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An Approach to Autonomous Control for Space Nuclear Power Systems

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1. Introduction

Under Project Prometheus, the National Aeronautics and Space Administration (NASA) investigated deep space missions that would utilize space nuclear power systems (SNPSs) to provide energy for propulsion and spacecraft power. The initial study involved the Jupiter Icy Moons Orbiter (JIMO), which was proposed to conduct in-depth studies of three Jovian moons. Current radioisotope thermoelectric generator (RTG) and solar power systems cannot meet expected mission power demands, which include propulsion, scientific instrument packages, and communications. Historically, RTGs have provided long-lived, highly reliable, low-power-level systems. Solar power systems can provide much greater levels of power, but power density levels decrease dramatically at ~1.5 astronomical units (AU) and beyond. Alternatively, an SNPS can supply high-sustained power for space applications that is both reliable and mass efficient.

Terrestrial nuclear reactors employ varying degrees of human control and decision-making for operations and benefit from periodic human interaction for maintenance. In contrast, the control system of an SNPS must be able to provide continuous operation for the mission duration with limited immediate human interaction and no opportunity for hardware maintenance or sensor calibration. In effect, the SNPS control system must be able to independently operate the power plant while maintaining power production even when subject to off-normal events and component failure. This capability is critical because it will not be possible to rely upon continuous, immediate human interaction for control due to communications delays and periods of planetary occlusion. In addition, uncertainties, rare events, and component degradation combine with the aforementioned inaccessibility and unattended operation to pose unique challenges that an SNPS control system must accommodate. Autonomous control is needed to address these challenges and optimize the reactor control design.

1.1 State of the technology

To support JIMO development, Oak Ridge National Laboratory (ORNL) and the University of Tennessee (UT) conducted an investigation of autonomous control. Overviews of autonomous control characteristics, capabilities, and applications were found that establish the existing experience and current technology readiness (Antsaklis & Passino, 1992; Astrom, 1989; Chaudhuri et al., 1996; Passino, 1995; Zeigler & Chi, 1992; Basher & Neal, 2003). The desirable characteristics of autonomous control include intelligence, robustness, optimization, flexibility, adaptability, and reliability.

Control systems with varying levels of autonomy have been employed in robotic, transportation, spacecraft, and manufacturing applications. However, autonomous control has not been implemented for an operating terrestrial nuclear power plant, and there has not been any experience beyond automating simple control loops for space reactors. Current automated control technologies for nuclear power plants are reasonably mature, and basic control for an SNPS is clearly feasible under optimum circumstances. Autonomous control is primarily intended to account for non-optimum circumstances when degradation, failure, and other off-normal events challenge the performance of the reactor, and near-term human intervention is not possible. There are clear gaps in the development and demonstration of autonomous control capabilities for the specific domain of nuclear power operations.

1.2 Advanced control in nuclear power applications

In the nuclear power industry, single-input, single-output classical control has been the primary means of automating individual control loops. The use of multivariate control, such as three element controllers for steam generators, has been employed in some cases. In a few cases, efforts were made to coordinate the action of individual control loops, based on an overall control goal, and extend the range of automated control.

The application of most advanced techniques for nuclear power control has primarily been the domain of universities and national laboratories. Some of the techniques employed in controls research for both power and research reactors include adaptive robust control for the Experimental Breeder Reactor II (EBR-II), fuzzy logic control for power transition, H-infinity control and genetic-algorithm based control for steam generators, neural network control for power distribution in a reactor core, and supervisory control for the multi-modular advanced liquid-metal reactor (ALMR). Proceedings of past American Nuclear Society (ANS) International Topical Meetings on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies provide a useful compendium of findings from such research activities (ANS, 1993, 1996, 2000, 2004, 2006, 2009, 2010). In recent research for the U.S. Department of Energy (DOE), UT demonstrated aspects of near-autonomy for a representative SNPS design through the development of a model-predictive controller using a simulation of the SP-100 reactor system (Upadhyaya et al., 2007; Na & Upadhyaya, 2007). The approach demonstrated the fault-tolerance and reconfiguration features of the control strategy.

1.3 Autonomy in space exploration

NASA has pursued autonomy for spacecraft and surface exploration vehicles (e.g., rovers) to reduce mission costs, increase efficiency for communications between ground control and the vehicle, and enable independent operation of the vehicle during times of communications blackout. For rovers, functional autonomy addresses navigation, target identification, and science package manipulation. For spacecraft, functional autonomy has focused on automated guidance, navigation, and control.

Autonomy for rovers has progressed during the last decade with prominent examples from efforts to explore the surface of Mars. The Mars Pathfinder rover, Sojourner, explored the Martian terrain beginning in July 1997 (Mishkin et al., 1998). The Sojourner had very limited autonomy to enable navigation and provide for resource management and contingency

response. Because it only provided supervised autonomy, repetitive ground monitoring was required. In January 2004, Spirit and Opportunity, the twin Mars Exploration Rovers (MERs), began a surface exploration mission that has continued into 2011. These rovers employ expanded autonomy over what was feasible for Sojourner and provide model-based recovery, resource management, and autonomous planning capabilities in addition to autonomous obstacle detection and navigation. The integration software architecture used to facilitate MER autonomy is the "Coupled Layer Architecture for Robotic Autonomy" or CLARAty (Volpe et al., 2001). CLARAty provides a dual-layer architecture consisting of a decision layer for artificial intelligence (AI) software and a functional layer for controls implementations. Implicit granularity in each layer allows for a functional hierarchy with nested capabilities.

Spacecraft autonomy has been demonstrated with the Deep Space 1 mission. Deep Space 1 was launched in October 1998 as a test platform to validate high-risk advanced technologies in space (Rayman et al., 1999). In support of autonomous navigation of the spacecraft, a principal experiment involved demonstration of the remote agent (RA) AI system for on-board planning and execution of spacecraft activities.

2. Autonomous control functional definition

2.1 The nature of autonomy

There is a distinction between automated control and autonomous control. Consideration of the Greek root words illustrates the difference. *Automatos* means self-acting, while *autonomos* means independent. Similarly, automated control involves self-action, while autonomous control involves independent action. Autonomous control implies an embedded intelligence. Although automation includes at least a limited inherent authority within the control system, automated control often consists of straightforward automatic execution of repetitive basic actions. It is clear that autonomous control encompasses automated control.

Automated control provides control actions that result from a fixed set of algorithms with typically limited global state determination. As a result, automated control is often implemented as rigidly defined individual control loops rather than as fully integrated process/plant control. Although automated control requires no real-time operator action for normal operational events, most significant decision-making is left to the human rather than being incorporated as part of the control system. In contrast, autonomous control integrates control, diagnostic, and decision capabilities. A flexible functional architecture provides the capability to adapt to evolving conditions and operational constraints and even support self-maintenance over the control system lifetime. While automated control is common in numerous applications, autonomous control is more difficult to achieve, and the experience base is very limited.

