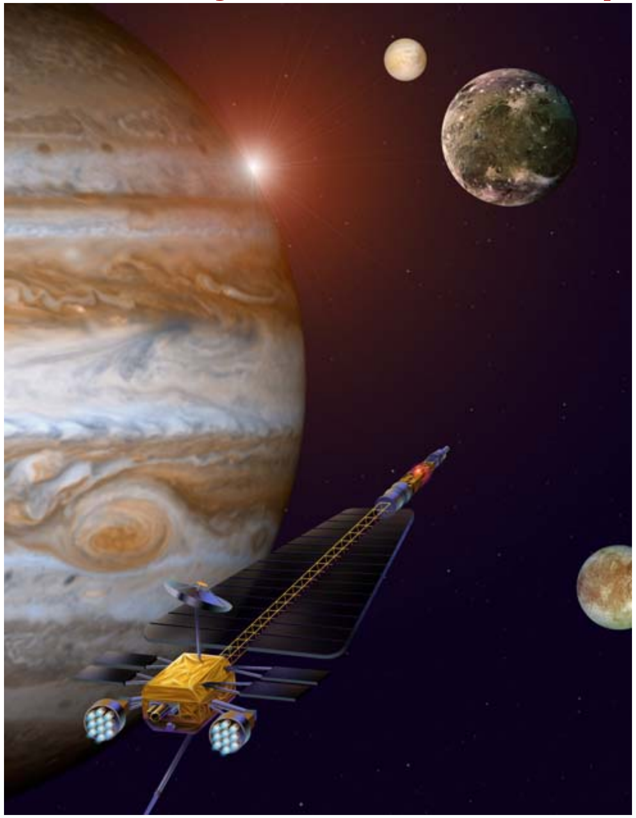
Autonomous Control Concepts

Exploring the water worlds of Jupiter: Callisto, Ganymede, and Europa



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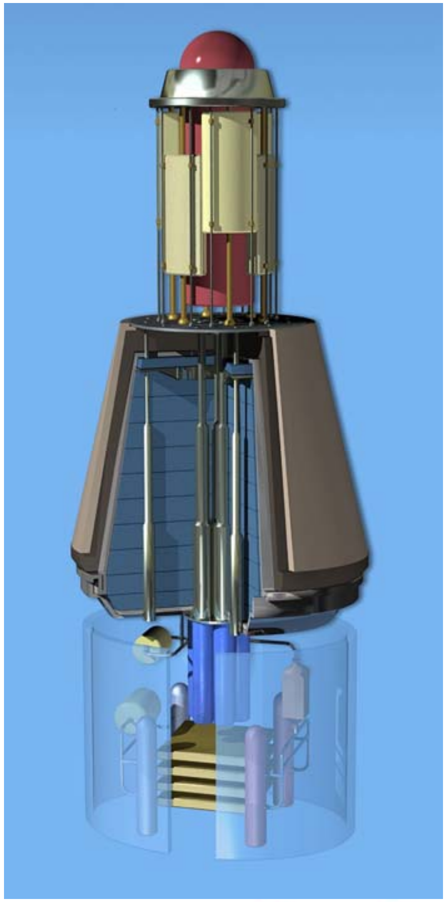
The JIMO Deep-Space Mission Planned to Use a Space Reactor System

- The Jupiter Icy Moons Orbiter, or JIMO, was to orbit three planet-sized moons of Jupiter—Callisto, Ganymede, and Europa—that may harbor vast oceans beneath their icy surfaces
- The JIMO mission would raise NASA's capability for space exploration to a new level with the use of an electric propulsion system that is powered by a nuclear fission reactor
- This technology not only makes it possible to orbit three of the moons of Jupiter, it also opens the rest of the outer Solar System to detailed exploration in future missions



