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Invited Article

An autonomous control framework for advanced reactors

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ABSTRACT

Several Generation IV nuclear reactor concepts have goals for optimizing investment recovery through phased introduction of multiple units on a common site with shared facilities and/or reconfigurable energy conversion systems. Additionally, small modular reactors are suitable for remote deployment to support highly localized microgrids in isolated, underdeveloped regions. The long-term economic viability of these advanced reactor plants depends on significant reductions in plant operations and maintenance costs. To accomplish these goals, intelligent control and diagnostic capabilities are needed to provide nearly autonomous operations with anticipatory maintenance. A nearly autonomous control system should enable automatic operation of a nuclear power plant while adapting to equipment faults and other upsets. It needs to have many intelligent capabilities, such as diagnosis, simulation, analysis, planning, reconfigurability, self-validation, and decision. These capabilities have been the subject of research for many years, but an autonomous control system for nuclear power generation remains as-yet an unrealized goal. This article describes a functional framework for intelligent, autonomous control that can facilitate the integration of control, diagnostic, and decision-making capabilities to satisfy the operational and performance goals of power plants based on multimodular advanced reactors.

1. Introduction

Advanced reactors encompass the Generation IV nuclear reactor concepts as well as small modular reactors (SMRs). Generation IV reactor concepts include both thermal and fast spectrum reactors using coolants such as gas (helium, carbon dioxide), liquid metal (sodium, lead—bismuth), molten salt (fluoride salts with dissolved fuel), and supercritical water. SMRs include water-cooled integral primary system reactors as well as nonwater-cooled integral and loop reactor system designs. The former types of reactors are generally referred to as near-term SMR designs, whereas the latter types of reactors are identified as advanced SMR designs. The subsequent discussions in this article will focus on SMRs because many Generation IV nuclear reactor concepts adopt or are suitable for the SMR approach to optimizing investment recovery through phased introduction of multiple small units on a common site with shared facilities and/or reconfigurable energy conversion systems. Additionally, nonwater-cooled SMR designs are subsets of larger-scale Generation IV nuclear reactor concepts.

An SMR is generally characterized by: (1) an electrical generating capacity of less than 300 MWe (megawatt electric), (2) a primary system that is entirely or substantially fabricated within a factory, and (3) a primary system that can be transported by truck or rail to the plant site. In addition to suitability for factory fabrication, modularity of SMRs also refers implementation of multiple modules (i.e., reactor units) at a plant site. These reactors can present lower capital costs than large reactors, allow for incremental additions to generation capacity at a centralized power park, and support multiple energy applications (e.g., process heat, desalination, hydrogen production, and electricity generation). Additionally, SMRs can serve as a highly reliable foundation for smaller grids and even be remotely deployed to support highly localized microgrids in isolated, underdeveloped regions.

Two critical factors for the economic competitiveness of SMRs are (1) the up-front capital cost to construct the plant and (2) the day-to-day cost of plant management. The capital cost competitiveness factor is primarily dependent on the size and complexity of the components that must be fabricated and the methods of installation. In this area, SMRs have a clear advantage over large plants. Because of their small size and, in many cases, simplified nuclear island configurations, it is expected that capital costs will be much lower for SMRs compared to those of large, Generation III+ light-water reactors. Advanced SMRs, which use coolants other than water as the primary heat transport medium, introduce several passive safety concepts and controllability features that

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further reduce the complexity of primary system designs by eliminating redundant components and systems.

The latter competitiveness factor for SMRs (i.e., plant management costs) is strongly affected by the loss of economy of scale. The most significant controllable contributor to day-to-day costs arises from operations and maintenance (O&M) activities, which heavily depend on staffing size and plant availability. The operation of a nuclear power plant is labor intensive. The O&M staff at a plant is composed of operator teams for each shift at each unit, and on-site maintenance personnel can involve a large number of technicians and specialists. The current US nuclear industry average for O&M staff is roughly one person per every 2 megawatts of generated power. Staffing size is affected by regulatory constraints, which establish minimum licensed operator and senior operator staffing requirements for each reactor unit. These staffing requirements are primarily driven by resource demands to respond to transients and accidents and are based on traditional operational models with limited automation. Without a significantly higher degree of automation than is customary for current nuclear power plants, high staffing levels relative to unit power production will pose the threat of unsustainable O&M costs for SMRs.