Autonomy extends the scope of primary control functions. Such capabilities can consist of automated control during all operating modes, process performance optimization (for example, self-tuning), continuous monitoring, and diagnosis of performance indicators as well as trends for operational and safety-related parameters, diagnosis of component health, flexible control to address both anticipated and unanticipated events and to provide protection of life-limited components (such as batteries and actuators), adaptation to changing or degrading conditions, and validation and maintenance of control system performance.

Key characteristics of autonomy include intelligence, robustness, optimization, flexibility, and adaptability. Intelligence facilitates minimal or no reliance on human intervention and can accommodate an integrated, whole system approach to control. It implies embedded decision-making and management/planning authority. Intelligence in control provides for anticipatory action based on system knowledge and event prediction. To support control and decision, real-time diagnostic/prognostic capabilities are important for state identification and health/condition monitoring. Additionally, self-validation is an aspect of intelligence that addresses data, command, and system performance assessment and response.

In addition to providing an environmentally rugged implementation, robustness is addressed by accounting for design uncertainties and unmodeled dynamics. Fault management is an important consideration in achieving robustness. Fault management involves techniques such as fault avoidance, fault removal, fault tolerance, and fault forecasting. Robustness can also involve self-maintenance or self-healing. This capability is promoted through means such as captured design knowledge and self-correcting features, prognostics to identify incipient failure, and fault detection and isolation.

Optimization implies rapid response to demands, minimal deviation from target conditions, and efficient actuator actions. Optimized control can be facilitated by self-tuning and other forms of adaptation. Flexibility and adaptability are enabled by diverse measurements, multiple communication options, and alternate control solutions. Functional reconfigurability facilitates the effective use of these systems options, while an inherent redesign capability permits adaptation to unanticipated conditions.

The characteristics discussed above represent the possibilities of autonomy, but they do not constitute a necessary set. Therefore, autonomous control can be viewed as providing a spectrum of capabilities with automated control representing the lowest extreme or baseline of the continuum. The incorporation of increasing intelligence and fault tolerance moves the control capabilities further along the spectrum. The higher degrees of autonomy are characterized by greater fault management, more embedded planning and goal setting, and even self-healing. The realization of full autonomy involves learning, evolving, and strategizing independent of human interaction or supervision.

2.2 Space nuclear power mission challenges

The space reactor control and protection paradigm is different from conventional terrestrial reactor applications. Terrestrial reactors have relied upon immediate interaction from readily available human resources. This includes varying degrees of direct human control and decision-making for operations and periodic human intervention for maintenance and refurbishment. In contrast, the SNPS control system must be able to provide continuous, remote, often-unattended operation for a mission lasting up to a decade or more. Because of communication delays and blackouts, immediate human interaction for continuous operational supervision and event management is not feasible. This isolation drives the need for a high level of autonomy. Because of launch considerations, size and mass constraints significantly limit the options for redundancy and diverse systems. This limitation drives the need for functional and environmental robustness. Because of distance from the Earth for deep space or planetary surface power applications, maintenance and refurbishment are improbable if not impossible. This inaccessibility drives the need for long-life dependability. Also, because of the critical and time-sensitive nature of some spacecraft maneuvers, space reactor power must be available on demand. This operational imperative, coupled with the likelihood that an SNPS restart capability will be unavailable, requires that reactor scrams as

a response to plant events must be minimized if not completely avoided. Thus, unlike the design criteria for terrestrial nuclear power plants, mission assurance must be emphasized over reactor protection for space reactors.

Automated control can provide the necessary automation of normal operational control to permit ground control personnel to assume a supervisory role for an SNPS rather than taking on direct, active control responsibilities. This control capability for full-power range maneuverability, including startup, has been developed and demonstrated for terrestrial reactors (Winks et al., 1992). However, considering the challenges of a deep space mission, the SNPS control system must do more than provide automated control of normal operational activities. In addition to automation, the control system must provide a level of autonomy that can detect, diagnose, and adapt to evolving conditions (e.g., failures or degradation) as well as rapidly respond to anticipated events without requiring a reactor scram. As a result, autonomous control is clearly necessary to ensure the successful application of an SNPS for deep space missions. This conclusion is based on the understanding that autonomous capabilities permit the SNPS control system to satisfy essential control objectives under significant uncertainties, disturbances, and degradation without requiring any human intervention. In a sense, the role of the autonomous control system is to act as an extension of and occasional proxy for the ground-based human operators to ensure reliable, continuous operation of an SNPS over an extended lifetime under adverse conditions.

2.3 Space Nuclear Power System control

Autonomous control functions of an SNPS can be defined based on the expected operational modes, which include startup, normal power operation, reactor protection, contingent operation, and end-of-mission shutdown. As a minimum requirement of autonomy, the SNPS control system must be able to switch between normal operational modes automatically (i.e., automated control). Additionally, reactor protective action must be available if the desired operational conditions cannot be achieved.

The phases of power operation include power ascension, steady state power and load following, and power reduction. Under normal conditions, power operation can be relatively simple, with inherent feedback effects serving to maintain stability and provide the means for load following in response to minor fluctuations. Thermal load transients (e.g., turbine failure) can be treated as off-normal events. Other off-normal events include design uncertainties, load/power interruptions, control element jamming, control motor burnout, control linkage failure, unintended control element motion, actuator signal interruption or interference, heat rejection system degradation or damage, control processor fault, rare-event software error, sensor failure, sensor signal interruption or interference, sensor drift, signal conditioning electronics drift, sensor noise increase, and communication failures or retransmissions. The most likely protective action would consist of a rapid power runback. Contingent operation occurs when SNPS operation may be restricted either because of environmental limitations, such as an abnormal thermal environment, or because of power system limitations, such as component failures.

The response to off-normal events is where autonomy becomes especially relevant. The autonomous response includes a reflexive element and a deliberative element. The first element addresses reactor protection. Unlike terrestrial reactors, in which the primary defense against potentially adverse conditions resulting from off-normal events is to scram the reactor, it is quite likely that an SNPS must not shut down until the end of the

mission because a restart capability may not be feasible. Thus, reactor protection is provided through diversity and defense-in-depth to anticipate potential challenges to power operation. A limitation system is one means of protecting the reactor. This is accomplished by defining acceptable operational regimes and overriding control actions that would drive the reactor conditions to violate the limitation boundaries. In effect, the limitation system acts as a bounding system whose primary purpose is to provide a check against operations outside of analyzed conditions. The principal response of the limitation system would be to run back the reactor power to assume a safe low-power condition when necessary. Because of the operational imperative that power must remain available during critical spacecraft actions for deep space missions, the SNPS control system must provide the capability to switch out the protection element (or at least expand the operational boundaries it maintains) on demand from the spacecraft or mission control.