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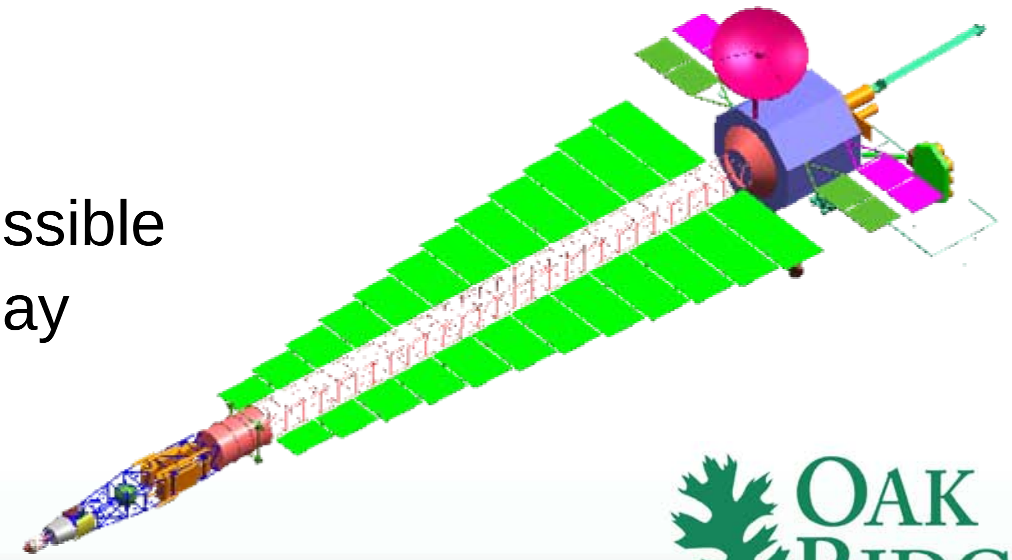
The Requirements for a Deep-Space Mission Present Formidable Constraints

Challenges for a Space Reactor Control System

- High sustained power
- Mass efficient
- Reliable
- Long-term operation
- Continuous operation
- No maintenance; inaccessible
- Communication time delay
- Severe environment



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Distinct Control Scenarios Must be Accommodated over Mission Lifetime

- Startup (sequence of actions/events)
- Power maneuvering (ascension, load following, and reduction)
  - Direct reactivity control (move control element)
  - Indirect inherent feedback control (manage heat removal)
- Response to off-normal events
  - Reactor protection (diversity and defense-in-depth — limitation, rapid runback)
  - Autonomous control (fault tolerance — detection, diagnosis, adaptation/reconfiguration)
- Shutdown and reactor safing

JIMO Space Reactor System Must Be Capable Of Extended Operation Without Human Intervention

- Terrestrial nuclear reactors and deep-space missions have used varying degrees of direct human control and decision-making for operations
- Terrestrial nuclear reactors allow periodic human intervention for maintenance
- Deep-space missions allow human intervention for control, diagnosis, recovery, and reconfiguration

- **Space reactor systems are intended to provide continuous unattended operation for up to 20 years**

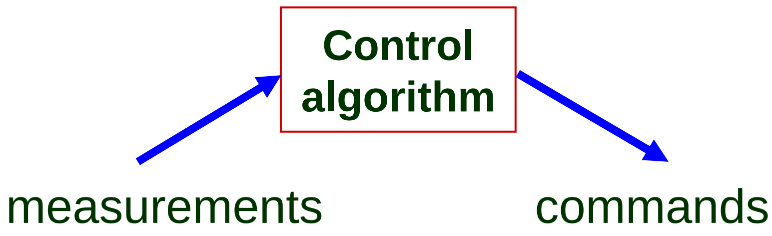
Space Reactor Control Poses Unique Issues that Require Autonomy

- Space Reactor paradigm is different
  - Immediate human interaction for continuous operational control and event management is not feasible → high level of autonomy
  - Size and mass matter (e.g., distance location and local shielding restricted) → functional and environmental robustness
  - Maintenance/refurbishment are likely not possible → long-life dependability
  - Reactor power must be available on demand → minimize or avoid reactor scram
    - Operational imperative favors mission assurance over reactor protection
- Autonomy must provide functional capability to accommodate challenging conditions
  - Physical and practical constraints on direct human interaction for the operation of space reactors
  - Immediate, unsupervised detection and response for fast acting events without requiring reactor scram
  - Adaptation to degraded or off-normal conditions

