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Changing the World's Energy Future

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ABSTRACT

Advanced nuclear reactors offer new capabilities such as the ability to adapt to variable energy demand, operate autonomously with remote supervision, be deployable in rural locations, be compact in size, afford lower power ratings, and rely on novel techniques for increased operational safety. However, realizing these capabilities requires intelligent control systems that can track changing power demands and make autonomous decisions based on these demands. The unique aspects of advanced reactors (e.g., strict regulatory requirements, harsh operating environments, high consequences, highly coupled dynamics, evolving knowledge, and limited operating histories) directly impact the design and deployment of control systems for these reactors. The present work identifies and evaluates these aspects so as to develop a set of control system requirements to guide future research and development. To meet these requirements, a layered control system approach is proposed that integrates digital twins with different control paradigms. This work aims to demonstrate how different methods interface with enabling solutions, and to identify any gaps that need to be researched.

Keywords: advanced nuclear reactors, control systems, digital twins

1. INTRODUCTION

Advanced nuclear reactors are next-generation reactors whose features include the ability to (1) operate in rural areas, at lower or variable power ratings, and with a high degree of autonomy; (2) be small or compact in size; (3) undergo offsite or modular manufacturing and assembly; and (4) afford safer operations, often thanks to increased reliance on passive safety technologies. While these features increase the deployment potential for advanced reactors, they also introduce challenges that must be overcome before these reactors can be used in the manner envisioned.

A key challenge for advanced reactors is the enabling of highly autonomous—and possibly remote—operations, thus necessitating more intelligent and powerful forms of reactor control. Such control can be either passive or active. Passive control refers to the system's ability to track a desired state without the use of actuation. This feature is often designed into the system by using the laws of physics (e.g., gravity and natural convection). In the nuclear power industry, an example of this is seen when making a reactor "walk-away safe," meaning that under loss of power, it will employ natural convection or other physics-based means to passively cool itself until fully shut down. By contrast, active control (the focus of this work) employs actuation to achieve the desired outcome. Active control loops are abundant in light-water reactors, and control such parameters as the pressurizer pressure and level, primary-side water temperatures, and reactor power output. Both passive and active control can coexist within a given system.

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Historically, active control methods have leveraged both logical control and high-performance (HP) control, each of which offers its own advantages and limitations. Recently, however, types of control based on artificial intelligence (AI) and machine learning (ML) have garnered increased interest.

This work utilizes a systematic approach to identify the unique aspects of advanced reactors and to translate them into control requirements (Section 2). An integrated high-level approach is then presented regarding advanced reactor control using advanced control methods, digital twins, and other intelligent forms of control (Section 3). The paper concludes with Section 4.

2. CONTROL REQUIREMENTS FOR ADVANCED REACTORS

Advanced reactors have many unique aspects that directly impact control system design and deployment. These aspects include strict regulatory requirements, harsh operating environments, high consequences, highly coupled dynamics, evolving knowledge, and limited operating histories. Table 1 presents the challenges associated with each of these aspects, along with our proposed requirements.

Table 1: Unique aspects and challenges of advanced reactor control systems, along with the proposed requirements.

Aspect	Challenge	Requirement
Regulatory requirements	AI/ML control may not meet regulatory requirements such as those pertaining to deterministic and explainable behavior	(1) Include an interface control layer between the plant and any AI/ML decision-making processes
Operating environment	Instrumentation and control equipment must endure harsh environments for extended periods, increasing the probability of failures	(2) Identify and compensate for sensor, communication, and electronics failures
High consequences	Manual investigation to reduce uncertainty and avoid shutdown may be infeasible	(3) Incorporate risk elements to prevent unnecessary loss of power generation
Coupled dynamics	Simpler, more compact designs will produce strongly coupled systems, making “isolated” control less feasible	(4) Integrate highly coupled control loops and state-awareness methods
Evolving knowledge	Novel concepts of physics and operation will be used that may not be fully understood or validated	(5) Incorporate robustness into the control loop design
Operating histories	There will be limited operating histories on which to base operational decisions	(6) Use software models to identify and react to or track unanticipated physical phenomena (7) Define the human role and allowable human interventions

3. INTEGRATED CONTROL APPROACH

This section aims to develop a generic approach or framework for enabling all the desired control functions for advanced reactors, with all technological gaps highlighted. Our approach combines digital twins with various methods of control.

Though methods of control inherently differ in terms of both operations and design, this section focuses squarely on the operations side. When extending the approach to the design side, the main difference is that, in the design stage, a model (not a physical system) is used to incorporate all or part of the physical system, which may not yet have been constructed at that point. Cases in which the physical system has only partially been constructed (e.g., simulation of a reactor when the actual core has not been constructed but the rest of the plant has been) necessitate a hardware-in-the-loop approach.