The second element of the response to off-normal events addresses mission assurance. The deliberative nature (i.e., determination and decision) of this element contributes the most relevant attribute of autonomous control that distinguishes it from conventional automation. In the operational control context, the autonomous control functionality involves detection and immediate response to degraded or failure conditions. Fault management is a crucial part of this element of autonomous control; it provides for detection, diagnosis, and adaptation (or reconfiguration) given changing SNPS conditions. An additional aspect of the deliberative element is the monitoring, diagnosis, and validation of control system and SNPS performance. Through this capability, the SNPS control system is able to identify incipient events (transients or failures) for anticipatory rather than reactionary action, determine measures to protect life-limited or vulnerable components, and ensure continued dependable operation of the power plant.

As noted, the SNPS autonomous control functionality revolves around automated control for normal operational modes. In essence, the primary function of the control system is command generation to achieve the desired operational state. Additional functionality to support confirmation of control system performance includes features such as command verification, control coordination with interconnected systems, and strategy enforcement. Mechanisms for implementing these features can involve multiple diverse algorithms for comparison with the principal controller command, inclusion of feedforward action or some representation of unmodeled dynamics (e.g., exogenous variables) in control algorithms, event management according to predetermined sequences of events, and adaptation of the control strategy.

Performance management as part of the SNPS autonomous control functionality involves continuously assessing the condition of the control system and the SNPS to identify when predetermined adjustments to the controller should be invoked. The needed assessments include monitoring control system effectiveness, identifying the dynamic state of the SNPS, and determining the condition of key components. Methods that can be employed are state estimation algorithms, process system diagnostics, component condition monitoring, and control parameter adaptation.

Data management and communications are related capabilities with traditional and autonomous functionality intended to support autonomy and system integration. Data acquisition and signal processing methods provide the data needed for control and monitoring, while signal validation adds information about data quality. For communications, the functional elements include device-level data and control signals,

system-level information and commands, and spacecraft-level status and demands. The effective integration of data and information at each level requires a well-defined functional architecture with a capable physical infrastructure that supports reliable, timely information flow.

Desired functionality for fault management includes detection and identification of field device faults, change tracking for system parameters, detection of off-normal transients and identification of anticipated events, and configuration control. Field device monitoring can be accomplished through model-based and/or data-driven algorithms. Parameter tracking can involve empirical models or first principles estimation. Each capability can be used to facilitate an adjustable system dynamic model that can be used for fault prediction or control system performance validation. Configuration control functions are needed to manage transitions among predefined control strategies or algorithms for the autonomous control system. This is essential for effective fault recovery.

To illustrate the autonomous functionality that can be provided for the SNPS control system, two fault management scenarios are considered in which detection and response are described. The first scenario relates to fault adaptation in the case of sensor failure. The indicators from surveillance and diagnostic functions that the SNPS control system can employ include divergence of redundant measurements, conflict between predicted (based on analytical or relational estimation) and measured values, and detection and isolation of a confirmed fault. The prospective response can include substitution of a redundant measurement or utilization of a diverse measurement. An example of the latter would be using neutron flux instead of temperature (i.e., core thermal power) as a power measurement. Switching to an alternate control algorithm may prove necessary for faulted or suspect measurements.

The second scenario relates to fault avoidance in the case of a degrading actuator. The indicators of an incipient failure can be prediction of actuator failure based on prognostic modeling (e.g., fault forecasting) or detection of sluggish response to commands. The prospective response can be to switch to an alternate control strategy to avoid incipient failure by reducing stress on the suspect component. An example would be utilizing manipulation of core heat removal (e.g., coolant density change) instead of direct reactivity insertion (e.g., control element movement) to control reactor power.

2.4 Enabling autonomous control

Autonomous control must be addressed early in the design of an SNPS to determine the degree of autonomy required. Mission requirements, technology readiness, design trade-offs, and resource constraints will affect the autonomous capabilities to be included. The extent to which the key characteristics of autonomy are realized depends on the level of responsibility that is to be entrusted to the autonomous control system and the degree of mission risk that the autonomous control system must mitigate.

Several factors can influence the degree of autonomy selected for an SNPS control system. These factors include the potential for human interaction (which is physically limited but also may be practically limited due to the economics of maintaining a ground-based team), performance goals, complexity of system demands, technological constraints, mission risk considerations, and the balance between simplicity (i.e., reliability) and complexity (i.e., the capacity to detect and adapt). The trade-off between reliability and mission assurance profoundly affects the level of autonomy employed for SNPS control. While having a highly reliable SNPS control system is important, that fact is meaningless if it cannot accommodate

SNPS degradation. In such a case, the result is a highly reliable control system that becomes useless because the plant has changed.
Finally, as previously described, the experience base for autonomous control is not deep. In particular, autonomous control has not been implemented for an operating terrestrial nuclear power plant. The technology gaps indicated by investigation of the state of the technology for reactor control in general and autonomous control in particular suggest research, development, and demonstration (RD&D) activities that need to be accomplished to fully realize the goal of autonomous control for an SNPS. Key elements of the needed RD&D effort involve establishing a suitable functional architecture, developing foundational modules to support autonomy, and demonstrating the integrated application of autonomous capabilities.

3. Functional architecture for autonomous control

3.1 Architectural approaches

As observed from examples of autonomous control for nuclear and space applications, the principal functional architectures that have been employed, in most cases, involve some form of hierarchical framework with varying distributions of intelligence.
A three-level hierarchy is typical for robotic applications (Antsaklis & Passino, 1992; Alami et al., 1998; Gat, 1998). The general concept of the hierarchy is that commands are issued by higher levels to lower levels, and response data flows from lower levels to higher levels in the multi-tiered framework. Intelligence increases with increasing level within the hierarchy. Each of the three interacting tiers has a principal role. Basically the functional layer provides direct control, the executive layer provides sequencing of action, and the planner layer provides deliberative planning.
As previously described, an autonomous control architecture, based on the CLARAty software environment, was developed to support the MER mission. The CLARAty dual-layer architecture provides an upper (decision) layer for AI software and a lower (functional) layer for controls implementations. The development of CLARAty addresses perceived issues with the three-tiered architecture (Volpe et al., 2001). Those issues are the tendency toward a dominant level that depends on the expertise of the developer, the lack of access from the deliberative or planner level to the control or functional level, and the difficulty in representing the internal hierarchy of each level (e.g., nested subsystems, trees of logic, and multiple time lines and planning horizons) using this representation. In one sense, the CLARAty architecture collapses the planner and executive levels, which are characterized by high levels of intelligence, into the decision layer. Essentially, the deliberative and procedural functionalities are merged into an architectural layer that parallels the functional layer and provides a common database to support decision-making. Additionally, a system granularity dimension is maintained to explicitly represent the system hierarchies of the functional layer and the multiple planning horizons of the decision layer.
The functional layer is an object-oriented hierarchy that provides access to the capabilities of the plant/system hardware and serves as the interface for the decision layer to the subject (robot, spacecraft, plant) under control. The interaction between the two layers depends on the relative granularity of each layer at the interface. At lower granularity, the decision layer has almost direct access to the basic capabilities of the plant/system. At higher granularity, the decision layer provides high-level commands that are broken down and executed by the