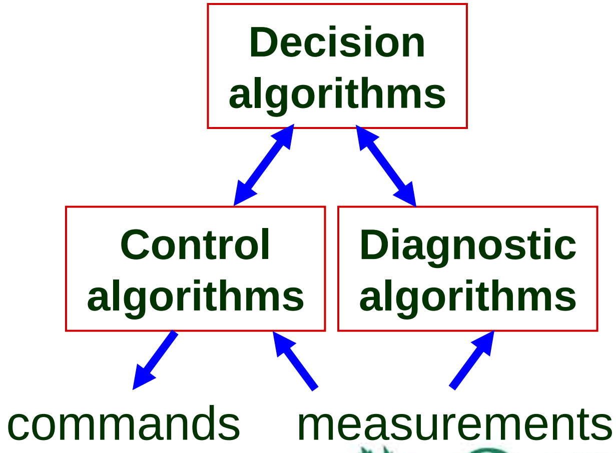
Autonomous Control Encompasses Automated Control

- Automated Control
  - Self acting (*automatos*)
  - Control action is the result of fixed algorithms with limited global state determination
  - No real-time operator action needed
  - Typically individual control loops, not full system integration
  - Decision making left to the human
- Autonomous Control
  - Independent (*autonomos*)
  - Integrated control, diagnostic, and decision capabilities
  - No human intervention required
  - Flexible functional architecture
    - Self-maintenance over lifetime
    - Adaptation to changing conditions and constraints
  - Never implemented for any power generation system

Automated Control Structure



Autonomous Control Structure



Autonomy Extends the Scope of Primary Control Functions

- Provide automatic control during all operating modes
- Optimize system performance
- Continuously monitor and diagnose performance and trends of operational and safety-related parameters
- Diagnose the condition of key components
- Provide flexible control and protection of limited-life devices (e.g., batteries, actuators)
- Adapt to changing/degraded conditions
- Validate and maintain control system performance

Space Reactor Autonomy Embodies Innovative Characteristics

- Intelligence
  - Minimal or no reliance on human intervention
  - Integrated whole system approach
  - Embedded decision-making capability
  - Anticipatory action based on system knowledge/prediction
  - Real-time diagnostic capability for state identification and condition monitoring
  - Self-validating
    - Data
    - Command
    - System

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Space Reactor Autonomy Embodies Innovative Characteristics (cont)

- Robustness
  - Accounts for uncertainties and unmodeled dynamics
  - Environmentally rugged
  - Fault Tolerant
    - Diversity
    - Redundancy
    - Reliability
  - Self-maintaining
    - Captured design knowledge and self-correcting capability
    - Prognostics to identify incipient failure
    - Fault detection and isolation

Space Reactor Autonomy Embodies Innovative Characteristics (cont)

- Optimization
  - Rapid response to demands
  - Minimal deviation from target
  - Efficient actuator action
- Flexible and Adaptable
  - Functional reconfigurability and redesign capability
  - Diverse measurement parameters
  - Multiple communications options
  - Alternate control solutions

Autonomy is Distinguished by Decision-making Capabilities and Fault Management Approaches

- Control system autonomy (monitor, trend, detect, diagnose, decide, self-adjust)
  - Recognizing system degradation (or incipient failure) and adjusting control system in response
  - No human intervention for long periods compared to event propagation time frames
- Fault management (avoidance, removal, tolerance, forecasting)
  - Detect and identify (preferably incipient) field device faults
    - Model-based and/or data driven surveillance
  - Track changes in system parameters
    - Empirical and/or first principles estimation
    - Adjustable system dynamic model for fault prediction
  - Detect off-normal conditions and identify anticipated events
  - Configuration control (Manage transition among pre-defined control strategies/algorithms)

