Autonomous Control Capabilities for Space Reactor Power Systems

Richard T. Wood, John S. Neal, C. Ray Brittain, James A. Mullens

Oak Ridge National Laboratory. P.O. Box 2008, Oak Ridge, TN 37831-6010
(865) 574-5578, woodrt@ornl.gov

Abstract. The National Aeronautics and Space Administration's (NASA's) Project Prometheus, the Nuclear Systems Program, is investigating a possible Jupiter Icy Moons Orbiter (JIMO) mission, which would conduct in-depth studies of three of the moons of Jupiter by using a space reactor power system (SRPS) to provide energy for propulsion and spacecraft power for more than a decade. Terrestrial nuclear power plants rely upon varying degrees of direct human control and interaction for operations and maintenance over a forty to sixty year lifetime. In contrast, an SRPS is intended to provide continuous, remote, unattended operation for up to fifteen years with no maintenance. Uncertainties, rare events, degradation, and communications delays with Earth are challenges that SRPS control must accommodate. Autonomous control is needed to address these challenges and optimize the reactor control design. In this paper, we describe an autonomous control concept for generic SRPS designs. The formulation of an autonomous control concept, which includes identification of high-level functional requirements and generation of a research and development plan for enabling technologies, is among the technical activities that are being conducted under the U.S. Department of Energy's Space Reactor Technology Program in support of the NASA's Project Prometheus. The findings from this program are intended to contribute to the successful realization of the JIMO mission.

INTRODUCTION

The National Aeronautics and Space Administration's Project Prometheus, the Nuclear Systems Program, is investigating a possible Jupiter Icy Moons Orbiter (JIMO) mission, which would conduct in-depth studies of three Jovian moons by using a space reactor power system (SRPS) to provide energy for propulsion and spacecraft power for more than a decade. This selection is being studied for long duration, high sustained power, outer solar system missions such as JIMO because their power requirements cannot be met by current radioisotope thermoelectric generator (RTG) power systems or solar power systems. Power demands include propulsion, scientific instrument packages, and communications. Historically, RTGs have provided long-lived, highly reliable, low power level systems, up to 300 Watts-electric (We) per RTG unit, with Pu-238 dioxide fuel and a variety of thermo electrics (e.g. PbTe, SiGe). Solar power systems can provide much greater levels of power but power density levels decrease dramatically at ~ 1.5 astronomical units (AU) and beyond. Use of solar power in the inner solar system missions can also be limited in locations where solar power is not always available (e.g., high Martian latitudes, lunar craters). Space reactor power systems provide a range of unique capabilities that could enable missions such as JIMO and other prospective National Aeronautics and Space Administration (NASA) space exploration missions.

The control system for an SRPS will be subject to unique challenges as opposed 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, an SRPS control system must be able to provide continuous operation for up to fifteen years with limited immediate human interaction and no opportunity for hardware maintenance. As a result, the ability to respond to rapidly changing or degraded conditions without immediate human intervention is also required to support mission goals. Therefore, autonomous control is necessary to ensure the successful application of an SRPS. Not only will the nature of the mission (interplanetary space travel) sometimes preclude human supervision/control but fully autonomous control could contribute to lower mission lifetime costs by permitting a reduced mission control staff for monitoring and directing the spacecraft.

Autonomous control can satisfy essential control objectives under significant uncertainties, disturbances, and degradation without requiring any human intervention. Overviews of autonomous control characteristics, capabilities, and applications are given in Antsaklis (1992), Astrom (1989), Chaudhuri (1996), and Passino (1995). 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. A discussion of considerations important for achieving autonomous or intelligent control for nuclear power systems is given by Uhrig (1989) while Basher (2003) documents a survey of recent research efforts within the nuclear power community. Capturing the state of the technology, conducting targeted applied research on advanced methods, and demonstrating the integrated application of autonomous control capabilities for specific space reactor concepts are necessary steps toward achieving the autonomous control system to support the successful, dependable implementation of an SRPS.