intelligent control capability of the functional layer. The decision layer provides functionality to break down goals into objectives, establish a sequential task ordering based on the plant/system state and known constraints, and assess the capability of the functional layer to implement those commands. At lower granularity within the decision layer, executive functions such as procedure enforcement are dominant while, at higher granularity, planning functions such as goal determination and strategy development are dominant.

There is an architectural approach for nearly autonomous control systems that have been applied through simulated nuclear power applications (see Fig. 1). As part of research into advanced multi-modular nuclear reactor concepts, such as the International Reactor Innovative and Secure (IRIS) and the ALMR, a supervisory control system architecture was devised (Wood et al., 2004). This approach provides a framework for autonomous control while supporting a high-level interface with operations staff, who can act as plant supervisors. The final authority for decisions and goal setting remains with the human, but the control system assumes expanded responsibilities for normal control action, abnormal event response, and system fault tolerance. The autonomous control framework allows integration of controllers and diagnostics at the subsystem level with command and decision modules at higher levels.

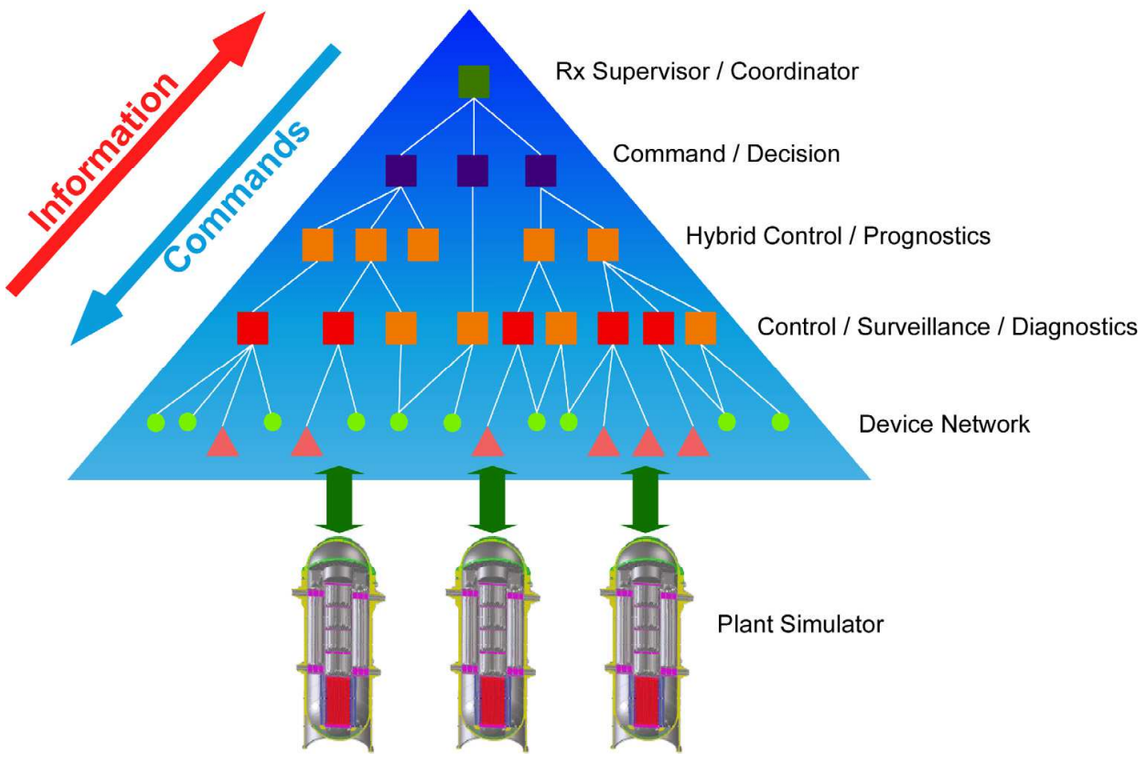


Fig. 1. Supervisory control architecture for multi-modular nuclear power plants

The autonomous control system architecture is hierarchical and recursive. Each node in the hierarchy (except for the terminal nodes at the base) is a supervisory module. The

supervisory control modules at each level within the hierarchy respond to goals and directions set in modules above it and to data and information presented from modules below it. Each module makes decisions appropriate for its level in the hierarchy and passes the decision results and necessary supporting information to the functionally connected modules.

The device network level consists of sensors, actuators, and communications links. The next highest level consists of control, surveillance, and diagnostic modules. The coupling of the control modules with the lower-level nodes is equivalent to an automated control system composed of controllers and field devices. The surveillance and diagnostic modules provide derived data to support condition determination and monitoring for components and process systems. The hybrid control level provides command and signal validation capabilities and supports prognosis of incipient failure or emerging component degradation (i.e., fault identification). The command level provides algorithms to permit reconfiguration or adaptation to accommodate detected or predicted plant conditions (i.e., active fault tolerance). For example, if immediate sensor failure is detected by the diagnostic modules and the corresponding control algorithm gives evidence of deviation based on command validation against pre-established diverse control algorithms, then the command module may direct that an alternate controller, which is not dependent on the affected measurement variable, be selected as principal controller. The actions taken at these lower levels can be constrained to predetermined configuration options implemented as part of the design. In addition, the capability to inhibit or reverse autonomous control actions based on operator commands can be provided. The highest level of the autonomous control architecture provides the link to the operational staff.

3.2 Framework for autonomous control functionality

A variation on the nuclear plant supervisory control architecture and the CLARAty architecture for microrovers seems appropriate for consideration as the framework to support autonomy for an SNPS control system. Figure 2 illustrates the concept. Essentially, the approach of a hierarchical distribution of supervisory control and diagnostic functionality throughout the control system structure is adopted, while the overlaid decision functionality is maintained. It is possible to blend the decision and functional layers for this application domain because the planning regime for nuclear power system operation is much more restricted than for robotic or spacecraft applications. For example, while there are a multitude of paths that a robot may traverse as it navigates to its next site, the states are allowed for an SNPS are much more constrained. Even in the event of transients or faults, the control system will try to drive the plant back to a known safe state. This compression of the dual layers into a truncated three-sided pyramid allows for a deeper integration of control, diagnostics, and decision to provide the necessary capability to respond to rapid events and to adapt to changing or degraded conditions.