Autonomy is Most Relevant for Off-Normal Conditions

- Fault management scenarios
  - Fault adaptation: Switching to alternate control algorithm(s) to reconfigure for faulted or suspect measurements
    - Indicator examples: Divergence of redundant measurements, conflict between predicted and measured values (e.g., analytical or relational estimation), detection and isolation of confirmed fault
    - Response example: Utilize diverse measurements (e.g., thermal power estimation and neutron flux as power measurements) for alternate control algorithms
  - Fault Avoidance: Switching to alternate control strategy to reconfigure for faulted actuator or avoid incipient failure by reducing stress on key components
    - Indicator examples: Prediction of control drive failure based on prognostic modeling (e.g., failure forecasting) or detection of sluggish/stuck element
    - Response example: Utilize flow control (i.e., heat removal) rather than control element movement (i.e., flux) for reactor power control

Necessary Degree of Autonomy Depends on Mission Definition

- Mission requirements determine necessary autonomy characteristics
  - Concept of operations
  - Potential hazards
  - Trades (e.g., technology readiness, mass penalty, risk, cost)
- Several factors influence degree of autonomy
  - Potential for human interaction
  - Performance goals
  - Complexity of system demands
  - Technological constraints
  - Mission risk considerations
  - Balance between simplicity (reliability) and complexity (capacity to detect and adapt)

Clear Gaps Remain in the Development and Demonstration of Autonomous Control

- Varying degrees of autonomy have been employed in limited applications in other domains
  - Robotics
  - Transportation
  - Spacecraft
  - Manufacturing
- Autonomous control has never been implemented for nuclear power plants
  - Automation of simple loops based on classical control
  - Some integrated plant-wide digital control for normal power operation
  - Advanced control techniques demonstrated using simulation and research reactors

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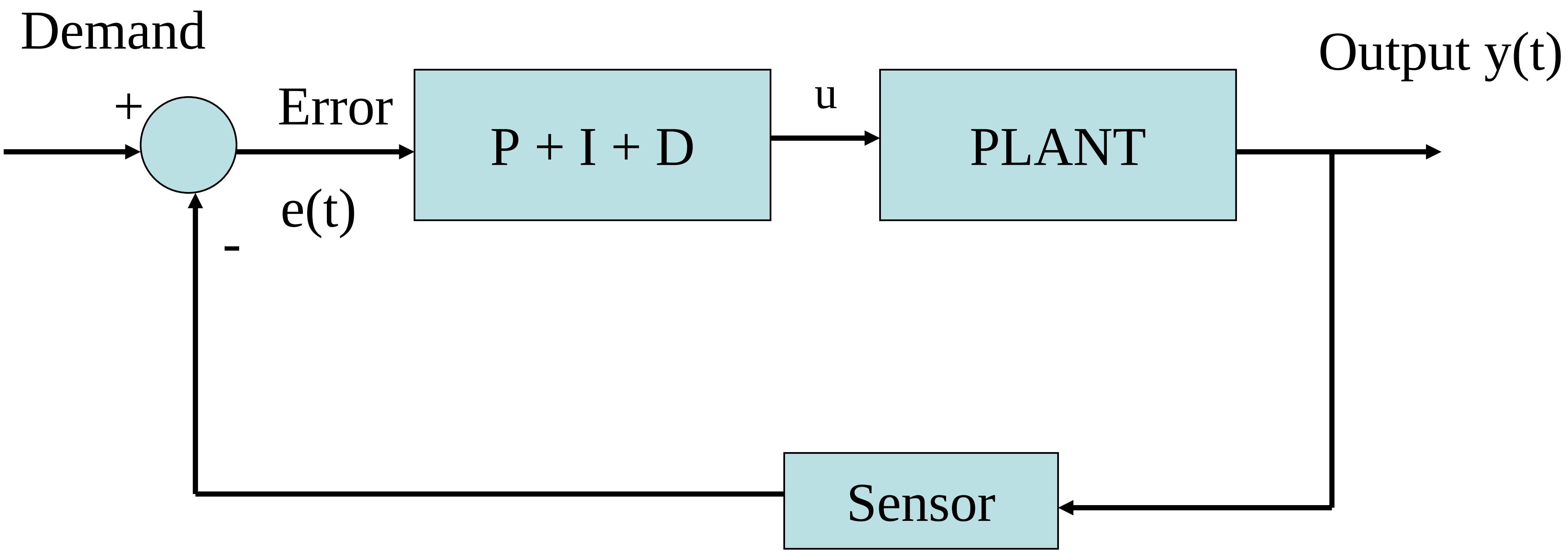
Classical Control Remains the Primary Means of Automating Individual Control Loops in the Nuclear Power Industry