The benefits of SMRs can include reduced financial risk, operational flexibility, and modular allocation of power production capacity. Achieving these benefits can lead to a new paradigm for plant design, construction, and management to provide for multiunit, multiproduct-stream generating stations while addressing the need to compensate for reduced economy-of-scale savings. However, there are technology needs that must be addressed to resolve challenges to establishing this new paradigm [1]. Automation to the point of near autonomy is the enabling technology that can support achievement of the desired operational and staffing efficiencies (i.e., the economy of automation).

2. State of the technology

To support a technology assessment, the authors conducted an investigation of autonomous control. Control systems with varying levels of autonomy have been employed in robotics, transportation, spacecraft, and manufacturing applications. For manufacturing and robotics [2], much of the work involves augmenting automation of routine tasks with the capability to diagnose and adapt to varying conditions, often based on a constrained, predefined set of responsive actions. Robotic applications can also employ unmanned maneuverable platforms to enable transit within harsh or remote environments. The basis for this autonomy is equivalent to that of unmanned vehicles (both aerial and ground) [3], which involve autonomous capabilities as part of guidance, navigation, and control systems. In transportation, recent developments have focused on self-driving automobiles [4,5]. Deep-space robotic missions have been the primary focus of autonomous flight control for space exploration [6].

Although the level of autonomy and the specific control algorithms differ, each case illustrates key characteristics and a high-level functional framework to enable autonomy. Overviews of autonomous control characteristics, capabilities, and applications were found that establish the existing experience and current technology readiness [7–13]. The desirable characteristics of autonomous control include intelligence, robustness, optimization, flexibility, adaptability, and reliability.

Although various degrees of autonomy have been demonstrated in the cited application domains, autonomous control has not been implemented for an operating nuclear power plant nor have it been extensively developed for any emerging advanced emerging advanced reactor concept. Current automated control technologies for nuclear power plants are reasonably mature, and highly automated control for an SMR is clearly feasible under optimum circumstances. Autonomous control is primarily intended to account for the nonoptimum circumstances when degradation, failure, and other off-normal events challenge the performance of the reactor, and the capability for immediate human intervention is constrained. There are clear gaps in the development and demonstration of autonomous control capabilities for the specific domain of nuclear power operations.

2.1. 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.

Current Generation III+ reactor designs involve a substantial increase in the use of digital I&C technology, but their control systems maintain traditional control strategies. One of the most fully digital plants currently in operation in the United States is the Oconee Nuclear Station [14]. The three units at Oconee have digital reactor protection systems and a digital integrated control system (ICS). The digital ICS coordinates the main control actions of multiple control loops through an integrated master controller that establishes feedforward control demands based on desired overall core thermal power. The ICS also has provisions for supplementary support actions among control loops to facilitate optimized performance.

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, fuzzy logic control for power transition, H-infinity control and genetic algorithm-based control for steam generators, and neural network control for power distribution in a reactor core, and model predictive control to enable fault tolerance and reconfiguration features for primary power control of advanced reactors. Proceedings of past International Topical Meetings on Nuclear Plant Instrumentation, Control and Human–Machine Interface Technologies provide a useful compendium of findings from such research activities [15–23].

As part of the Advanced Liquid Metal Reactor (ALMR) Program for the US Department of Energy, the Oak Ridge National Laboratory developed the concept of supervisory control for multimodular advanced reactors [24,25]. Recent activity on the DOE (U.S. Department of Energy) Advanced Reactor Technologies Program has extended that concept for advanced multimodular SMR plants [26].