Uncertainties, rare events, degradation, and communications delays with Earth are challenges that SRPS control must accommodate. Autonomous control is needed to address these challenges and optimize the reactor control design. The formulation of an autonomous control concept, which includes identification of high-level functional requirements and generation of a research and development plan for enabling technologies, is among the technical activities that are being conducted under the U.S. Department of Energy's (DOE's) Space Reactor Technology Program (SRTP) in support of NASA's Project Prometheus. The objective of this paper is to present initial findings from this research effort. In this paper, we describe an autonomous control concept for generic SRPS designs, present high-level functional requirements that must be addressed to achieve autonomous control, and discuss recent technology developments that are relevant for establishing an autonomous control system concept.

AN SRPS AUTONOMOUS CONTROL CONCEPT

The JIMO mission would challenge the SRPS control system to accommodate unattended operation, extended operational life, varying power demands, and a severe operating environment. As the nuclear-powered spacecraft leaves earth orbit and travels towards the outer solar system, it will not be possible to rely upon continuous, immediate human interaction for the control of the SRPS due to communications delays and periods of inaccessibility. Automatic control provides the necessary automation of normal operational control to permit ground control personnel to assume a supervisory role rather than taking on direct, active control responsibilities. This control capability for full power range maneuverability, including start up, has been previously developed and demonstrated for terrestrial reactors (Winks, 1992; Berkan, 1991). However, the role of an autonomous control system is to do more than provide automatic control of normal operational activities. In addition to automation, the control system must provide a level of autonomy that can detect and respond to anticipated events and conditions (e.g., failures or degradation). In a sense, the role of the autonomous control system is to act as an extension of the ground-based human operators to assure reliable, continuous operation of the SRPS over an extended lifetime under adverse conditions. The nuclear power industry has not implemented autonomous control for terrestrial reactors but there have been selected applications of the technologies that are its foundation (Basher, 2003).

Autonomous control must be addressed early in the design of the SRPS 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. Key characteristics of autonomy include intelligence, optimization, robustness, flexibility, and adaptability. The extent to which these characteristics are realized depends on the level of responsibility that is to be entrusted to the autonomous control system. For example, intelligence and adaptability can include an unrestrained redesign capability based on artificial intelligence algorithms. Given the desire that the JIMO mission 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 is the most realistic goal for this application of SRPS autonomous control.

Another aspect of the SRPS design phase that will impact the autonomous capabilities that can be achieved is SRPS controllability. Design for controllability can include providing diverse control mechanisms, advanced measurement devices, and redundant communication links. These features contribute to the ability of the autonomous control system to incorporate fault avoidance by design and permit fault tolerance by adaptation given the prospect of component degradation or failure. Diverse control mechanisms allow alternate control strategies to be employed when the primary controllers are not available. An example is to use inherent feedback control through active manipulation of the power conversion system as an alternate means of power maneuvering instead of reflector repositioning. Johnson noise thermometry is an example of an advanced measurement technique that avoids faults such as sensor drift. Redundant communications links can also contribute to fault avoidance through multiple signal paths. Providing diverse communications technology, such as wireless or power line transmission, can provide backup communications paths that can be employed as needed should fault conditions require communication reconfiguration.

AUTONOMOUS CONTROL REQUIREMENTS

An SRPS consists of a reactor module, a power conversion system, and a heat rejection system. The integration of these segments constitutes the electrical power generation system. The reactor module generates thermal energy from nuclear power production, the power conversion system converts the thermal energy to electrical power, and the heat rejection system radiates waste heat from the conversion process to the heat sink of space. The reactor module provides three functional elements necessary for power operations: the reactor core and reflectors, the primary heat transport system, and the reactor instrumentation and control (I&C) system. These elements, coupled with the radiation shield and the aeroshell and superstructure, comprise the physical reactor module. The power conversion system may involve a dynamic conversion technology with rotating machinery, such as the Brayton or Stirling systems, or a static conversion technology, such as thermoelectric converters. The I&C system of the SRPS includes sensors (e.g., neutron, temperature, flow, pressure, position, etc.), control actuators, communications links (e.g., cables, signal conditioning equipment, multiplexers, etc), and computer hardware and software.