$$u = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt}$$

P = Proportional, I = Integral and D = Derivative

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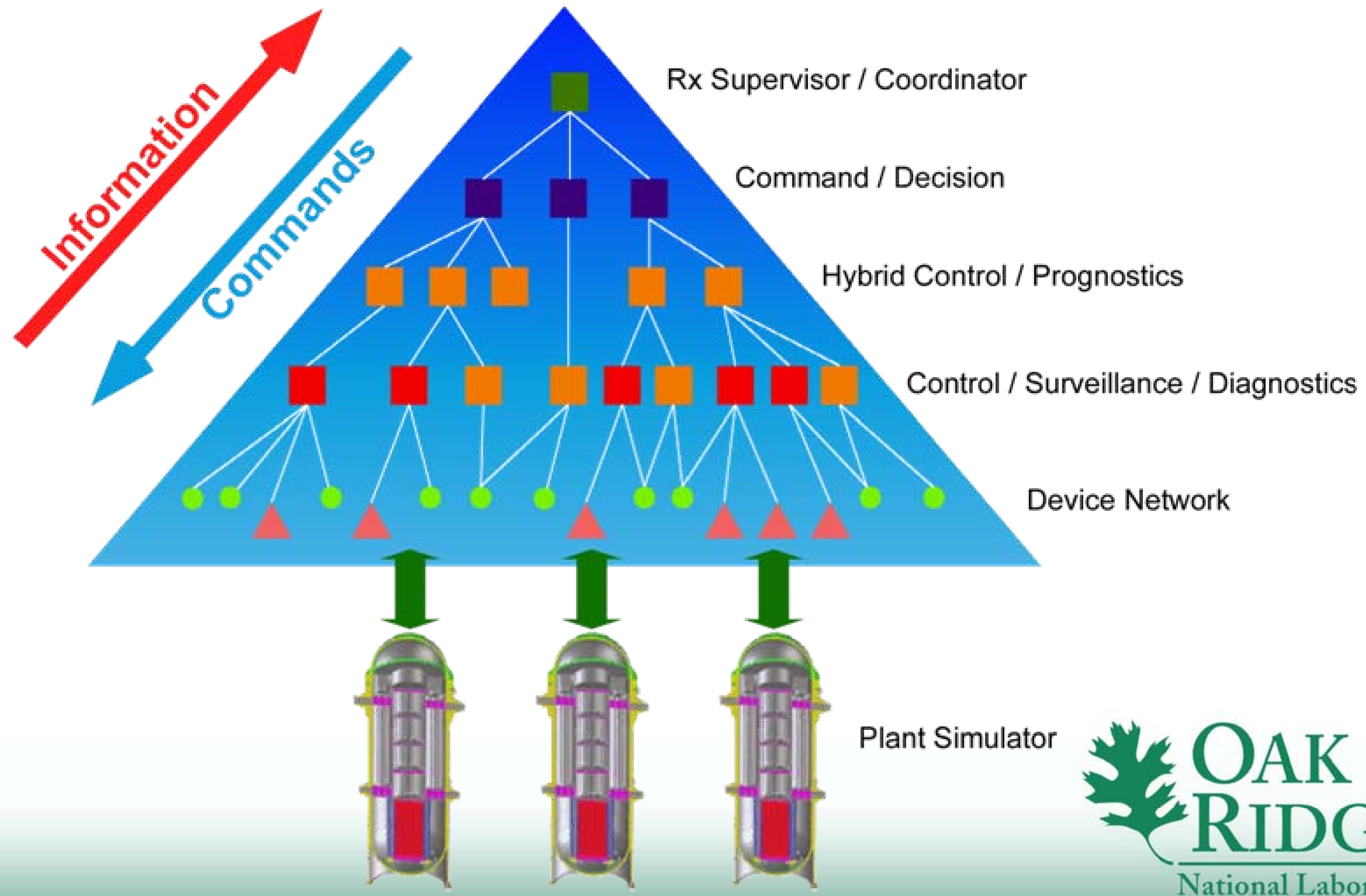
Advanced Control Techniques Have Been Primarily Employed in Research at Universities and National Laboratories

