Mars, the Moon, and the Ends of the Earth: Autonomy for Small-Reactor Power Systems

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In recent years, the National Aeronautics and Space Administration (NASA) has been considering deep space missions that utilize a small-reactor power system (SRPS) to provide energy for propulsion and spacecraft power. Additionally, application of SRPS modules as a planetary power source is being investigated to enable a continuous human presence for nonpolar lunar sites and on Mars. A SRPS can supply high-sustained power for space and surface applications that is both reliable and mass efficient.

The use of small nuclear reactors for deep space or planetary missions presents some unique challenges regarding the operations and control of the power system. Current-generation 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 a SRPS employed for deep space missions must be able to accommodate unattended operations due to communications delays and periods of planetary occlusion while adapting to evolving or degraded conditions with no opportunity for repair or refurbishment. While surface power systems for planetary outposts face less extreme delays and periods of isolation and may benefit from limited maintenance capabilities, considerations such as human safety, resource limitations and usage priorities, and economics favor minimizing direct, continuous human interaction with the SRPS for online, dedicated power system management. Thus, a SRPS control system for space or planetary missions must provide capabilities for operational autonomy.

For terrestrial reactors, large-scale power plants remain the preferred near-term option for nuclear power generation. However, the desire to reduce reliance on carbon-emitting power sources in developing countries may lead to increased consideration of SRPS modules for local power generation in remote regions that are characterized by emerging, less established infrastructures. Additionally, many Generation IV (Gen IV) reactor concepts have goals for optimizing investment recovery and economic efficiency that promote significant reductions in plant operations and maintenance staff over current-generation nuclear power plants. To accomplish these Gen IV goals and also address the SRPS remote-siting challenges, higher levels of automation, fault tolerance, and advanced diagnostic capabilities are needed to provide nearly autonomous operations with anticipatory maintenance. Essentially, the SRPS control system for several anticipated terrestrial applications can benefit from the kind of operational autonomy that is necessary for deep space and planetary SRPS-enabled missions.

Investigation of the state of the technology for autonomous control confirmed that control systems with varying levels of autonomy have been employed in robotic, transportation, spacecraft, and manufacturing applications. As an example, 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. However, autonomous control has not been implemented for an operating terrestrial nuclear power plant nor has there been any experience beyond automating simple control loops for space reactors.

Current automated control technologies for nuclear power plants are reasonably mature, and fully automated control of normal SRPS operations is clearly feasible. However, the space-based and remote terrestrial applications of SRPS modules require autonomous capabilities that can accommodate nonoptimum operations when degradation, failure, and other off-normal events challenge the performance of the reactor while immediate human intervention is not possible. The independent action provided by autonomous control, which is distinct from the more limited self action of automated control, can satisfy these conditions. Key characteristics that distinguish autonomous control include:

- 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.

Oak Ridge National Laboratory has developed a concept for a flexible functional architecture that can support the desired autonomous control capabilities through high-level integration of control, diagnostic, and decision-making algorithms and modules. This architectural concept is hierarchical with a recursive nature. Each node in the hierarchy (except for the terminal nodes at the base, which correspond to sensors and actuators) is a supervisory control module. These modules respond to goals and directions set in higher level modules within the hierarchy and to data and information presented from lower level modules. Each module makes decisions appropriate for its level in the hierarchy and passes the result and necessary supporting information to the modules above and below. The bottom two levels of the hierarchy are the equivalent of an automated whole-plant control system. The distributed decision functionality of the higher levels blend detection, diagnosis, command, and planning capabilities to facilitate autonomous operations.

The conceptual definition of this functional architecture provides a basis for establishing and maturing SRPS autonomous control capabilities. The gaps indicated by the state-of-the-technology investigation indicate research, development, and demonstration (RD&D) activities that need to be accomplished to fully realize the goal of autonomous operations for a SRPS. Key elements of the needed RD&D effort involve developing foundational modules to support autonomy, implementing a prototypic functional architecture, and demonstrating the integrated application of autonomous capabilities.