The SRPS interfaces with the spacecraft mechanically, thermodynamically, electrically, and functionally (i.e., command, control, and data interactions). The control strategy employed must address the dynamic behavior of the integrated SRPS and should take advantage of the self-regulating characteristics. Because of feedback dynamics, the reactor will respond to conditions and events in the power conversion system and heat rejection system. This dynamic coupling can permit inherent control of reactor power during normal operation. However, the modest thermal inertia and compact size that are characteristic of SRPS conceptual designs also increase the prospect that off-normal or degraded conditions in the heat removal systems may have a pronounced effect on reactor conditions. Thus, control of the SRPS must be integrated so that events and conditions in the main systems are detected and appropriate, coordinated action is taken. This approach would allow the SRPS control system to efficiently and reliably satisfy the power demands of the spacecraft in response to the full range of operational transients and anticipated recoverable off-normal events.

Anderson (1984) laid out performance goals for a generic SRPS control system, though not necessarily autonomous, to include:

- unattended startup from cold, safe condition,
- monitoring and control for reactor operational events (e.g., power ascension, runback, etc.) resulting from changing mission conditions,
- stable control under anticipated or unanticipated load changes, and
- provisions for continued operation with limited failures.

Ongoing studies in support of the JIMO mission have identified autonomous control system goals/requirements that include, but are not limited to, the following:

- autonomous startup and achievement of full power after being launched in a cold shutdown state and following initiation by ground command,
- operation at any constant operational power between 20% and 100% of full power,
- performance of reactor protective actions including reducing power and providing status updates (e.g., condition identification, performance constraints) to spacecraft/ground control,
- recovery to full power following operation at some reduced power level,
- detection of and response to anticipated equipment degradation or failure through predefined adjustments, compensations, or alternate control paths (e.g., active and passive fault tolerance), and
- end-of-mission shutdown and placement in a safe configuration.

TECHNOLOGY DEVELOPMENTS FOR AUTONOMOUS CONTROL

The establishment of an autonomous control concept for SRPS application can build on previous technology developments. One example is a self-validating control system capability devised under a recent DOE Nuclear Energy Research Initiative (NERI) project, entitled "Automatic Development of Highly Reliable Control Architecture for Future Nuclear Power Plants" (March-Leuba, 2003). Another relevant activity involves the development of a hierarchical framework for integrating control, diagnostic, and decision functions to support control of advanced modular reactors (Wood, 2003).

Self-Validating Control Capability

There will be uncertainties in the fidelity of engineering simulators used to design the SPRS control system. In particular, nuclear parameters such as the temperature dependence of feedback coefficients may not be precisely characterized. In addition, reactor conditions will change over the core lifetime and component degradation or failure (e.g., sensor drift, control actuator seizure, heat exchanger fouling, etc.) may well occur. The SRPS autonomous control system should be capable of adapting to changing conditions and reconfiguring based on predefined options to respond to detected degradation or failures. An automatic control design technology has been developed for DOE. The result is a control engine that can be used during the design phase for automatic generation of a control system and then implemented as part of the control structure to permit periodic confirmation of the control system performance. Because the control engine captures the functional requirements used to define the design, the self-validation results can be traced directly to the technical basis for the control system at any point during the life of the system.

The control engine captures the high-level requirements and stress factors that the control system must accommodate (e.g., a list of transients, periodic movement of control elements to prevent freeze up, or a requirement to withstand a single failure) as mathematical constraints or conditions. The control engine is able to subsequently generate the control-system algorithms and parameters that optimize a design goal and satisfy all requirements. As conditions change during the SRPS lifetime (e.g., component degradation or subsystem failures), the control engine can automatically determine if a requirement is no longer satisfied. The response can be a simple as a "flag" that is communicated to the spacecraft/ground control or it could be a trigger to switch to pre-configured alternate controllers. An off-line (probably ground-based) control engine could be used to provide a redesign of the control algorithms if necessary.

Once proper design requirements are identified, each must be expressed in a mathematical form and implemented as software modules within the control engine. The input to these modules during the self-validation step consists of results of a computer simulation of the dynamic behavior of the SRPS/control system interaction. Following comparison against performance indicators, the modules return values that indicate whether particular requirements are satisfied. The set of modules that document all requirements then become a complete description of the control problem. In the design phase, the results of the comparison against the requirements are integral elements of the control system design process. In the implemented control system structure, satisfaction of the full requirements set constitutes a successful self-validation loop.