The granularity dimension is retained with more complexity shown at the lower hierarchical levels. Additionally, the information and command flow reflects granularity as well. At lower granularity, volumes of data are present. As the granularity increases moving up the hierarchy, the data are processed into system state and diagnostic/prognostic information that are subsequently refined into status and indicator information. On the command side, the transition from the top is demands to commands to control signals with the resolution of the plant/system control growing increasingly more detailed.

As with the supervisory control architecture, the bottom two levels of the hierarchy are the equivalent of an automated control system. The embedded functionality that enables a reliable, fault-tolerant implementation is indicated as a base intelligence. It is expected that there will be some decision capability associated with the control/surveillance/diagnostics level of that baseline system. The higher levels of the hierarchy assume greater degrees of decision capabilities.

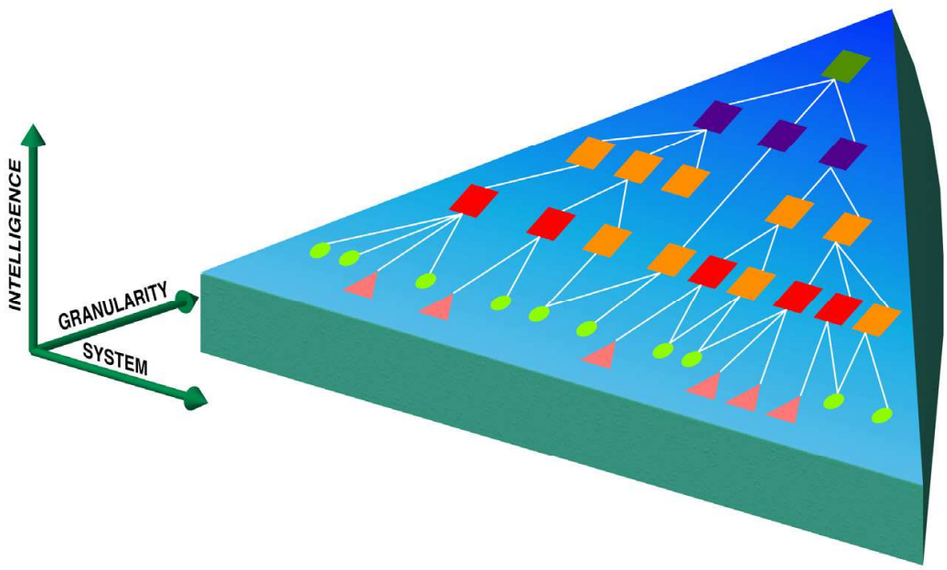


Fig. 2. Hierarchical framework to support SNPS control system autonomy

In addition to managing the communications within the hierarchy, the autonomous control system must coordinate with the spacecraft control system and keep the mission control staff informed. To this end, the reactor supervisor/coordinator node must communicate information about the status of the SNPS and the control system and also receive directives and commands. The information provided by the supervisor node can include SNPS operational status and capability (e.g., constraints due to degradation), control action histories, diagnostic information, self-validation results, control system configuration, and data logs. Additional communication outside of the hierarchy may be required to coordinate control actions with other segments of the spacecraft, such as the power conversion system.

The functionality that is embodied in the hierarchy can be decomposed into several elements. These include data acquisition, actuator activation, validation, arbitration, control, limitation, checking, monitoring, commanding, prediction, communication, fault management, and configuration management. The validation functionality can address signals, commands, and system performance. The arbitration functionality can address redundant inputs or outputs, commands from redundant or diverse controllers, and status indicators from various monitoring and diagnostic modules. The control functionality includes direct plant or system control and supervisory control of the SNPS control system itself. The limitation functionality involves maintaining plant conditions

within an acceptable boundary and inhibiting control system actions. The checking functionality can address computational results, input and output consistency, and plant/system response. The monitoring functionality includes status, response, and condition or health of the control system, components, and plant, and it provides diagnostic and prognostic information. The commanding functionality is directed toward configuration and action of lower level controllers and diagnostic modules. The prediction functionality can address identification of plant/system state, expected response to prospective actions, remaining useful life of components, and incipient operational events or failures. The communication functionality involves control and measurement signals to and from the field devices, information and commands within the control system, and status and demands between the SNPS control system and spacecraft or ground control. The fault management and configuration management functionalities are interrelated and depend on two principal design characteristics. These are the ability of the designer to anticipate a full range of faults and the degree of autonomy enabled by the control system design.

Finally, the distribution of functions throughout the hierarchy must be established based on the degree of autonomy selected, technology readiness, reliability and fault management considerations, software development practices and platform capabilities, and the physical architecture of the SNPS control system hardware. Because an autonomous control system has never been implemented for a nuclear reactor and because several functional capabilities remain underdeveloped (as seen in the overview of the state of the art), there is clearly a critical need for further development and demonstration of a suitable architectural framework.

4. Application of model-based control to Space Nuclear Power Systems

Key functionality that is necessary to establish the basis for autonomous control has been demonstrated through a simulated space reactor application under university research sponsored by DOE. These capabilities related to control elements within the lower layers of the functional hierarchy. Specifically, the research conducted at UT involved development of a highly fault tolerant power controller for the SP-100 space power reactor design (Upadhyaya et al., 2007; Na & Upadhyaya, 2007).

The SP-100 design provides for a fast spectrum, lithium-cooled fuel pin reactor coupled with thermo-electric converters (TE) with the waste heat removed through a heat pipe distribution system and space radiators. The TE generator output is rated at 112 kW, with a nominal reactor thermal power 2000 kW.

A lumped parameter simulation of a representative SNPS was developed based on physics models specific to the SP-100 reactor, which were derived in prior academic work at the University of New Mexico (El-Genk & Seo, 1987). The reactor system modules include a model of reactor control mechanism, a neutron kinetics model, a reactor core heat transfer model, a primary heat exchanger (HX) model, and a TE conversion model. Figure 3 illustrates the elements of the SNPS model. The integrated SP-100 SNPS model was assembled through an iterative algorithm. The model involves both nonlinear ordinary differential equations and partial differential equations. The code development was performed under the MATLAB™/SIMULINK™ environment. The SNPS simulation provided the demonstration platform for the fault tolerant controller development.

