

From Cold Start to Critical: Formal Synthesis of Hybrid Controllers

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Project Summary

Overview

This research will develop a methodology for creating autonomous hybrid control systems with mathematical guarantees of safe and correct behavior. Nuclear power plants require the highest levels of control system reliability, where failures can result in significant economic losses or radiological release. Currently, nuclear operations rely on extensively trained human operators who follow detailed written procedures to manage reactor control. However, reliance on human operators prevents introduction of autonomous control capabilities and creates fundamental economic challenges for next-generation reactor designs. Without introducing automation, emerging technologies like small modular reactors face significantly higher per-megawatt staffing costs than conventional plants, threatening their economic viability.

To address this need, we will combine formal methods from computer science with control theory to build hybrid control systems that are correct by construction. Hybrid systems use discrete logic to switch between continuous control modes, similar to how operators change control strategies. Existing formal methods can generate provably correct switching logic from written requirements, but they cannot handle the continuous dynamics that occur during transitions between modes. Meanwhile, traditional control theory can verify continuous behavior but lacks tools for proving correctness of discrete switching decisions. By synthesizing discrete mode transitions directly from written operating procedures and verifying continuous behavior between transitions, we can create hybrid control systems with end-to-end correctness guarantees.

Intellectual Merit

The intellectual merit lies in unifying discrete synthesis and continuous verification to enable end-to-end correctness guarantees for hybrid systems. This research will advance knowledge by developing a systematic, tool-supported methodology for translating written procedures into temporal logic, synthesizing provably correct discrete switching logic, and developing verified continuous controllers. The approach addresses a fundamental gap in hybrid system design by bridging formal methods from computer science and control theory.

Broader Impacts

This research directly addresses the multi-billion dollar operations and maintenance cost challenge facing nuclear power deployment. By synthesizing provably correct hybrid controllers, we can automate routine operational sequences that currently require constant human oversight, enabling a shift from direct operator control to supervisory monitoring. Beyond nuclear applications, this research will establish a generalizable framework for autonomous control of safety-critical systems including chemical process control, aerospace systems, and autonomous transportation.

Research Description

1 Objectives

The goal of this research is to develop a methodology for creating autonomous control systems with event-driven control laws that have guarantees of safe and correct behavior.

Nuclear power relies on extensively trained operators who follow detailed written procedures to manage reactor control. Based on these procedures and operators' interpretation of plant conditions, operators make critical decisions about when to switch between control objectives. While human operators have maintained the nuclear industry's exceptional safety record, reliance on human operators has created an economic challenge for next-generation nuclear power plants. Small modular reactors face significantly higher per-megawatt staffing costs than conventional plants, threatening their economic viability. Autonomous control systems are needed that can safely manage complex operational sequences with the same assurance as human-operated systems, but without constant supervision.

To address this need, we will combine formal methods from computer science with control theory to build hybrid control systems that are correct by construction. Hybrid systems use discrete logic to switch between continuous control modes, similar to how operators change control strategies. Existing formal methods generate provably correct switching logic but cannot handle continuous dynamics during transitions, while traditional control theory verifies continuous behavior but lacks tools for proving discrete switching correctness. We will bridge this gap through a three-stage methodology. First, we will translate written operating procedures into temporal logic specifications using NASA's Formal Requirements Elicitation Tool (FRET), which structures requirements into scope, condition, component, timing, and response elements. This structured approach enables realizability checking to identify conflicts and ambiguities in procedures before implementation. Second, we will synthesize discrete mode switching logic from these specifications using reactive synthesis tools such as Strix, which generates deterministic automata that are provably correct by construction. Third, we will develop and verify continuous controllers for each discrete mode using standard control theory and reachability analysis. We will classify continuous modes based on their transition objectives, and then employ assume-guarantee contracts and barrier certificates to prove that mode transitions occur safely and as defined by the deterministic automata. This compositional approach enables local verification of continuous modes without requiring global trajectory analysis across the entire hybrid system. We will demonstrate this methodology by developing an autonomous startup controller for a Small Modular Advanced High Temperature Reactor (SmAHTR) and implementing it on an Emerson Ovation control system using the ARCADE hardware-in-the-loop platform. This approach will demonstrate autonomous control can be used for complex nuclear power operations while maintaining safety guarantees.