2.2. Autonomy in space exploration

National Aeronautics and Space Administration 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 two decades with prominent examples from efforts to explore the surface of Mars. The Mars Pathfinder rover, *Sojourner*, explored the Martian terrain beginning in July 1997 [27]. 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 2006. 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 (CLARAty) [28]. 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 [6]. In addition to demonstrating autonomous navigation of the spacecraft, a principal experiment involved demonstration of the Remote Agent AI system for on-board planning and execution of spacecraft activities.

Finally, an approach for fault-tolerant control of the SP-100 reactor system was developed by Upadhyaya et al [29] and demonstrates the feasibility of applying this method for space fission reactors, either for propulsion or as an energy source.

3. Autonomous control functional definition

3.1. 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, whereas *autonomos* means independent. Similarly, automated control involves self-action, whereas 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 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 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 (e.g., 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. Additionally, 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, whereas 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.

3.2. Near-autonomous SMR plant control

Autonomous control functions for an advanced reactor can be defined based on the expected operational modes, which include startup, normal power operation, reactor protection, contingent operation, and end-of-cycle shutdown. As a minimum requirement of autonomy, the SMR plant control system must be able to switch between normal operational modes automatically (i.e., automatic 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, loss of heat sink) can be treated as off-normal events. Other off-normal events include load/power interruptions, actuator degradation or failure, actuator signal interruption or interference, heat removal 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 immediate protective action for a significant event would consist of a rapid power runback. Contingent operation occurs when SMR operation may be restricted because of power system limitations, such as component failures, degradation or loss of heat sink, or station blackout.

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 conventional reactor operational concepts, in which the primary defense against potentially adverse conditions resulting from off-normal events is to scram the reactor, the objective of autonomous control is to limit the progression of off-normal events and minimize the need for shutdown. This is especially true in situations where the nuclear power plant is the stabilizing generation source on a small electric grid. Thus, an enhanced, layered reactor protection can be provided through diversity and defense-in-depth to anticipate potential challenges to power operation. A limitation system is one means of protecting the reactor while minimizing the risk of costly scrams. This is accomplished by defining acceptable operational regimes and overriding control actions that would drive the reactor conditions to acceptable operational states that do not 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 principle response of the limitation system would be to run back the reactor power to assume a safe low-power condition when necessary. In cases driven by the operational objective that power should remain available to support critical power needs and ensure grid stability, the SMR plant control system must provide the capability to address off-normal events over an extended range of operating conditions without challenging the safety boundary of the reactor and, thus, triggering reactor scram.

The second element of the response to off-normal events addresses availability 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, which provides for detection, diagnosis, and adaptation (or reconfiguration) given changing plant or equipment conditions. An additional aspect of this deliberative element is the monitoring, diagnosis, and validation of control system and reactor performance. Through this capability, the plant 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, 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 autonomous control functionality involves continuously assessing the condition of the control system and the reactor 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 plant, 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, whereas 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 plant-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. Finally, 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 SMR plant 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 plant 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.

3.3. Enabling autonomous control

Autonomous control must be addressed early in the design of the SMR to determine the degree of autonomy required. Operational 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 operational risk that the autonomous control system must mitigate.

Several factors can influence the degree of autonomy selected for a plant control system. These factors include the potential for continuous direct human interaction (which may be limited because of shared operator supervision responsibilities over multiple units or because of constrained on-site staffing at remote installations), performance goals, complexity of system demands, technological constraints, operational risk considerations, and the balance between simplicity (i.e., reliability) and complexity (i.e., the capacity to detect and adapt). The trade between reliability and operational assurance profoundly affects the level of autonomy employed for plant control. Although having a highly reliable plant control system is important, that fact is of limited value if the control system cannot accommodate plant degradation without immediate human intervention or scram. In such a case, the result is a highly reliable control system that becomes ineffective 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 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 indicate research, development, and demonstration (RD&D) activities that need to be accomplished to fully realize the goal of autonomous control for a SMR. 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.

