Formally Verified Autonomous Hybrid Control

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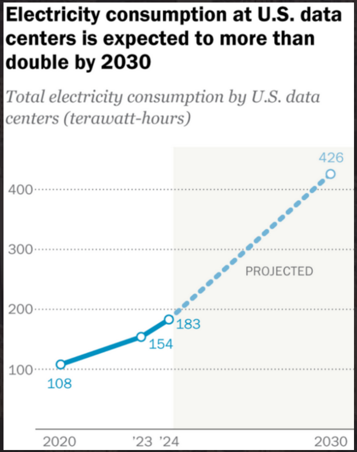
The United States stands on the precipice of a severe energy crisis



Source: Pew Research Center, Data from IEA

How much baseload power increase is this?

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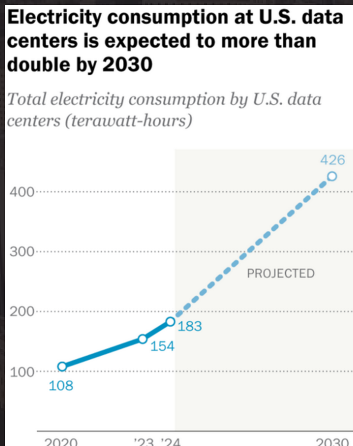

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How much baseload power increase is this?

30 gigawatts!

Nuclear reactors are operated with prescriptive handbooks and legacy control technologies

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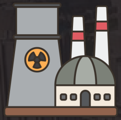
Building a fleet of new reactors with current requirements will be an incredible staffing challenge

How many reactor operators are required to staff this new fleet?



For one Small Modular Reactor (SMR)...

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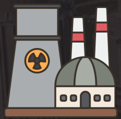

For one Small Modular Reactor (SMR)...

24/7 operations require ∼6 shifts:

12 SROs

12 ROs

24 licensed operators per reactor

To meet demand we require 2,400 new licensed operators!

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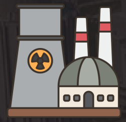

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We currently have only 3,600 licensed operators total...

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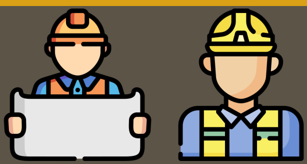
Human reactor operators have key limitations that limit nuclear buildout

Humans cannot meet labor demand



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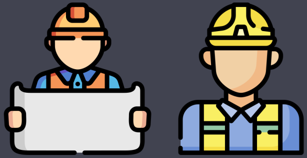

Procedures are not formally verified

Human factors cannot be trained away

The goal of this research is to create verified autonomous control systems

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

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1. Translate written procedures into discrete control logic
2. Verify continuous control behavior across discrete mode transitions
3. Demonstrate autonomous reactor startup with verifiable safety guarantees

First, we will formalize written procedures into logical statements

APPENDIX 19-1
Plant Startup from Cold Shutdown

I. INITIAL CONDITIONS

1. Cold Shutdown - MODE 5:

   - $K_{eff} < 0.99$
   - 0% power
   - $T_{avg} < 200°F$

2. Reactor Coolant System: solid.
3. RCS Temperature: 150 - 160°F.

Note:
Temperature may be less than 150°F depending upon the decay heat load of the core.

4. RCS Pressure: 320 - 400 psig.
5. Steam Generators: filled to wet layup (100% wide-range level indication).
6. Secondary Systems: shutdown, main turbine and feedwater pump turbines on their turning gears.
7. Pre-Startup Checklists: completed.

Westinghouse Technology Systems Manual, Section 19.0 - Plant Operations

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LTL Formula

$$\Box\ (\texttt{initial} \rightarrow (\texttt{mode\_5\_active} \land \texttt{k\_eff\_subcritical} \land \texttt{zero\_power} \land \texttt{temp\_safe} \land \ldots))$$

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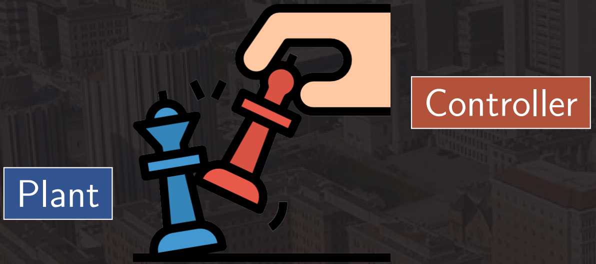
Second, we will use reactive synthesis to convert the logical formulae to generate discrete automata