- Linear matrix optimal control
  - LQG/LTR, H_∞, μ-synthesis
- Nonlinear control
  - Inverse dynamics, Lyapunov, Chaos Theory
- Intelligent control
  - Fuzzy logic, artificial neural networks
- Genetic algorithm-based control
- Multi-mode control
  - Pre-designation of specific operational regimes
  - Command validation
- Hierarchical supervisory control

Advanced Control Techniques Have Been Primarily Employed in Research at Universities and National Laboratories (Cont)

- Expert system control (*if-then-else* rules)
  - stated-based
  - data-based
- Intelligent agent-based control
  - autonomous, adaptive software objects
- Multilevel flow model control
- Decision-making methods
  - model-based
  - rule-based (heuristics)
  - data-driven
  - knowledge-based

Supervisory Control Architectures Enable Intelligent Control for Multi-Modular Reactors



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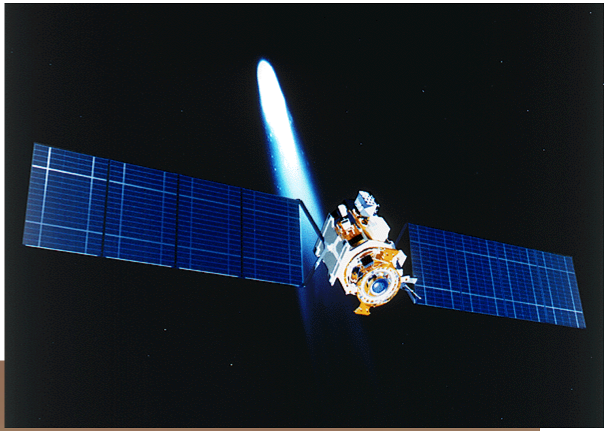
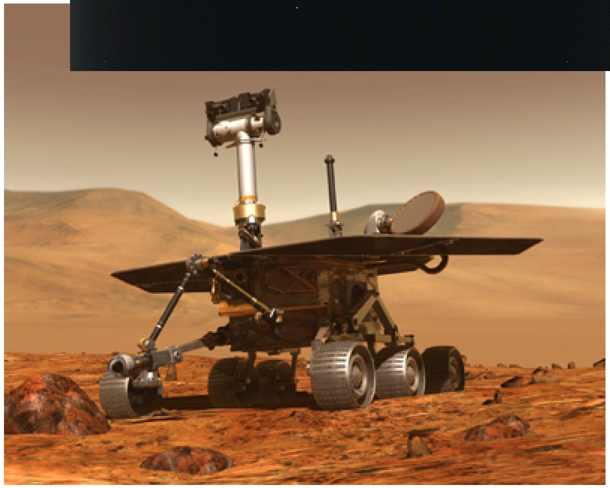
NASA Continues Development of Functional Autonomy for Spacecraft and Rovers

- Sojourner (Mars Pathfinder rover - 1997)
  - Limited autonomy for navigation, resource management, and contingency response
- Deep Space 1 (Spacecraft – 1998)
  - Autonomous navigation and on-board planning and execution of mission tasks
- Mars Exploration Rovers (MER rovers Spirit and Opportunity – 2004)
  - Obstacle detection, navigation, model-based recovery, resource management, and task planning