4. Functional architecture for autonomous control

4.1. 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 [8,30,31]. The three layers in top-to-bottom hierarchical order are the planner layer, the executive layer, and the functional layer. 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, 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 (see Fig. 1). The development of CLARAty addresses perceived issues with the three-tiered architecture [28]. 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, whereas 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 has been developed through simulated nuclear power applications (see Fig. 2). As part of research into advanced multimodular nuclear reactor concepts, such as the ALMR, the International Reactor Innovative and Secure (IRIS), and representative advanced SMR concepts, a supervisory control system architecture was devised [24–26]. 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.

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

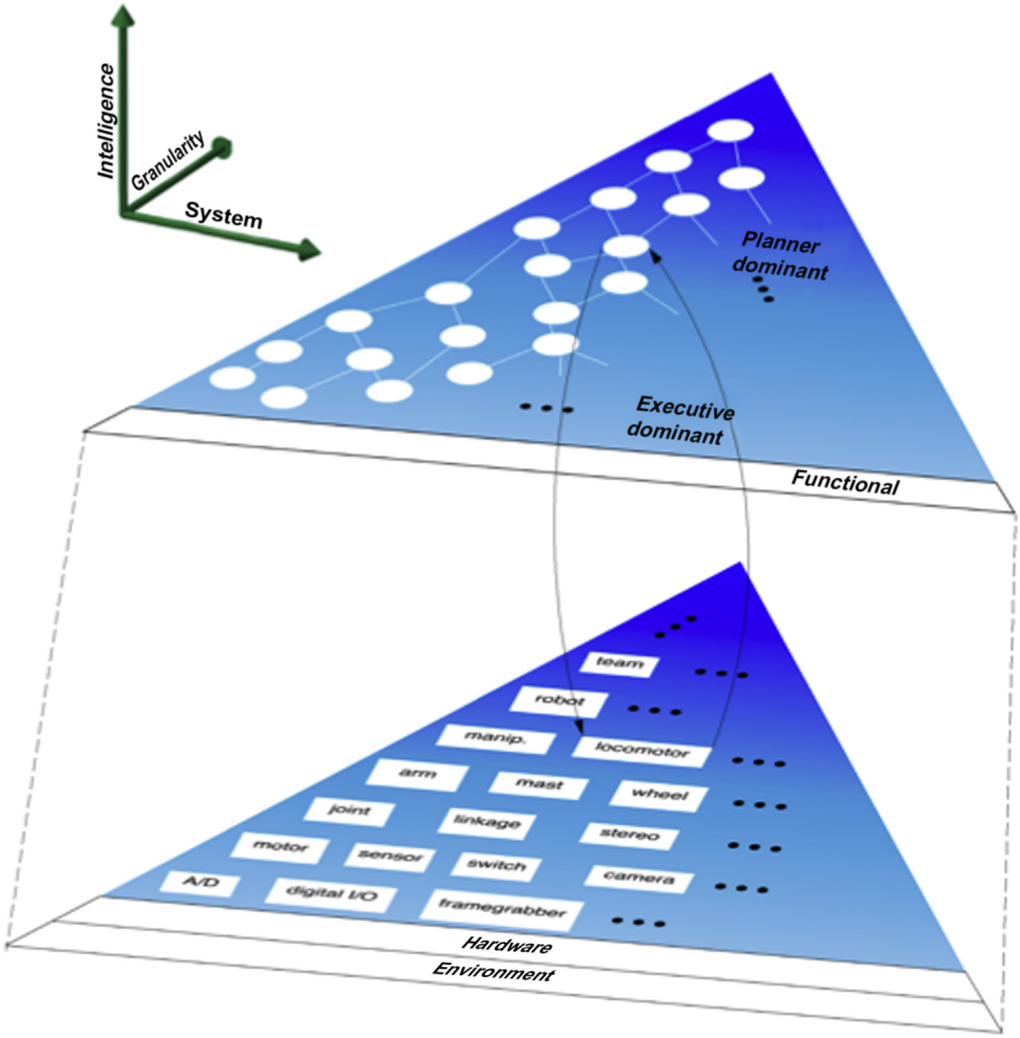

Fig. 1. Decision and functionality layers in CLARAty architecture. CLARAty, Coupled Layer Architecture for Robotic Autonomy.