If this research is successful, we will be able to do the following:

1. *Synthesize written procedures into verified control logic.* We will develop a methodology for converting written operating procedures into formal specifications. These specifications will be synthesized into discrete control logic using reactive synthesis tools. This process uses structured intermediate representations to bridge natural language and mathematical logic. Control engineers will be able to generate mode-switching controllers from regulatory procedures with little formal methods expertise, reducing barriers to high-assurance control

systems.

2. *Verify continuous control behavior across mode transitions.* We will develop methods using reachability analysis to ensure continuous control modes satisfy discrete transition requirements. Engineers will be able to design continuous controllers using standard practices while ensuring system correctness and proving mode transitions occur safely at the right times.
3. *Demonstrate autonomous reactor startup control with safety guarantees.* We will implement this methodology on a small modular reactor simulation using industry-standard control hardware. This trial will include multiple coordinated control modes from cold shutdown through criticality to power operation on a SmAHTR reactor simulation in a hardware-in-the-loop experiment. Control engineers will be able to implement high-assurance autonomous controls on industrial platforms they already use, enabling users to achieve autonomy without retraining costs or developing new equipment.

2 State of the Art and Limits of Current Practice

Automation of some nuclear power operations is already performed today. Highly automated systems handle reactor protection and emergency core cooling, while human operators retain strategic decision-making. Autonomous systems are trusted to handle emergency situations that are considered terminal operations, but otherwise introduce too much risk to reactor operations. Contrary to this notion is the fact that 70–80% of all nuclear power plant events are attributed to human error rather than equipment failures. The persistence of this ratio despite four decades of improvements to procedures and control rooms suggests fundamental cognitive limitations rather than remediable deficiencies.

The Nuclear Regulatory Commission has recognized that introducing automation into the control room is the only way forward. Recent efforts to apply formal methods to nuclear control have shown both promise and remaining gaps. The High Assurance Rigorous Digital Engineering for Nuclear Safety (HARDENS) project represents the most advanced application to date. HARDENS produced a complete Reactor Trip System with full traceability from NRC requirements through formal specifications to verified binaries of a controller implementation. The project employed formal methods along the control design stack. This comprehensive approach demonstrated that formal methods may be technically feasible and economically viable for nuclear protection systems.

But despite these accomplishments, HARDENS has a fundamental limitation directly relevant to our work. The project addressed only discrete digital control logic without modeling or verifying continuous reactor dynamics. Real reactor safety depends on interaction between continuous processes and discrete control decisions. HARDENS verified the discrete controller in isolation but not the closed-loop hybrid system behavior.

3 Research Approach

This research will overcome the identified limitations by combining formal methods from computer science with control theory to build hybrid control systems that are correct by construction. We accomplish this through three main thrusts:

1. We will translate natural language procedures and requirements into temporal logic specifications using the Formal Requirements Elicitation Tool (FRET).

2. We will synthesize these temporal logic specifications into the discrete component of the hybrid controller using reactive synthesis.
3. We will build continuous control modes that satisfy discrete controller transition requirements.

Commercial nuclear power operations remain manually controlled despite significant advances in control systems. The key insight is that procedures performed by human operators are highly prescriptive and well-documented. To formalize these procedures, we will use temporal logic, which captures system behaviors through temporal relations. Linear Temporal Logic provides four fundamental operators: next (X), eventually (F), globally (G), and until (U). These operators enable precise specification of time-dependent requirements. The most efficient path to accomplish this translation is through NASA's Formal Requirements Elicitation Tool (FRET). FRET employs FRETish, a specialized requirements language that restricts requirements to easily understood components while eliminating ambiguity. FRET enforces structure by requiring all requirements to contain six components: Scope, Condition, Component, Shall, Timing, and Response.

