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Neuromorphic Physically-Informed Neural Network for Prediction and Control of Engineered Systems

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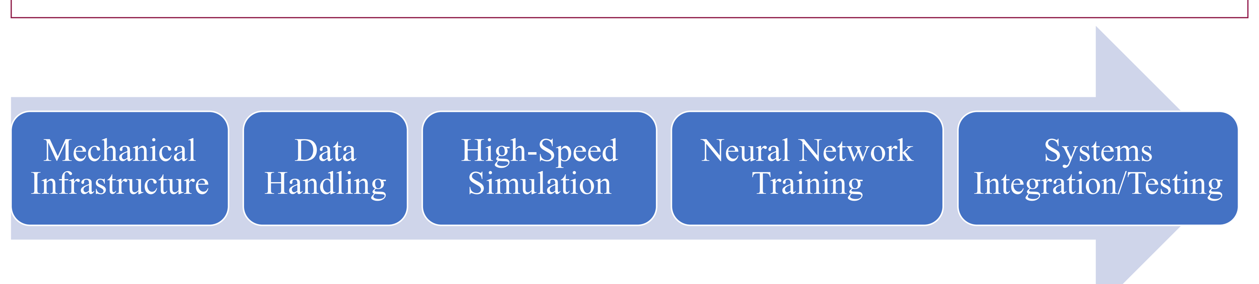
Mission/SOW

LANL requested NMSU to design and prototype a mechanism that integrates an event-based imaging and sensor-in-the-loop simulation methods to train a physically-informed neural network (PINN) that can identify, predict, and control non-linear systems.

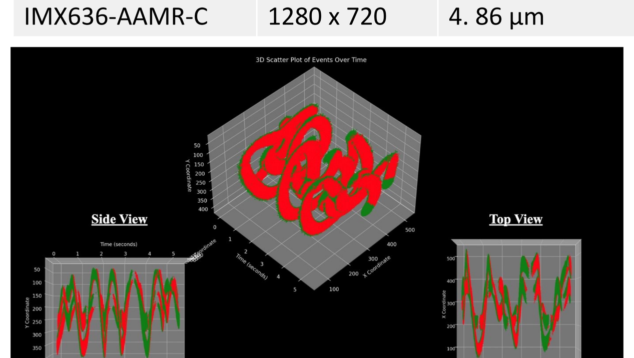
- Develop approach for identifying and controlling engineering systems via PINN.
- Use spike-based sensing to improve system.
- Test system using high-framerate monitor with event imaging hardware and optical anechoic chamber.
- Use PINN architecture to learn system dynamics and implement control actions.
- Test architecture on simulated pendulum systems.