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.

4.2. 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 a SMR plant control system. Fig. 3 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 and state transitions that are allowed for an SMR 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.

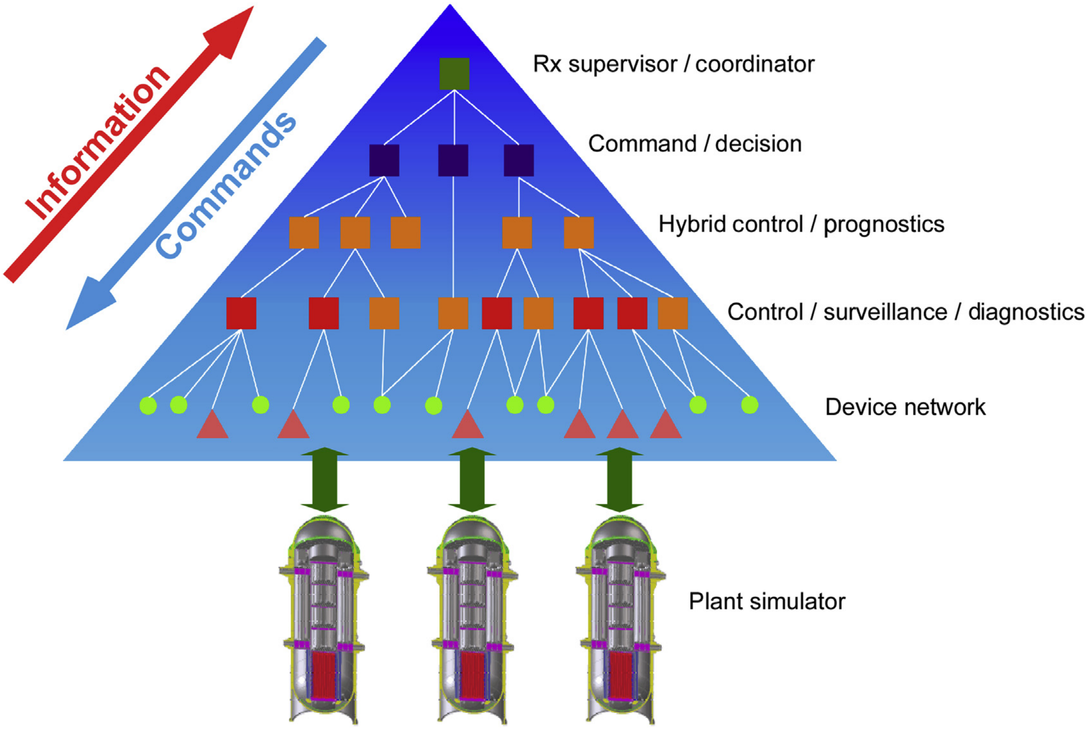

Fig. 2. Supervisory control architecture for multimodular SMR plants. SMR, small modular reactor.