FRET provides functionality to check realizability of a system. Realizability analysis determines whether written requirements are complete by examining the six structural components. Complete requirements neither conflict with one another nor leave any behavior undefined. Systems that are not realizable contain behavioral inconsistencies that represent the physical equivalent of software bugs. Using FRET during autonomous controller development allows us to identify and resolve these errors systematically. FRET exports requirements in temporal logic format compatible with reactive synthesis tools, enabling the second thrust of our approach.

Reactive synthesis is an active research field focused on generating discrete controllers from temporal logic specifications. The term reactive indicates that the system responds to environmental inputs to produce control outputs. These synthesized systems are finite in size, where each node represents a unique discrete state. The connections between nodes, called state transitions, specify the conditions under which the discrete controller moves from state to state. This complete mapping constitutes a discrete automaton.

We will employ reactive synthesis tools which translate linear temporal logic specifications into deterministic automata automatically while maximizing generated automata quality. Once constructed, the automaton can be straightforwardly implemented using standard programming control flow constructs. The discrete automata representation yields an important theoretical guarantee. Because the discrete automaton is synthesized entirely through automated tools from design requirements and operating procedures, we can prove that the automaton—and therefore our hybrid switching behavior—is correct by construction.

This correctness guarantee is paramount. Mode switching represents the primary responsibility of human operators in control rooms today. Human operators possess the advantage of real-time judgment. When mistakes occur, they can correct them dynamically. Autonomous control lacks this adaptive advantage. By synthesizing controllers from logical specifications with guaranteed correctness, we eliminate the possibility of switching errors.

While discrete system components will be synthesized with correctness guarantees, they represent only half of the complete system. The continuous modes will be developed after discrete automaton construction, leveraging the automaton structure and transitions to design multiple smaller, specialized continuous controllers.

The discrete automaton transitions mark decision points for switching between continuous con-

trol modes and define their strategic objectives. We will classify three types of high-level continuous controller objectives: Stabilizing modes maintain the hybrid system within its current discrete mode, corresponding to steady-state normal operating modes like full-power load-following control. Transitory modes have the primary goal of transitioning the hybrid system from one discrete state to another, such as controlled warm-up procedures. Expulsory modes are specialized transitory modes with additional safety constraints that ensure the system is directed to a safe stabilizing mode during failure conditions, such as reactor SCRAM.

Building continuous modes after constructing discrete automata enables local controller design focused on satisfying discrete transitions. The primary challenge in hybrid system verification is ensuring global stability across transitions. Current techniques struggle with this problem because dynamic discontinuities complicate verification. This work alleviates these problems by designing continuous controllers specifically with transitions in mind. By decomposing continuous modes according to their required behavior at transition points, we avoid solving trajectories through the entire hybrid system.

To ensure continuous modes satisfy their requirements, we will employ three complementary techniques. Reachability analysis computes the reachable set of states for a given input set. We will use reachability when continuous state ranges at discrete transition boundaries are defined and verify that continuous modes only can reach such defined ranges. Otherwise, assume-guarantee contracts will be employed when continuous state boundaries are not explicitly defined. For any given mode, the input range for reachability analysis is defined by the output ranges of discrete modes that transition to it. This compositional approach ensures each continuous controller is prepared for its possible input range. Finally, barrier certificates will prove that mode transitions are satisfied. Control barrier functions provide a method to certify safety by establishing differential inequality conditions that guarantee forward invariance of safe sets.