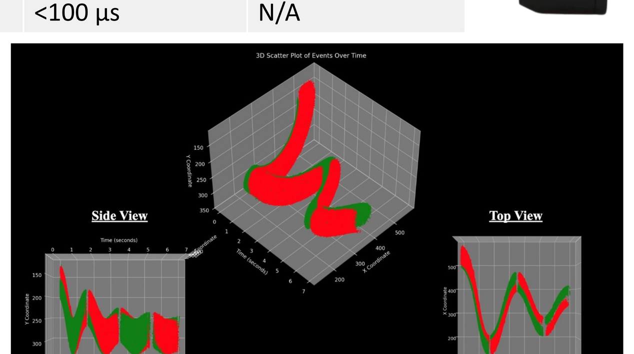


Research

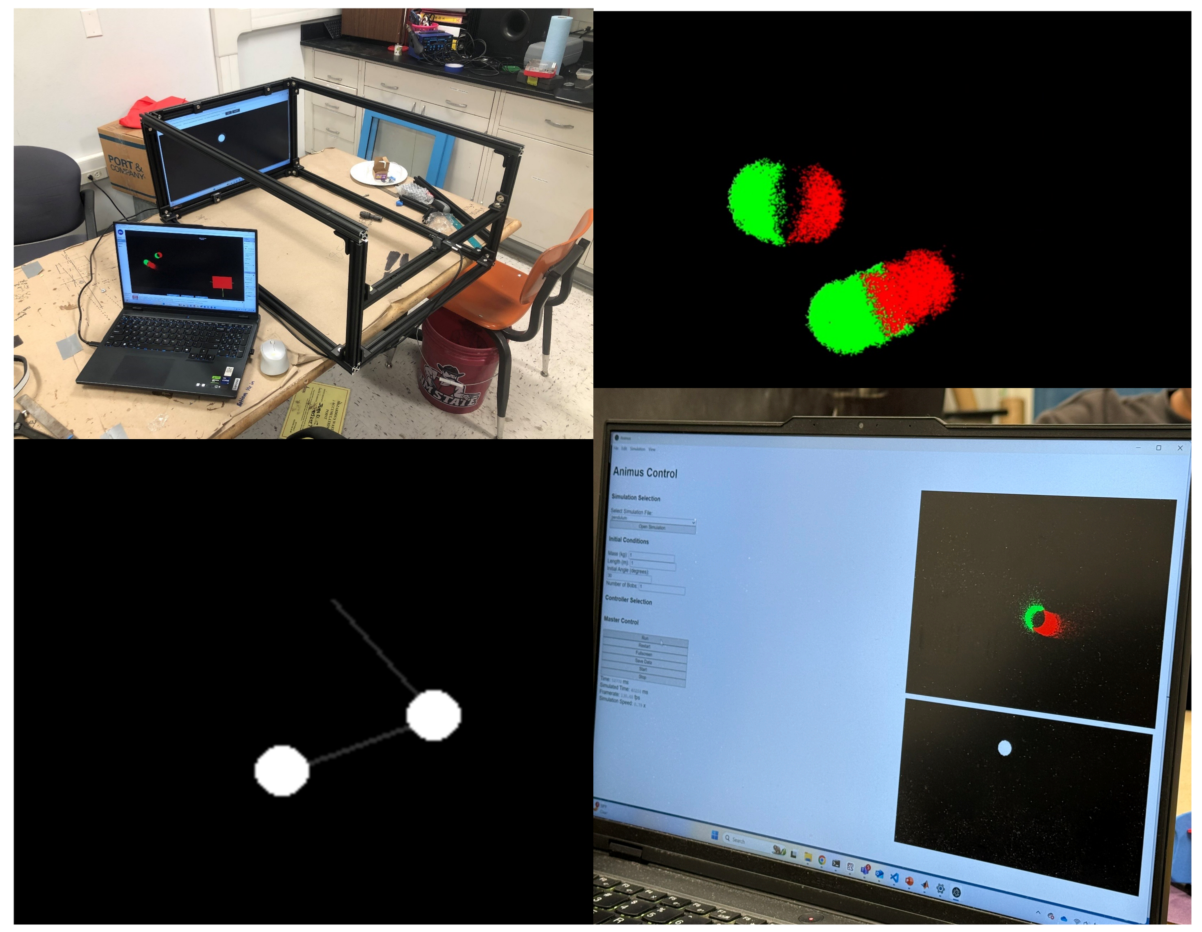
- Event imaging hardware capable of recording data based on ”events” rather than recorded frames.
- Pre-process data for use in PINN using singular value decomposition (SVD) and principal component analysis (PCA).
- Neural network based primarily on human biology in how sight can inform learning.
- Develop computer-based analog to rod cells in eye.
- Develop an approach to construct an anechoic chamber that allows the event camera to observe data in a clean environment.
- Create high-speed simulation environments capable of generating data at high temporal resolution to match the responsiveness of event-based sensors.
- Find low-latency programming languages/libraries.

Event Camera Model	Resolution	Pixel Pitch	Latency	Weight
DVXplorer	640 x 480	9 µm	<1 ms	100 g
DVXplorer Micro	640 x 480	9µm	<1 ms	16 g
DVXplorer Lite	320.x 240	18 µm	<1 ms	75 g
GENX320	320 x 320	6.3 µm	<150 µs	N/A
Triton2 EVS	640 x 512	4.86 µm	N/A	90 g
IMX636-AAMR-C	1280 x 720	4. 86 µm	<100 µs	N/A