This work proposes a layered approach to advanced reactor control (see Figure 1). The top layer is the supervisory control layer (called the AI/ML control layer because it may contain AI/ML). To meet Requirement 1, this layer does not directly control the plant but can influence the middle layers (i.e., the HP and logical control layers), which use information parsed by the supervisory control layer to calculate control actions for the plant. Finally, the bottom layers consists of the plant and digital twin layers.

To make decisions, the supervisory control layer utilizes sensor measurements from the plant, virtual sensors and information from the digital twin (Requirement 2), external requirements, and risk information (Requirement 3). All this information is then fed to the middle control layers, enabling the supervisory control layer to incorporate information about the broader plant into its decision-making processes. This can enable it to better understand and account for the coupled dynamics (Requirement 4). In addition, the supervisory control layer uses models (implemented by the digital twin) to gain additional insights into conditions that are unanticipated as a result of the lack of operating histories (Requirement 6), and adjusts the controllers to adapt to those conditions (Requirement 5). This layout also leaves open the potential for the human operator to modify the control layer as needed, particularly early on in the reactor's operational lifetime, as needed (Requirement 7).

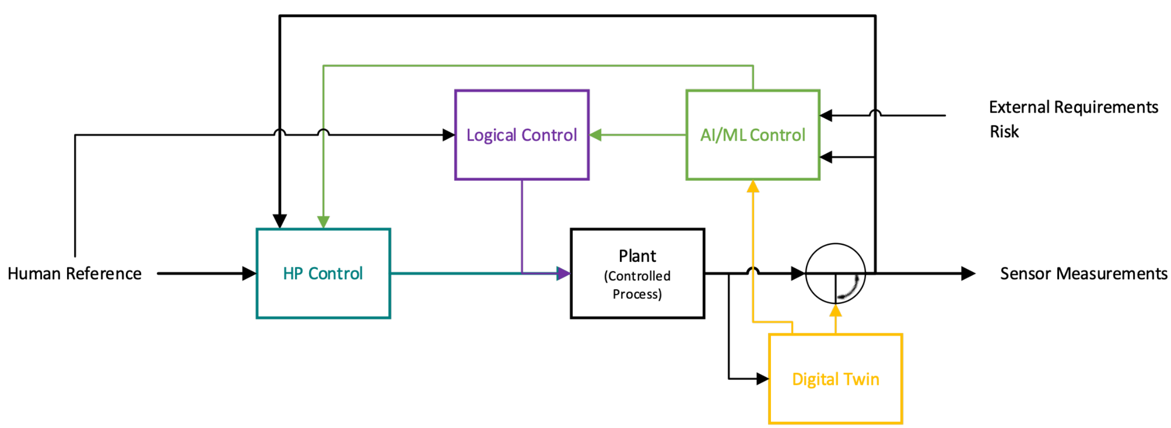

Figure 1: Abstract representation of the operational approach to integrating advanced control methods and digital twins for advanced nuclear reactors.

Figure 1 is expanded in Figure 2, which shows a detailed view of each element from Figure 1. Figure 2 also shows the research gaps, bordered in red. The plant is comprised of physical equipment and passive control, which is shown separately from the active control layers. Next, the digital twin is expanded to show both the high- and low-fidelity models. The high-fidelity model is better suited for condition monitoring because this task benefits from more accurate models, while not requiring extremely fast processing times. By contrast, the low-fidelity model was developed using various reduced-order modeling approaches and is used for time-critical decisions often associated with operational actions (e.g., control actions, which are time sensitive). Information from the plant and digital twin is then sent to the supervisory control layer, which primarily acts as an optimizer. If AI/ML is used as the supervisory control layer, the digital twin can train such an optimizer. In addition, a risk model must be developed to support the various operational decisions that affect the plant, and those decisions must be fed to the supervisory control optimizer.

The supervisory control layer then passes decisions to one or both of the other control layers. The HP control layer is expanded into three forms of control. *Control multiplexing* enables a control system to switch back and forth between various distinct control strategies, where each could be favorable during different operational conditions. The proportional integral derivative [1] and H_∞ [2] are individual control strategies that fall into this bin. *Control optimization* enables calculation of control actions by defining control laws that minimize a cost function. An example of this is model predictive control [3]. *Change control compensators* track the plant state and adjust the controller parameters to compensate for sensor issues and changing plant conditions. An example of this is model reference adaptive control [4].

Figure 2 also highlights some of the research gaps resulting from this layered approach. Within the supervisory layer are gaps pertaining to (1) using risk information within the optimizer to make adjustments to the control layers, and (2) supporting an optimal decision-making process that combines interfacing information from both the plant and the digital twin. In examining the control layers, while logical and HP control methods are mature enough for use in various industries (including the nuclear industry), a gap was identified regarding the means by which supervisory control could interface with logical and HP controllers. Because both the logical and HP controllers can be used in a control loop, an interface is also needed to couple the two approaches. Reactors currently rely on a human to achieve this, but such an approach is infeasible for advanced reactors, given the reduced human role in their operations.