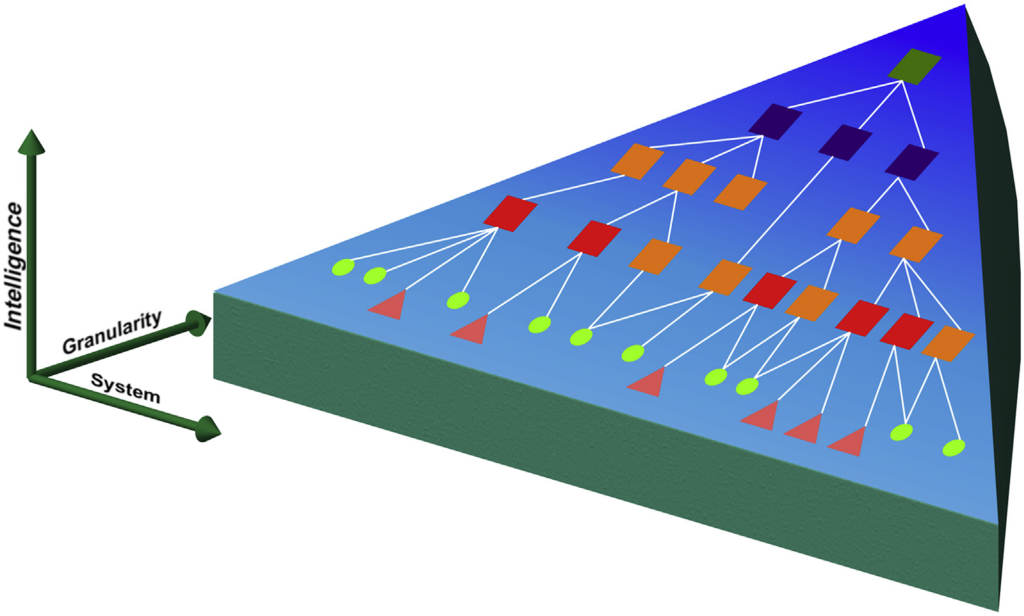

Fig. 3. Hierarchical framework to support SMR plant control system autonomy. SMR, small modular reactor.

In addition to the communications within the hierarchy, the autonomous control system must coordinate with the comparable control systems of other units with whom it is coupled or sharing plant production responsibilities. In addition, it must keep the operational staff informed. To this end, the reactor supervisor/coordinator node must communicate information about the status of the SMR and the control system and also receive directives and commands. The information provided by the supervisor node can include SMR 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 prospective elements of the energy conversion/utilization facilities other than the traditional power conversion system. For example, provisions may be incorporated in the plant implementation for dynamic transitions between end-use processes, which could include an interface to an industrial user of process heat.

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 operational control of the plant as well as supervisory control of the SMR plant 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, status and demands between the plant control system and operational staff. 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 plant control system hardware. Because an autonomous control system has never been implemented for a nuclear reactor and because several functional capabilities remain underdeveloped, there is clearly a critical need for further development and demonstration of a suitable architectural framework.

5. Conclusions

The control system for a multi-unit or remotely located advanced reactor plant will be subject to unique challenges as compared to conventional nuclear power plants, which employ varying degrees of direct human control and decision-making for operations. In contrast, the SMR plant control system should be able to provide continuous, remote, potentially unattended operation for an extended period with limited immediate human interaction. In addition, the SMR plant control system should accommodate system and equipment degradation or failure and rare or unanticipated operational events. As a result, the capability to respond to rapid events and to adapt to changing or degraded conditions without immediate direct human supervision is required to support operational goals. Autonomous control can satisfy essential control objectives under significant uncertainties, disturbances, and degradation without requiring any critical direct human intervention. Therefore, autonomous control is necessary to ensure the successful realization of SMR objectives while facilitating economic competitiveness.

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 SMR components and efficiently react to operational events without compromising system integrity
- Robustness to accommodate uncertainties and changing conditions
- Flexibility and adaptability to accommodate failures through reconfiguration among available control system elements or adjustment of control system strategies, algorithms, or parameters

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 operational 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 in first-generation SMRs. 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 SMR plant autonomous control. A hierarchical functional architecture providing integrated control, diagnostic, and decision capabilities that are distributed throughout the hierarchy can support this approach.

The vision of an autonomous nuclear power plant, which extends to a reactor that can be plugged in like a battery that is self-operating, self-protective, and self-managing, remains more imagination than reality. Although notable progress toward extending automation toward autonomy has been achieved in some application domains, the nuclear power industry has not advanced much in transferring the human roles and responsibilities to the machine (system). In particular, limited, mostly academic efforts have focused on developing advanced control and monitoring capabilities. The primary technical gap relates to decision capabilities (e.g., strategic, interpretive, adaptive, predictive). Technology development and demonstration activities are needed to provide the desired technical readiness for implementation of an SMR autonomous control system. In particular, the capabilities to monitor, trend, detect, diagnose, decide, and self-adjust must be established within an integrated functional architecture to enable control system autonomy.

Conflicts of interest

All authors have no conflicts of interest to declare.

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