Formally Verified Autonomous Hybrid Control

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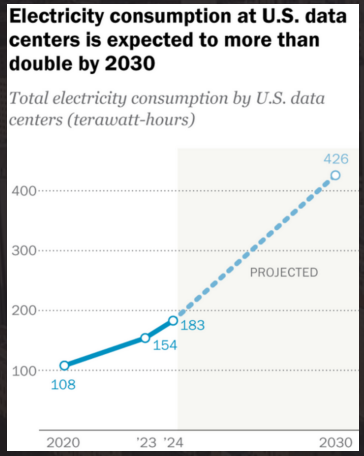
December 7, 2025

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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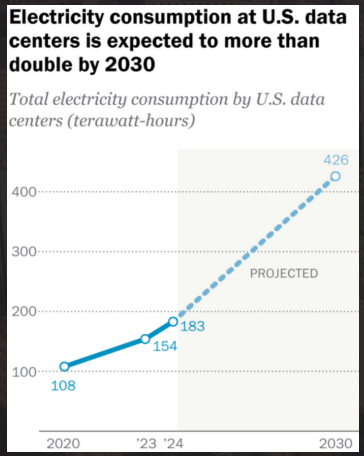

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How much baseload power increase is this?

30 gigawatts!

Nuclear reactors are operated with prescriptive handbooks and legacy control technologies

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

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24/7 operations require ∼6 shifts:

12 SROs

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24 licensed operators per reactor

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

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Human factors cannot be trained away

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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

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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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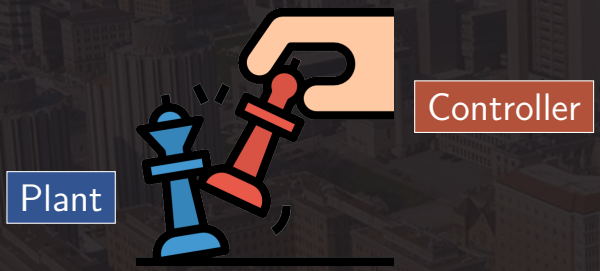
LTL Formula

$$\square\ (\text{initial} \rightarrow (\text{mode\_5\_active} \wedge \text{k\_eff\_subcritical} \wedge \text{zero\_power} \wedge \text{temp\_safe} \wedge \ldots))$$

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



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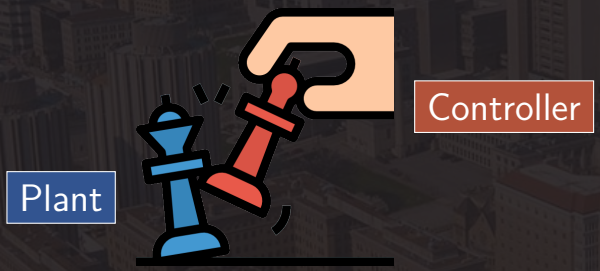
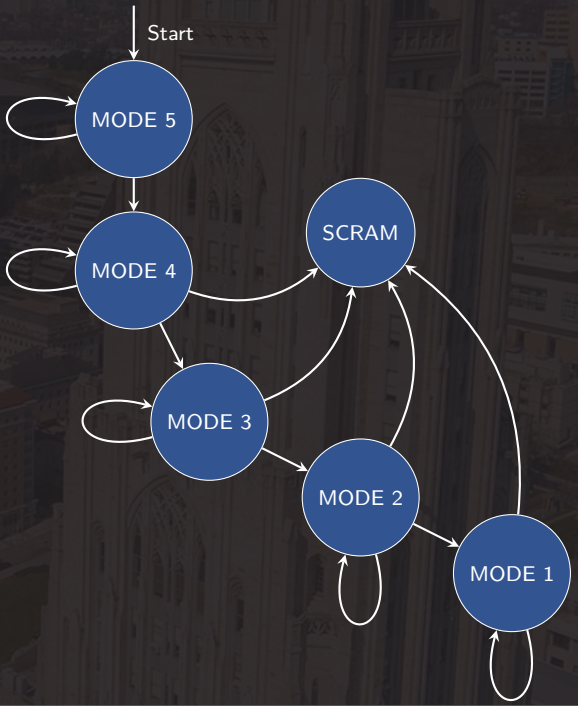
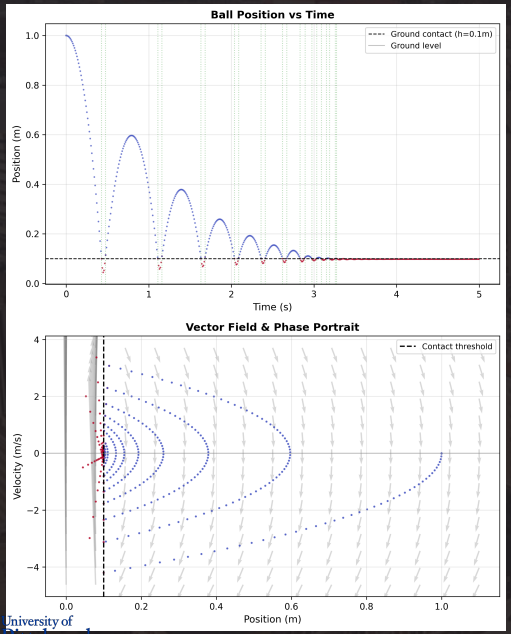