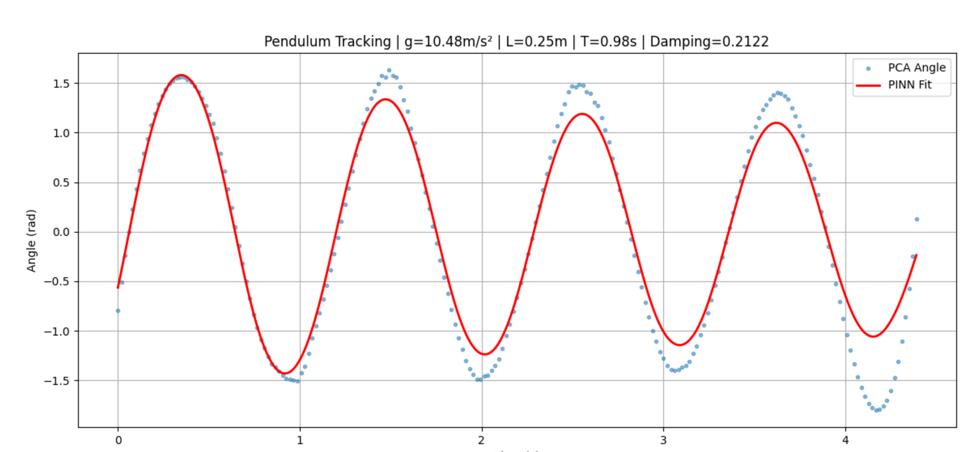
Final Design

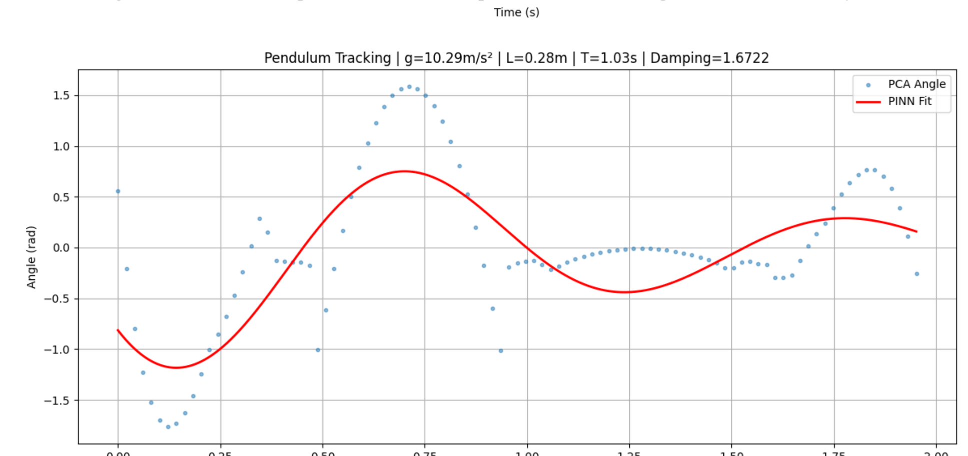


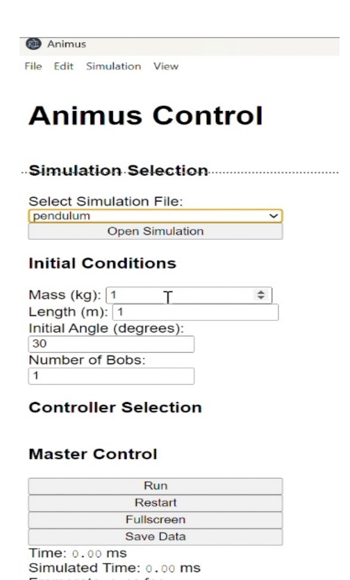
- Alienware 500-Hz Monitor was chosen for fast display of high-speed simulations.
- Monitor frame constructed from 80/20 aluminum, shrouded with light-resistant blackout fabric.
- DVXplorer Micro Event Camera was chosen for capture of simulation events for PINN training. Approach aligns with how human vision processes motion; rather than collecting continuous stream of images, only meaningful variations are recorded.
- Large amounts of collected data compressed using PCA to highlight dominant system behaviors.
- Simulation, data capture, and observation run synchronously utilizing JavaScript control panel.
- Collected data fed into PINN for training, identification of non-linear system dynamics.

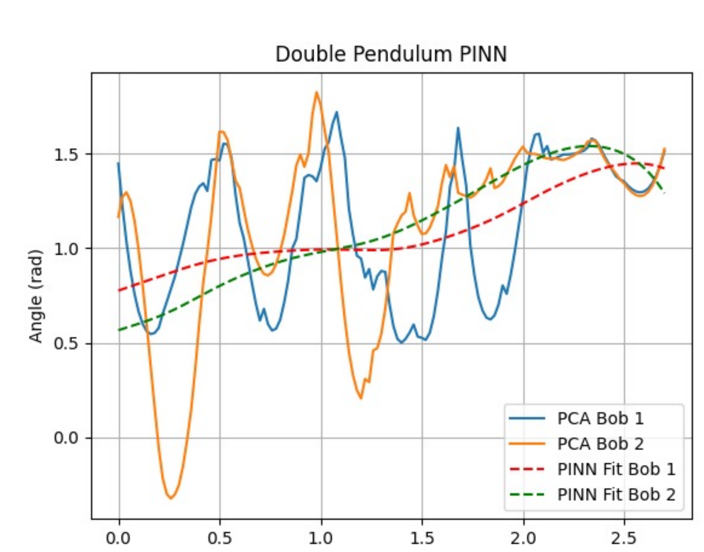
Results

With decent accuracy, the PINN can currently predict the motion of a single pendulum system. Further tuning is required for the modeling of systems with less ideality and higher degrees of freedom.