Finally, because advanced reactors lack operating histories, the human role must be defined, as it is nonetheless expected to be of significance during the initial operational phase of these reactors. In addition, a mechanism must be defined for ensuring that said intervention does not impact the condition, risk, or state of the reactor. However, this role will continually shrink as operational histories begin to be compiled.

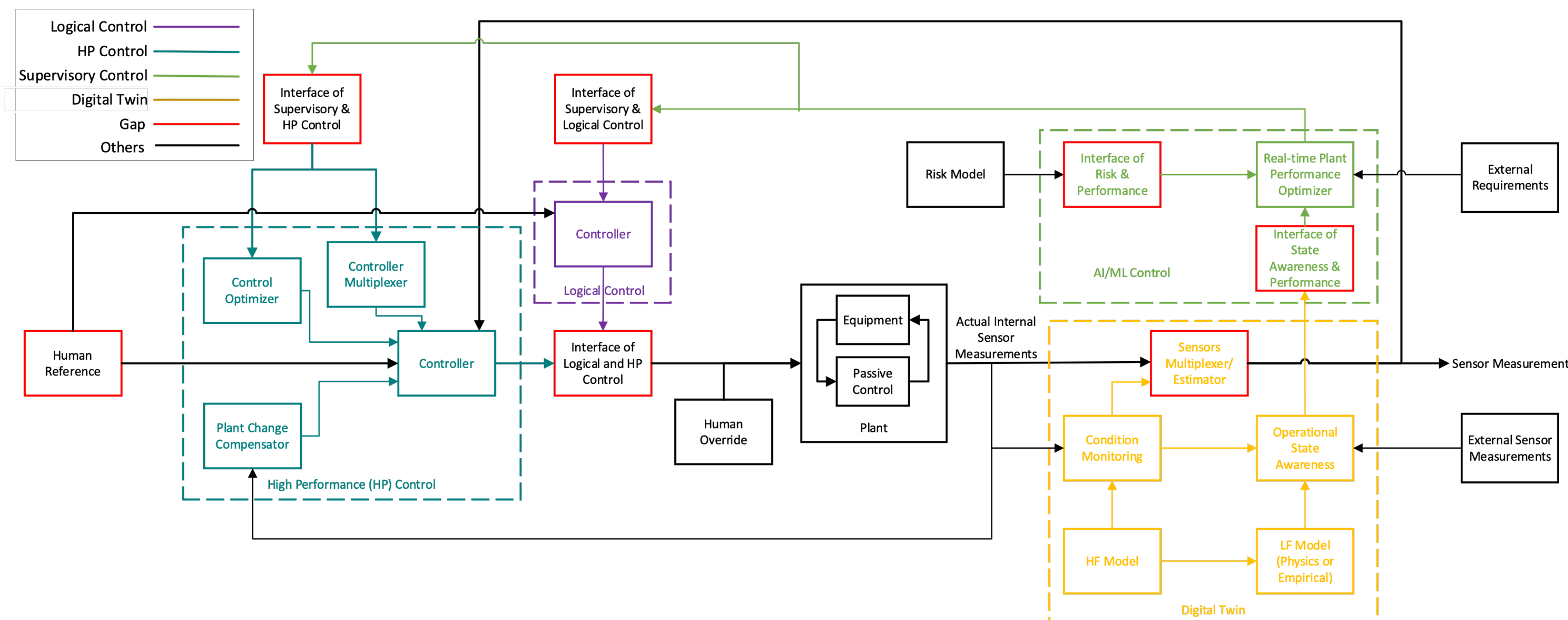

Figure 2: Operational approach to integrate advanced control methods and digital twins for advanced nuclear reactors.

4. CONCLUSIONS

This work assessed the unique aspects and challenges of highly autonomous operations for advanced reactors, resulting in a set of control system requirements. To meet these requirements, digital twins were combined with a layered controls approach that interfaced with a supervisory control system. Finally, this assessment led to the identification of research gaps, and can serve as a roadmap for future research on advanced reactor controls.

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DISCLAIMER

REFERENCES

[1] Astrom, K. J., and T. Hagglund. 2006. Advanced PID control. ISA Press: Research Triangle Park.

[2] Dullerud, G. E., and F. Paganini. 2000. A course in robust control theory: a convex approach. Springer: New York.

[3] Rawlings, J. B., D. Q. Mayne, and M. M. Diehl. 2017. Model predictive control: theory, computation, and design Second edition. Nob Hill Publishing: Madison.

[4] Astrom, K. J., and B. Wittenmark. 1994. Adaptive control. Second edition. Prentice Hall: Englewood Cliffs.