To automate the control system development, the control engine must have an available library of control algorithms. This library may include standard control algorithms such as proportional-integral-derivative conventional controllers, model-based control schemes, and advanced nonlinear methods. The remaining action is for those algorithms to be parameterized; the control engine will select the optimal parameters for each algorithm and then identify the optimal algorithm so that the final design satisfies all requirements.

Implementation of this control-engine design methodology requires the following steps:

1) Determination of design requirements for control system performance
2) Representation of requirements in mathematical form
3) Access to (or development of) a control algorithm library
4) Development and validation of plant models

5) Automated control design generation
6) Evaluation of control architectures
7) Control design implementation
8) Implementation (or development) of diagnostics methods to update the plant model

Figure 1 illustrates the implemented control system structure for the control engine.

The key elements of the implementation of this control design approach as part of a self-validating control structure are the control engine, the plant (or SRPS) model(s), and the diagnostic modules. The control engine maintains the functional requirements and design selection criteria. The diagnostic modules detect degradation or failure of critical components (e.g., sensors, actuators) or changing parameters (e.g., heat transfer coefficients, feedback coefficients). The plant model represents the dynamic behavior of the system. As changes in the dynamic condition of the plant are detected, the simulation of the physical system must be updated through modified parameters. These model parameters can represent plant physical parameters such as neutronic or thermal-hydraulic coefficients or they can correspond to coefficients related to predefined degradation such as drift, bias, or failure of sensors or nonlinear actuator responses. When changes in plant condition exceed some specified threshold, the control engine initiates an iterative minimization calculation to confirm that the control solution remains adequate. Should the control system be found to no longer satisfy the design requirements, a flag can generated to trigger a pre-selected response. In cases where the control system still satisfies the design requirements but does not represent an optimized solution, the control engine can also be employed as an adaptive loop to tune control parameters on demand.

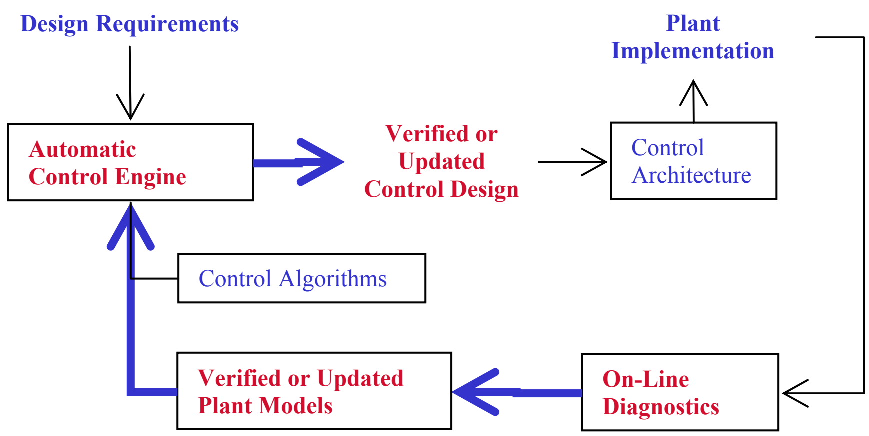

FIGURE 1. Schematic Diagram of the Automated Control Engine Structure.

Autonomous Control Framework

As previously described, the capability to respond to rapidly changing or degraded conditions without immediate human intervention is required to support missions such as JIMO. To fulfill this role, the autonomous control system must integrate control, diagnostic, and decision-making capabilities. As part of research to support multi-modular advanced nuclear reactor concepts, such as the International Reactor Innovative and Secure (IRIS), a supervisory control system architecture has been devised. This approach provides the 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. This framework is appropriate for application as the SRPS autonomous control system architecture.

The autonomous control system architecture envisioned for the SRPS, shown in Figure 2, 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 respond to goals and directions set in modules above it within the hierarchy and to data and information presented from modules below it within the hierarchy. 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 automatic 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. At this level, fault identification occurs. The command level provides algorithms to permit reconfiguration or adaptation of the control system to accommodate detected or predicted SRPS conditions. At this level, active fault tolerance is accomplished. 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 or inhibit or reverse autonomous control actions based on ground commands can be provided. The highest level of the autonomous control architecture provides the link to the spacecraft and to mission control.