Combining these three techniques will enable us to prove that continuous components satisfy discrete requirements and thus complete system behavior. To demonstrate this methodology, we will develop an autonomous startup controller for a Small Modular Advanced High Temperature Reactor (SmAHTR). SmAHTR represents an ideal test case with well-documented startup procedures that must transition through multiple distinct operational modes: initial cold conditions, controlled heating to operating temperature, approach to criticality, low-power physics testing, and power ascension to full operating capacity. We have access to an already developed high-fidelity SmAHTR model in Simulink that captures the thermal-hydraulic and neutron kinetics behavior.

The synthesized hybrid controller will be implemented on an Emerson Ovation control system platform, which is representative of industry-standard control hardware. This control system will be used in a hardware-in-the-loop simulation, where the Advanced Reactor Cyber Analysis and Development Environment (ARCADE) suite will serve as the integration layer. This hardware-in-the-loop configuration enables validation of the controller implementation on actual industrial control equipment.

4 Metrics of Success

This research will be measured by advancement through Technology Readiness Levels, progressing from fundamental concepts to validated prototype demonstration. The work begins at TRL 2–3 and aims to reach TRL 5, where system components operate successfully in a relevant laboratory environment. TRLs provide the ideal success metric because they explicitly measure the gap between academic proof-of-concept and practical deployment. This gap is precisely what our

work aims to bridge. TRLs capture both theoretical rigor and practical feasibility simultaneously. The nuclear industry already uses TRLs for technology assessment, making this metric directly relevant to potential adopters.

Moving from current state (TRL 2–3) to target (TRL 5) requires progressing through component isolation, system integration, and hardware validation. By reaching TRL 5, we will have demonstrated a complete autonomous hybrid controller operating on industrial control hardware through hardware-in-the-loop testing. Achieving TRL 5 establishes both theoretical validity and practical feasibility, proving that the methodology produces verified controllers implementable with current technology and providing a clear pathway for nuclear industry adoption and broader application to safety-critical autonomous systems.

5 Broader Impacts

Nuclear power presents both a compelling application domain and an urgent economic challenge. Recent interest in powering artificial intelligence infrastructure has renewed focus on small modular reactors for hyperscale datacenters. According to the U.S. Energy Information Administration, advanced nuclear power entering service in 2027 is projected to cost \$88.24 per megawatt-hour. With datacenter electricity demand projected to reach 1,050 terawatt-hours annually by 2030, operations and maintenance costs represent approximately 23–30% of total levelized cost, translating to \$21–28 billion annually for projected datacenter demand.

This research directly addresses the multi-billion dollar O&M cost challenge. Current nuclear operations require full control room staffing for each reactor. These staffing requirements drive high O&M costs, particularly for smaller reactor designs where the same overhead must be spread across lower power output. The economic burden threatens the viability of next-generation nuclear technologies. But, by synthesizing provably correct hybrid controllers, we can automate routine operational sequences that currently require constant human oversight. This enables a change from direct operator control to supervisory monitoring where operators oversee multiple autonomous reactors rather than manually controlling individual units. The transition fundamentally changes the economics of nuclear operations.

The correct-by-construction methodology is critical for this transition. Traditional automation approaches cannot provide sufficient safety guarantees for nuclear applications where regulatory requirements and public safety concerns demand the highest levels of assurance. By formally verifying both discrete mode-switching logic and continuous control behavior, this research will produce controllers with mathematical proofs of correctness. These guarantees enable automation to safely handle routine operations that currently require human operators to follow written procedures.

Beyond nuclear applications, this research will establish a generalizable framework for autonomous control of safety-critical systems. The methodology of translating operational procedures into formal specifications, synthesizing discrete switching logic, and verifying continuous mode behavior applies to any hybrid system with documented operational requirements. Potential applications include chemical process control, aerospace systems, and autonomous transportation. These domains share similar economic and safety considerations that favor increased autonomy with provable correctness guarantees. By demonstrating this approach in nuclear power this research will establish both technical feasibility and regulatory pathways for broader adoption across critical infrastructure.

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