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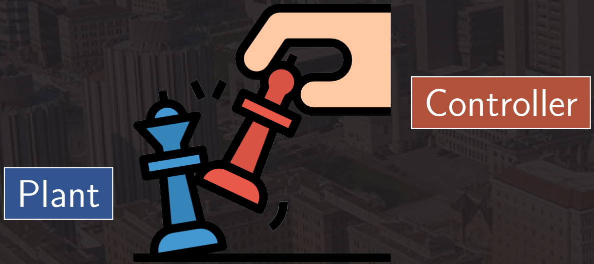

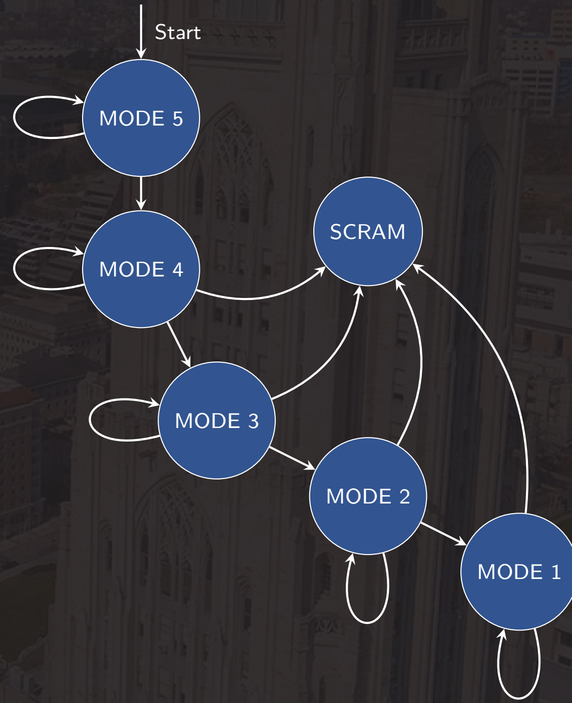

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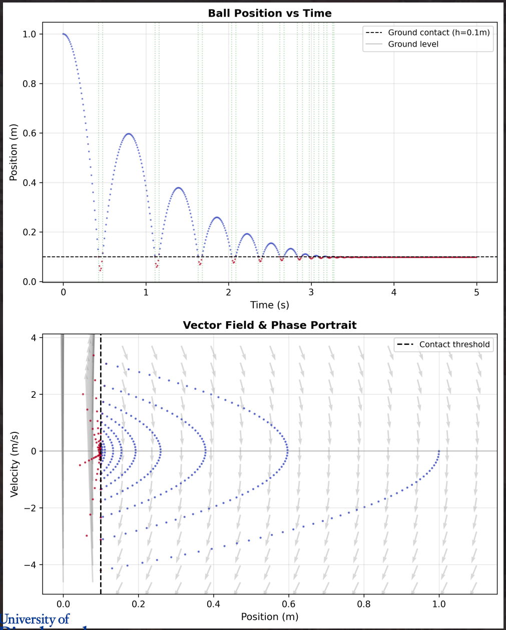

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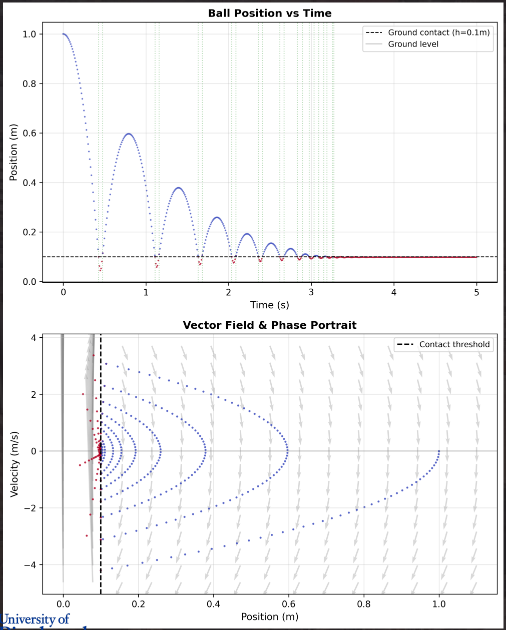