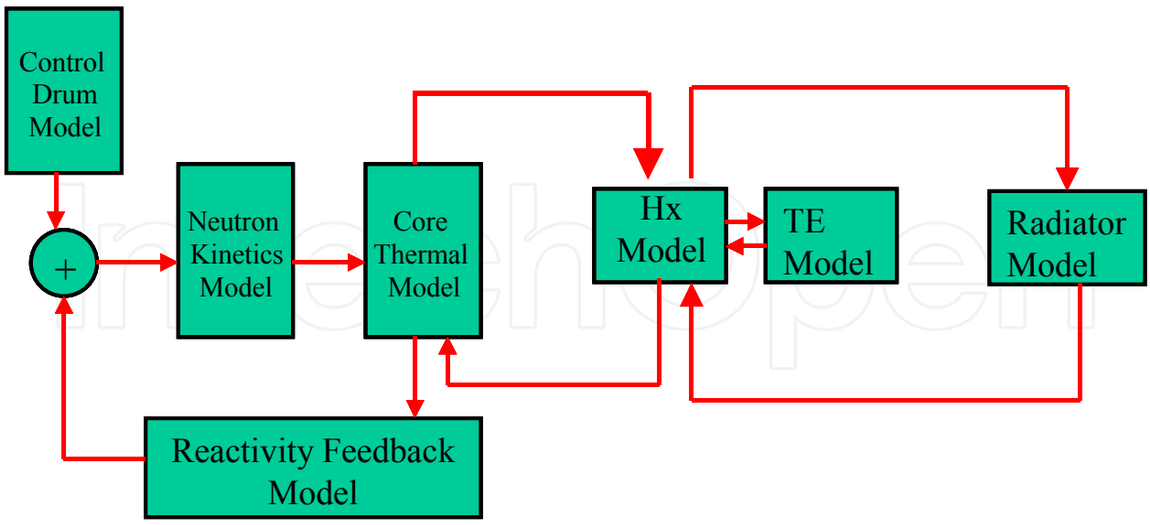


Fig. 3. Schematic of the model development of the SP-100 reactor system

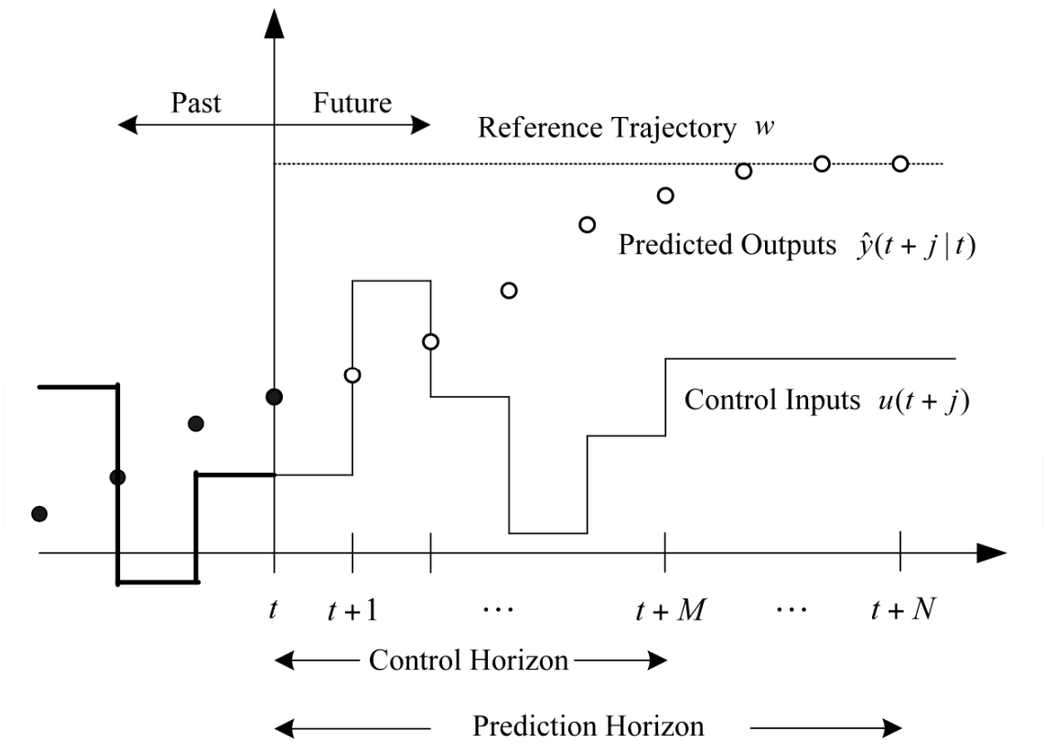


Fig. 4. Basic concept of a model predictive control method

The control approach adopted is a model-predictive controller (MPC) design. The basic concept of the model-predictive control method is illustrated in Fig. 4. The MPC

minimizes a quadratic cost function and takes into consideration any constraints imposed on the control action and the state variables. For a given set of present and future control actions, the future behavior of the state variables are predicted over a prediction horizon N, and M present and future control moves ($M \le N$) are computed to minimize the quadratic objective function. Out of the M control moves that are calculated, only the first control action is implemented. The prediction feature of the controller has an anticipatory effect, and is reflected in the current control action. These calculations are repeated in the next time step by appending the next measurement to the database. The new measurements compensate for the unmeasured disturbances and model inaccuracies, both of which result in the measured system output being different from that predicted by the model. The MPC requires the on-line solution of an optimization problem to compute optimal control inputs over the time horizon. The MPC calculates a sequence of future control signals by minimizing a multi-stage cost function defined over a prediction horizon.

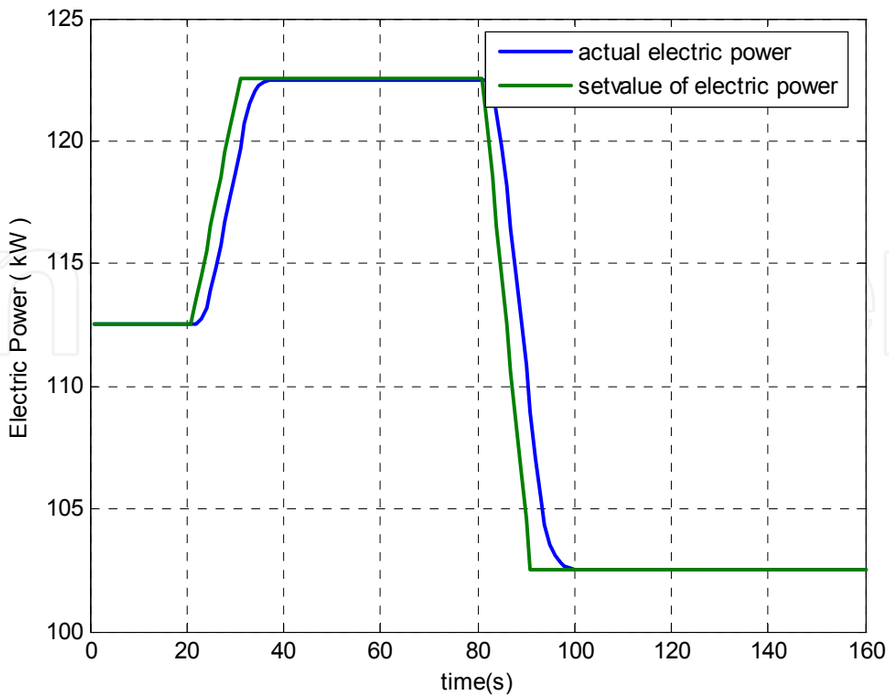
The performance index for deriving an optimal control input is represented by the quadratic objective function given in Eq. (1).

