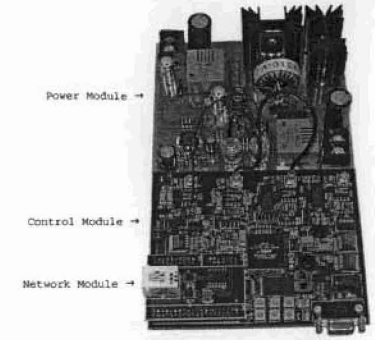
- MILESTONE
  - Demonstrate active stability control.
  - University of Colorado (CoPEC)
- SUMMARY
  - Develop control methods for DC-DC converter to actively maintain stability in the presence of internal failures and/or external system changes.
- STATUS/PROGRESS
  - Simple digital controller interfaced with DC-DC converter for control and "plant" identification.
  - Random signal injection technique developed.
  - Impulse response and frequency/phase identification demonstrated.
- PRODUCTS
  - Hardware demonstration at Colorado (April 2004).
  - Paper - "A Modified Cross-Correlation Method for System Identification of Power Converters with Digital Control, PESC 2004.
  - Paper - "Active System Identification of a DC-DC Converter Using Digital Control", IECEC 2004.

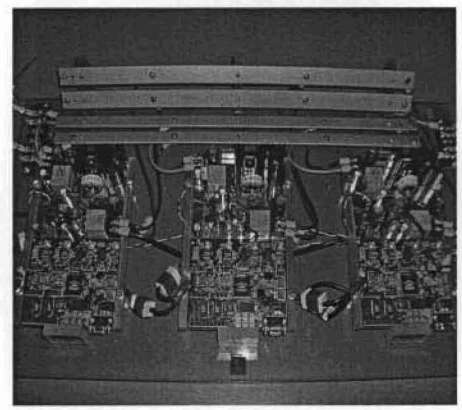


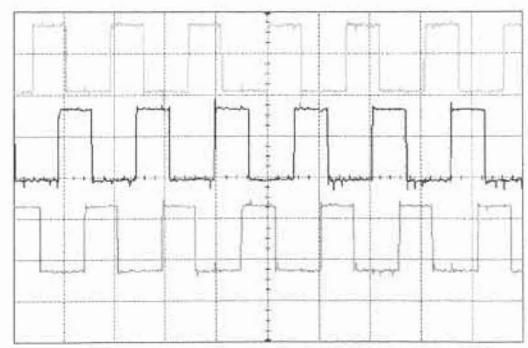


Intelligent PMAD System Accomplishments

- MILESTONE
  - Develop and demonstrate master-less, distributed control of paralleled DC-DC converters using digital control.
  - Cleveland State University
- SUMMARY
  - Develop distributed control in modular DC-DC converters and demonstrate active current sharing, efficiency optimization, and phase-stagger switching between multiple DC-DC converters
- STATUS/PROGRESS
  - Three digitally controlled DC-DC converters built.
  - Initial capabilities demonstrated 1Q04.
  - Communication improved to CANbus. Computer interface developed.
  - Full functionality demonstrated July 2004
- PRODUCTS
  - Hardware demonstration at CSU (July 2004) .
  - Paper - "Distributed, Master-less Control of Modular DC-DC Converters", IECEC 2004.

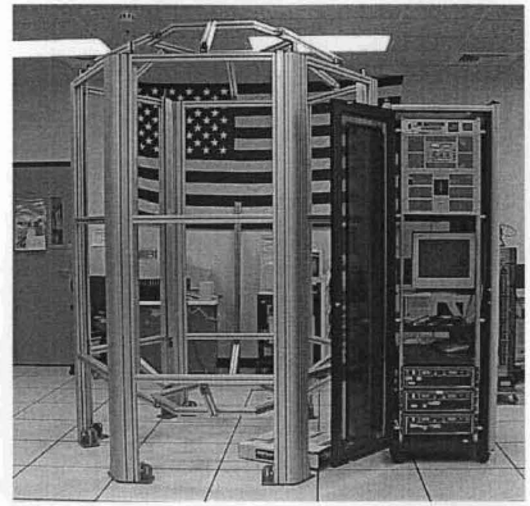






Intelligent PMAD System Accomplishments

- MILESTONE
  - Intelligent PMAD System Test Bed Design
- SUMMARY
  - Design and begin development of the multi-ring distribution power system.
- STATUS/PROGRESS
  - Concept formulated and sketches completed.
  - Ring-bus structure built. Integrated conductors procured and installed.
  - Support equipment (power supply, loads, etc.) procured.
  - Distribution switch initial design completed. Majority of parts procured.
  - Progress has been greatly delayed by ICP/ECP work.
- PRODUCTS
  - Conceptual design sketches and initial test bed hardware.



CONCLUSIONS

- Long term human and robotic exploration initiative demands more modular and intelligent sub-systems.

- Bottom-line Benefits are:
  - Lower costs.
  - Higher reliability and autonomy.

- Adoption can be incremental
  - “Bottom-up”, “Top-down”, “Middle-out” are all conceivable.

- Investments in development must be made early so technology is ready for missions.
  - Must get aerospace contractor and industry “buy-in”.