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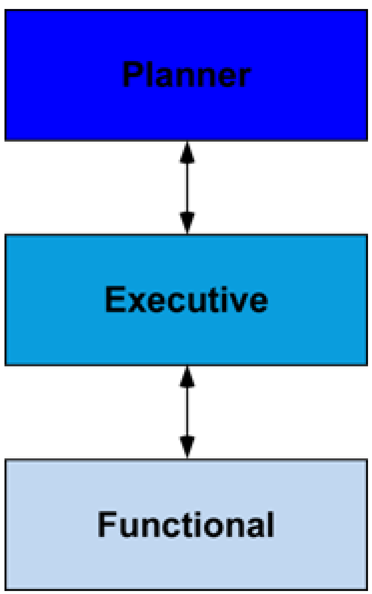
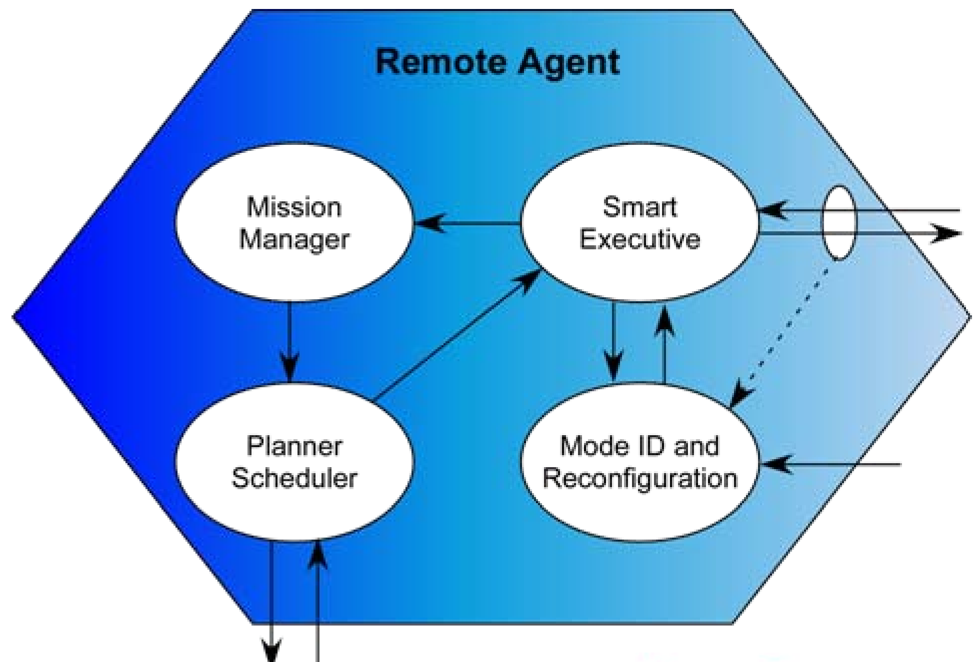
Functional Architectures for Autonomous Control have Evolved