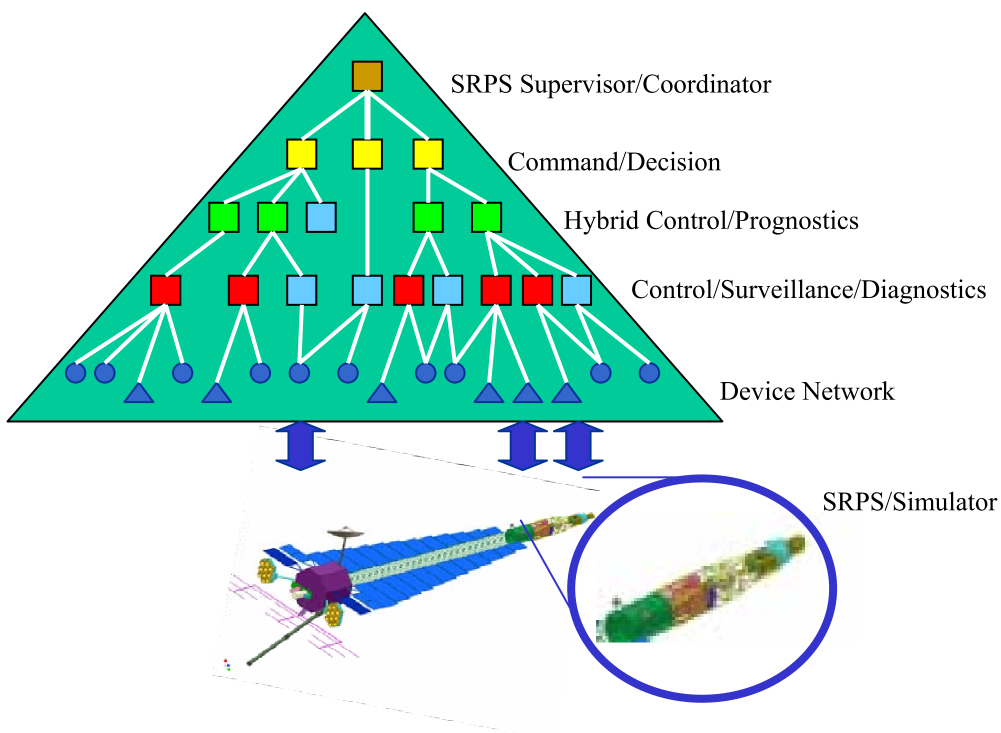

FIGURE 2. A Hierarchical Framework Facilitates Autonomous Control of the SRPS with Interfaces to Other Systems.

In addition to 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 supervisor node must communicate information about the status of the SRPS and the control system and receive directives and commands. The information provided by the supervisor node can include SRPS operational status and capability (e.g., constraints due to degradation), control action histories, diagnostic information, self-validation results, control system configuration, and data logs.

It should also be noted that the self-validating controller structure can be easily implemented at higher levels of the autonomous control architecture. By building in appropriate diagnostics and include high-fidelity simulation models that can be automatically updated, the autonomous control system can determine when subsystem performance has degraded to the point of possibly violating design goals. After the degradation has been diagnosed, corrective action can be taken by the autonomous control system through reconfiguration among pre-designed options and the mission control staff can be alerted.

CONCLUSION

For JIMO and similar space missions, the SRPS control system needs to provide continuous, remote, unattended operation in severe environments for up to fifteen years. Uncertainties, rare events, degradation, and communication delays present engineering challenges for the I&C system designer that cannot be completely addressed through an automated control solution. The necessary capability to respond to rapidly changing or degraded conditions without immediate human intervention requires autonomous control.

Autonomous control can provide:

- intelligence to confirm system performance and detect degraded or failed conditions,
- optimization to minimize stress on SRPS 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.

However, autonomous control has not yet been applied to an operating nuclear power system so technology development and demonstration activities are needed to provide the desired technical readiness for implementation of an SRPS autonomous control system. Areas of research that should be considered in establishing a comprehensive development plan include environmentally robust sensors, radiation hardened electronics, fault management and reliability assessment methodologies, software dependability assessment techniques (e.g., software reliability quantification), system diagnostics and component prognostics, and intelligent control and decision algorithms. The architectural framework, functional requirements, and technological developments that are presented in this paper provide the foundation of an autonomous control concept for a generic SRPS and can contribute to achieving an SRPS autonomous control system to support the JIMO mission.

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