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Verify continuous control behavior across discrete mode transitions

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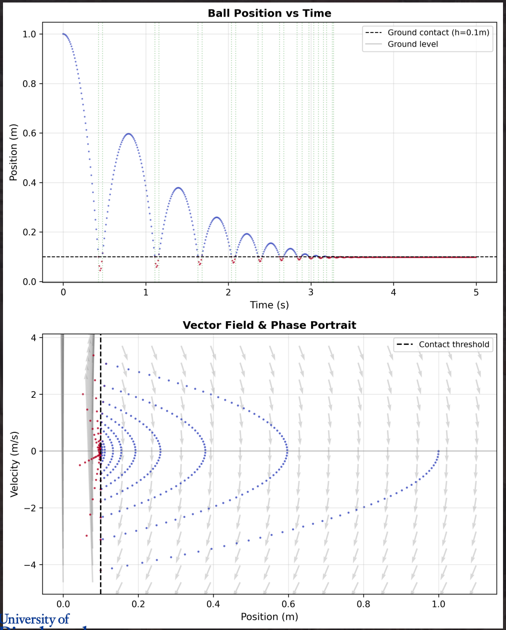

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Reachable Set

$$\mathcal{R}(t) = \{x(t) \mid x(0) \in X_0, \dot{x} = f(x)\}$$

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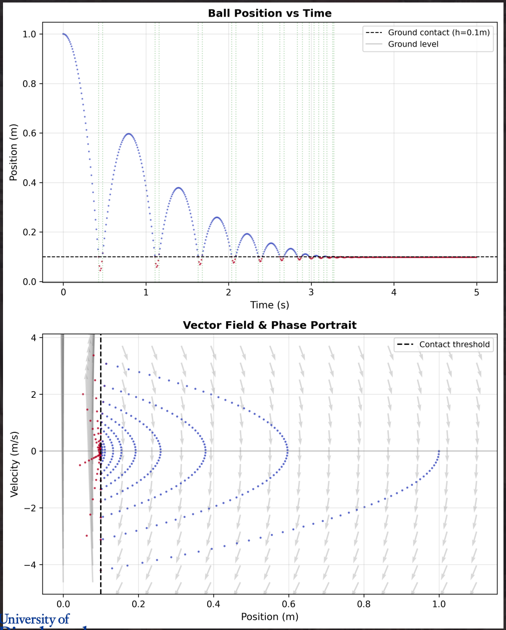

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Barrier Certificate

$B(x) > 0 \wedge \nabla B \cdot f(x) \leq 0 \implies x \in \text{Safe}$

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2. Synthesize discrete automata from LTL using reactive synthesis
3. Design continuous controllers for each discrete mode and verify safety across mode transitions using barrier certificates and reachability analysis

Result: Complete hybrid autonomous system with correctness guarantees by construction

Success will be measured through Technology Readiness Level advancement

Why TRLs?

Bridge gap between proof-of-concept and deployment

Measure both rigor and feasibility

TRL 3

Components

Current: TRL 2-3
Target: TRL 5

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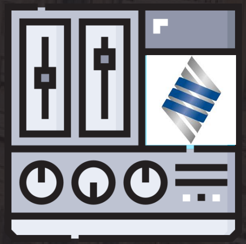

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2. Discrete-Continuous Interface Complexity
3. Procedure Formalization Completeness
4. Hardware-in-the-Loop Integration

Broader Impact: Multi-billion dollar O&M cost reduction

The Economic Opportunity

Datacenter electricity demand projected to reach **1,050 TWh/year by 2030**

If supplied by nuclear power:

$$\begin{aligned}\text{Total annual cost} &= 1,050\ \text{TWh/yr} \times \$88.24/\text{MWh} \\ &= \mathbf{\$92.7\ billion/year}\end{aligned}$$

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Beyond nuclear: A generalizable framework for safety-critical autonomy

Why Nuclear First?

- Highest regulatory requirements
- Most safety-critical domain
- Procedures already documented
- Establishes regulatory pathway

Future Applications

- Chemical process control
- Aerospace systems
- Autonomous transportation
- Critical infrastructure

Translate procedures → Synthesize logic → Verify behavior

Applicable to any hybrid system with documented operational requirements

Formally Verified Autonomous Hybrid Control

Enabling Economic Viability of Next-Generation Nuclear Power

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