$$J = \frac{1}{2}\sum_{j=1}^{N} Q\left[\hat{y}(t+j\,|\,t) - w(t+j)\right]^2 + \frac{1}{2}\sum_{j=1}^{M} R\left[\Delta u(t+j-1)\right]^2 , \tag{1}$$

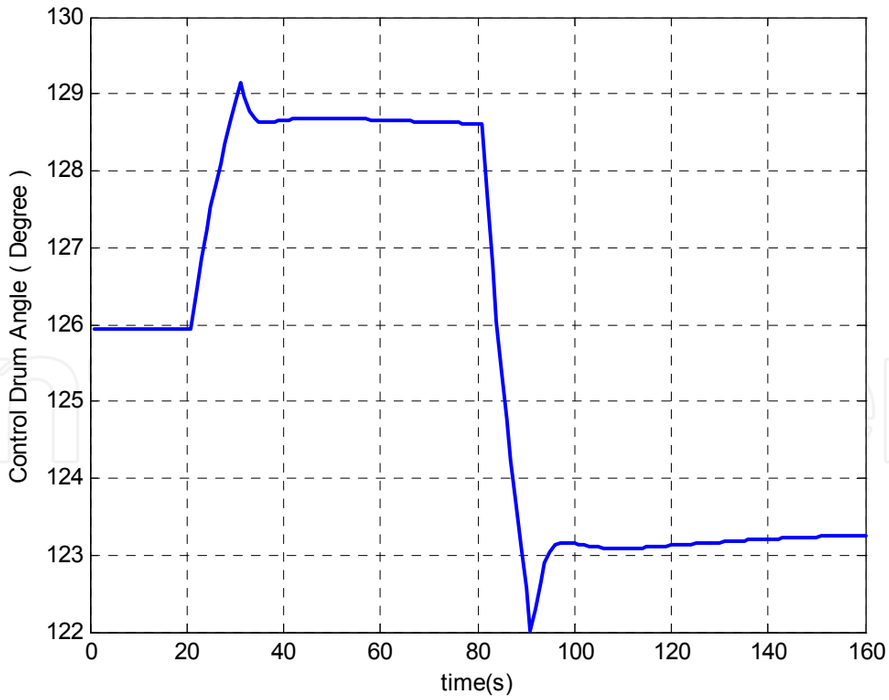
$$\text{subject to constraints} \quad \begin{cases} \Delta u(t+j-1) = 0 \ \text{ for } \ j > M , \\ u_{\min} \le u(t) \le u_{\max} , \\ \left|\Delta u(t)\right| \le \Delta u_{\max} . \end{cases}$$

where Q and R are the weights for the TE generator power (system output) error and the SP-100 control drum angle (reactivity as control input) change between time steps at certain future time intervals, respectively, and w is a set point (desired generator power). The estimate $\hat{y}(t+j\,|\,t)$ is an optimum j-step-ahead prediction of the system output (TE generator power) based on data up to time t; that is, the expected value of the output at time t as a function of the past input and output and the future control sequence are known. N and M are the prediction horizon and the control horizon, respectively. The prediction horizon represents the limiting time for the output to follow the reference sequence. In order to obtain control inputs, the predicted outputs are first calculated as a function of past values of inputs and outputs. The constraint, $\Delta u(t+j-1) = 0$ for $j > M$, indicates that there is no variation in the control signal after a certain time interval M < N, where M is the control horizon. $u_{\min}$ and $u_{\max}$ are the minimum and maximum values of input, respectively, and $\Delta u_{\max}$ is a maximum allowable control perturbation per time step.

The applicability and the effectiveness of the MPC approach were demonstrated through its simulated performance for several operational scenarios, including under degraded or ill-characterized conditions (Upadhyaya et al., 2007). The effectiveness of the MPC controller for tracking the TE power output is illustrated in Figure 6. Figure 6a shows the TE converter set point profile and the actual TE generator power. The corresponding reactivity changes (drum angle variations) are shown in Figure 6b.



(a)



(b)

Fig. 6. (a) Electric power (TE) set point profile and the controller performance. (b) Controller response (i.e., reactivity control) in terms of the drum angle

The MPC approach was shown to provide a fast response and robustness under changing system conditions. Specifically, fault tolerance and reconfigurability features of the control approach were demonstrated in response to sensor faults, drum actuator anomalies, and changes in model parameters (Upadhyaya et al., 2007; Na & Upadhyaya, 2007). Consequently, it is observed that several of the capabilities and characteristics that are necessary to enable autonomous control are provided by the MPC approach.

5. Conclusion

The control system for an SNPS will be subject to unique challenges as compared to terrestrial nuclear reactors, which employ varying degrees of human control and decision-making for operations and benefit from periodic human interaction for maintenance. In contrast, the SNPS control system must be able to provide continuous, remote, often unattended operation for a mission lasting a decade or more with limited immediate human interaction and no opportunity for hardware maintenance. In addition to the inaccessibility and periods of unattended operation, the SNPS control system must accommodate severe environments, system and equipment degradation or failure, design uncertainties, and rare or unanticipated operational events during an extended mission life. As a result, the capability to respond to rapid events and to adapt to changing or degraded conditions without near-term human supervision is required to support mission goals. Autonomous control can satisfy essential control objectives under significant uncertainties, disturbances, and degradation without requiring any human intervention. Therefore, autonomous control is necessary to ensure the successful application of an SNPS for deep space missions.

Key characteristics that are feasible through autonomous control include

- intelligence to confirm system performance and detect degraded or failed conditions,
- optimization to minimize stress on SNPS components and efficiently react to operational events without compromising system integrity,
- robustness to accommodate uncertainties and changing conditions, and
- flexibility and adaptability to accommodate failures through reconfiguration among available control system elements or adjustment of control system strategies, algorithms, or parameters.