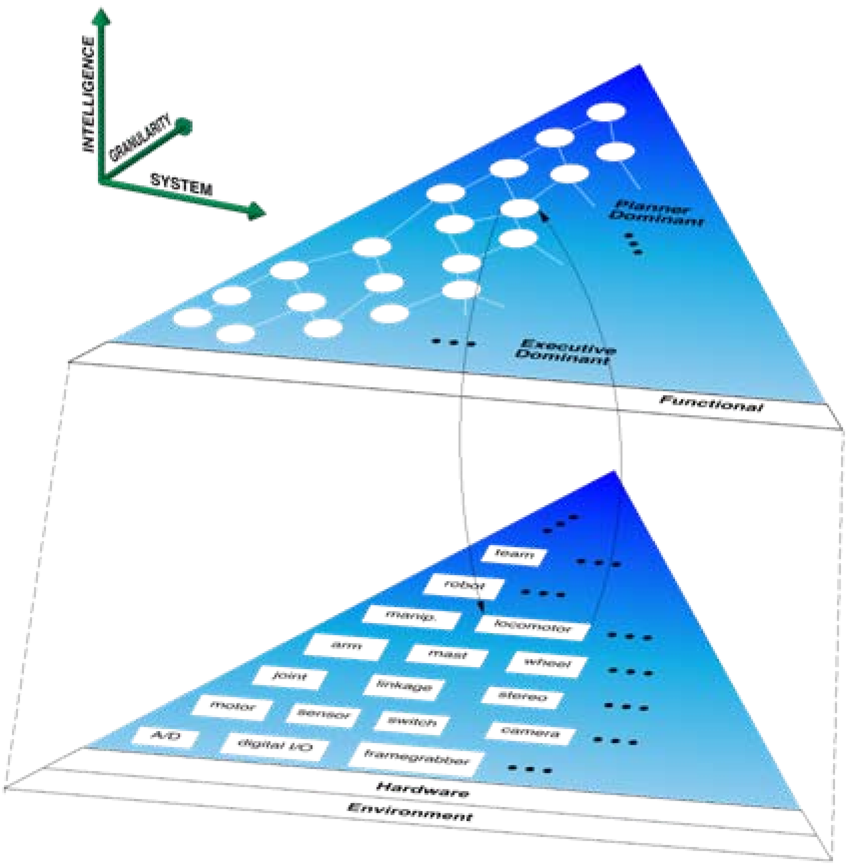
Traditional 3-level hierarchy



Remote Agent for Deep Space 1



Functional Architectures for Autonomous Control have Evolved (cont)

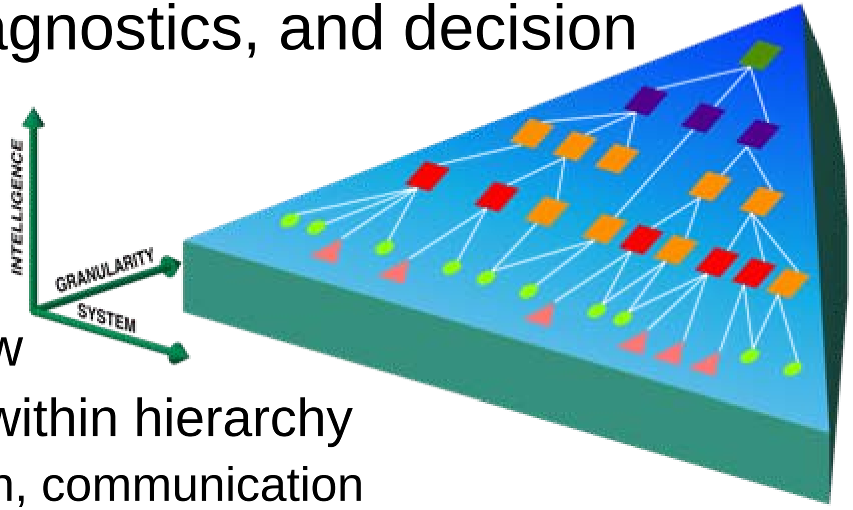


Coupled Layer Architecture
For Robotic Autonomy (CLARAty)

- CLARAty dual-layer architecture developed for MER
- Upper (decision) layer for AI software
- Lower (functional) layer for controls
- Granularity represents system hierarchy at lower level and multiple planning horizons at higher level

Autonomous Control Functional Framework Draws from Previous Architectural Concepts

- Hybrid architecture compresses dual layers to allow deeper integration of control, diagnostics, and decision
  - Hierarchical distribution of supervisory control functionality with overlaid decision functionality
  - Granularity reflected in complexity, information flow, and command flow
  - Functionality can be decomposed within hierarchy
    - Data acquisition, actuator activation, communication
    - Arbitration, control, limitation, commanding, planning
    - Checking, monitoring, prediction, validation
    - Fault management, configuration management



- Blending of decision and functional layers possible since planning regime more restricted in nuclear power domain

Autonomy Is Needed to Enable Space Reactor Applications for Challenging, Long-term Missions

- Space reactor control poses unique challenges compared to terrestrial reactor operational experience
- Autonomy involves key characteristics
  - Intelligence
  - Optimization
  - Robustness
  - Flexibility
  - Adaptability
- Autonomy incorporates embedded decision-making and flexible fault management
- Technology development and demonstration is needed to enable and mature control system autonomy
  - Autonomy has never been implemented for any power generation system
  - A suitable functional architecture can be established based on a hierarchical framework

Thank You

Any questions?