Finally, we will build continuous controllers to move between discrete states



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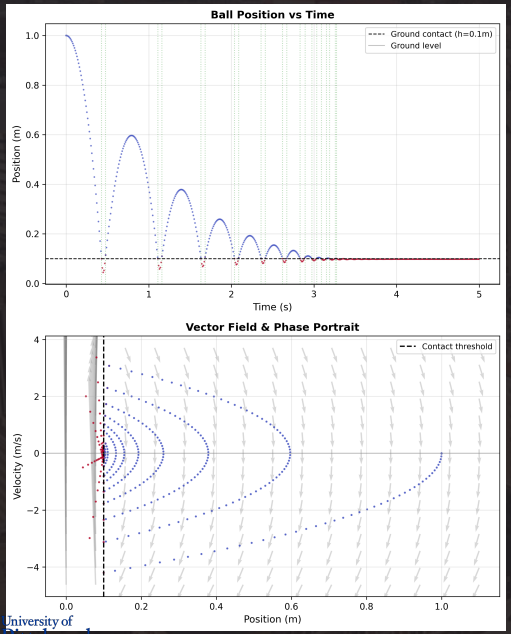

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Verify continuous control behavior across discrete mode transitions

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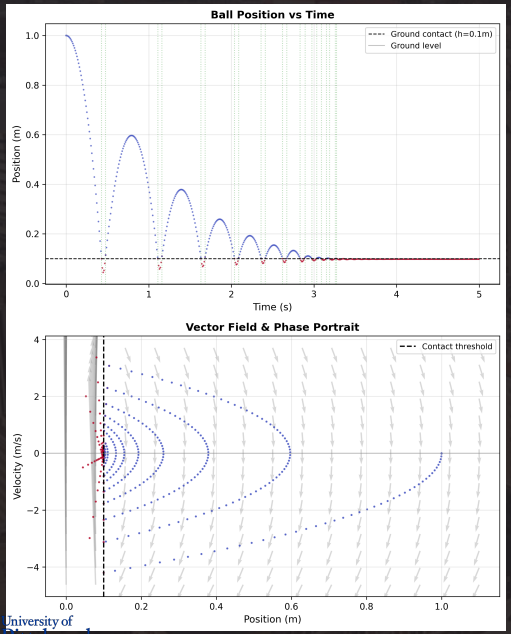

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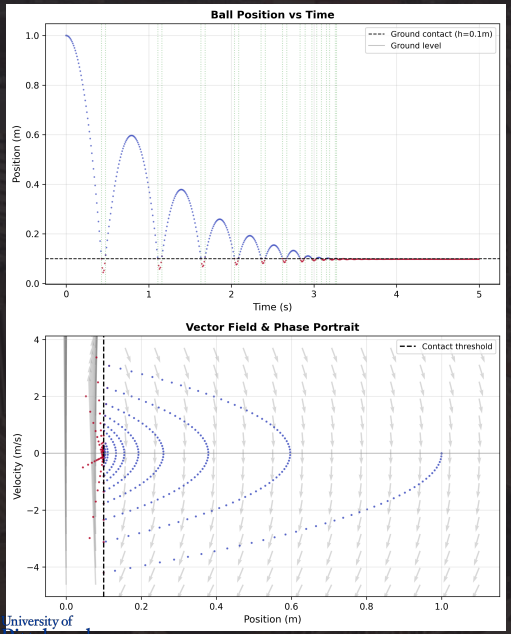

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Barrier Certificate

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

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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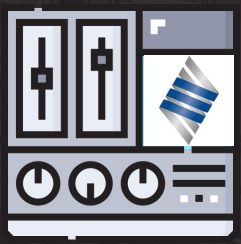

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4. Hardware-in-the-Loop Integration

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:

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

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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 $\rightarrow$ Synthesize logic $\rightarrow$ Verify behavior

Applicable to any hybrid system with documented operational requirements

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Formally Verified Autonomous Hybrid Control

Enabling Economic Viability of Next-Generation Nuclear Power

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