Autonomous control must be addressed early in the design of an SNPS to determine the degree of autonomy required. Mission requirements, design trade-offs, and the state of the technology will affect the autonomous capabilities to be included. The extent to which the key characteristics of autonomy are realized depends on the level of responsibility that is to be entrusted to the autonomous control system. Given anticipated mission imperatives to utilize technology with demonstrated (or at least high probability) readiness, it is not practical to strive for the high-end extreme of autonomy. Instead, modest advancement beyond fully automatic control to allow extended fault tolerance for anticipated events or degraded conditions and some predefined reconfigurability is the most realistic goal for an initial application of SNPS autonomous control. A hierarchical functional architecture providing integrated control, diagnostic, and decision capabilities that are distributed throughout the hierarchy can support this approach. The application of the MPC approach to the SP-100 reactor system and demonstration of key fault-tolerant and reconfigurable control features have been accomplished through simulation. The results illustrate the feasibility of incorporating these techniques in future space reactor designs.

Control systems with varying levels of autonomy have been employed in robotic, transportation, spacecraft, and manufacturing applications. However, autonomous control has not been implemented for an operating terrestrial nuclear power plant. Therefore, technology development and demonstration activities are needed to provide the desired technical readiness for implementation of an SNPS autonomous control system. In particular, the capabilities to monitor, trend, detect, diagnose, decide, and self-adjust must be established to enable control system autonomy. Finally, development and demonstration of a suitable architectural framework is also needed.

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7. References

Alami, R., et al. (1998). An Architecture for Autonomy, *International Journal of Robotics Research*, Vol. 17, No. 4, (April 1998), pp. 315–337

American Nuclear Society (1993). *Proceedings of the 1993 ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies*, ISBN 0-89448-185-1, Oak Ridge, Tennessee, USA, April 1993

American Nuclear Society (1996). *Proceedings of the ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 96)*, Vols. 1 & 2, ISBN 0-89448-610-1, State College, Pennsylvania, USA, May 1996

American Nuclear Society (2000). *Proceedings of the ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2000)*, ISBN 0-89448-644-6, Washington, District of Columbia, USA, November 2000

American Nuclear Society (2004). *Proceedings of the ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2004)*, ISBN 0-89448-688-8, Columbus, Ohio, USA, September 2004

American Nuclear Society (2006). *Proceedings of the ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2006)*, ISBN 0-89448-051-0, Albuquerque, New Mexico, USA, November 2006

American Nuclear Society (2009). *Proceedings of the ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2009)*, ISBN 978-0-89448-067-6, Knoxville, Tennessee, USA, April 2009

American Nuclear Society (2010). *Proceedings of the ANS Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC&HMIT 2010)*, ISBN 978-0-89448-084-3, Las Vegas, Nevada, USA, November 2010

Antsaklis, P. & Passino, K. (1992). An Introduction to Intelligent Autonomous Control Systems with High Degrees of Autonomy, In: *An Introduction to Intelligent and Autonomous Control*, P. Antsaklis & K. Passino (Eds.), pp. 1–26, Kluwer Academic Publishers, ISBN 0-7923-9267-1, Boston, USA

Astrom, K. J. (1989). Toward Intelligent Control, *IEEE Control System Magazine*, (April 1989), pp. 60–64

Basher, H. & Neal, J. (2003). *Autonomous Control of Nuclear Power Plants*, ORNL/TM-2003/252, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

Chaudhuri, T. R., et al. (1996). From Conventional to Autonomous Intelligent Methods, *IEEE Control System Magazine*, (October 1996), pp. 78–84

El-Genk, M. S. & Seo, J. T. (1987). SP-100 System Modeling: SNPSAM Update, *Transactions of the 4th Symposium on Space Nuclear Power Systems*, Albuquerque, New Mexico, USA, January 1987, pp. 513-516

Gat, E. (1998). Three-Layer Architectures, In: *Artificial Intelligence and Mobile Robots: Case Studies of Successful Robot Systems*, D. Kortenkamp et al. (Eds.), pp. 195–210, MIT Press, Cambridge, Massachusetts, USA

Mishkin, A. G., et al. (1998). Experiences with Operation and Autonomy of the Mars Pathfinder Microrover, *Proceedings of the 1998 IEEE Aerospace Conference*, ISBN 0-7803-4311-5, Aspen, Colorado, USA, March 1998, pp. 337–351

Na, M. G. & Upadhyaya, B. R. (2007). Development of a Reconfigurable Control for an SP-100 Space Reactor, *Nuclear Engineering and Technology*, Vol. 39, No. 1, (February 2007), pp. 63-74

Rayman, M. D., et al. (1999). Results from the Deep Space 1 Technology Validation Mission, *Proceedings of the 50th International Astronautical Congress*, American Institute of Aeronautics and Astronautics, *Acta Astronautica,* Vol. 47, pp. 475–488

Passino, K. (1995). Intelligent Control for Autonomous Systems, *IEEE Spectrum*, (June 1995), pp. 55–62

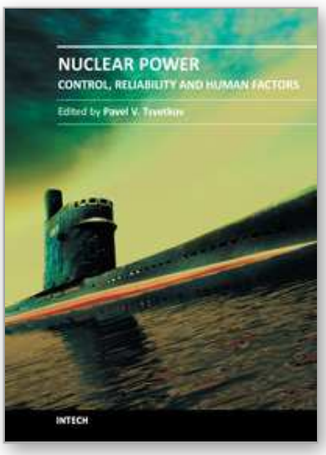
Upadhyaya, B., et al. (2007). *Autonomous Control of Space Reactor Systems*, DE-FG07-04ID14589/UTNE-06, University of Tennessee, Knoxville, Tennessee, USA

Volpe, R., et al. (2001). The CLARAty Architecture for Robotic Autonomy, *Proceedings of the 2001 IEEE Aerospace Conference*, Vol. 1, ISBN 0-7803-6599-2, Big Sky, Montana, USA, March 2001, pp. 121–131

Winks, R. W., et al. (1992). B&W PWR Advanced Control System Algorithm Development, *Proceedings: Advanced Digital Computers, Controls, and Automation Technologies for Power Plants*, EPRI TR-100804, Electric Power Research Institute, Palo Alto, California, USA

Wood, R. T., et al. (2004). Autonomous Control for Generation IV Nuclear Plants, *Proceedings of the 14th Pacific Basin Nuclear Conference*, ISBN 0-89448-679-9, Honolulu, Hawaii, USA, March 2004, pp. 517–522

Zeigler, B. & Chi, S. (1992). Model Based Architecture Concepts for Autonomous Control Systems Design and Simulation, In: *An Introduction to Intelligent and Autonomous Control*, P. Antsaklis & K. Passino (Eds.), pp. 57–78, Kluwer Academic Publishers, ISBN 0-7923-9267-1, Boston, USA



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