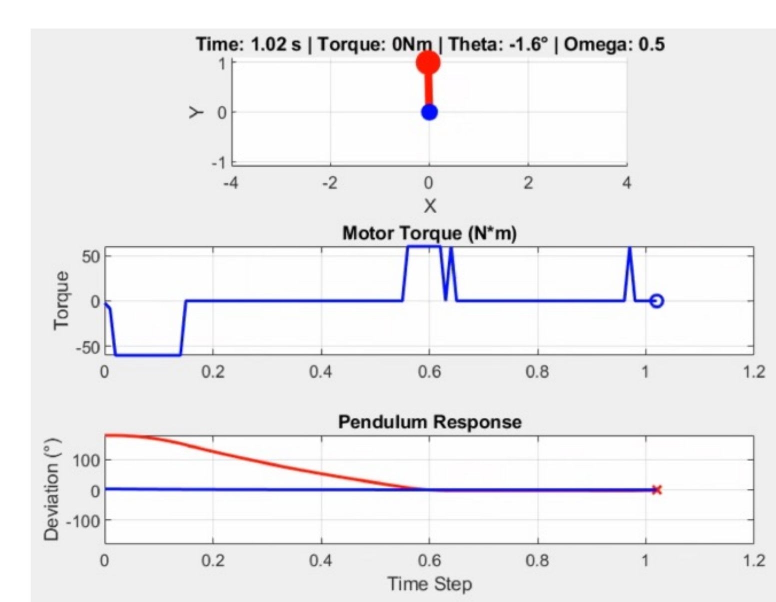


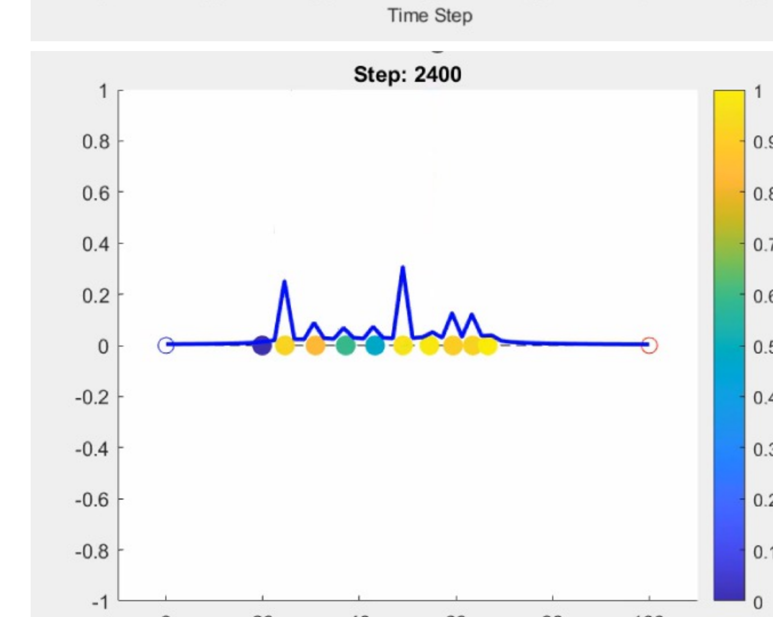




Improvements From Spike-Based Sensing

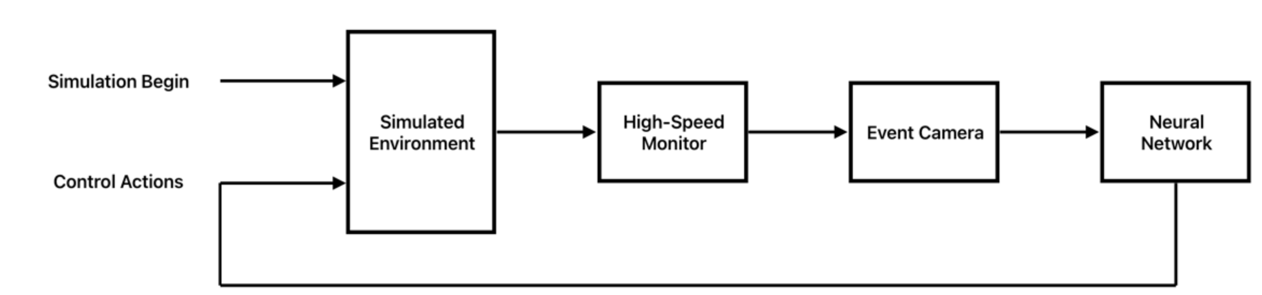
- Spike-based computing mimics biological neuron behavior by generating signals in response to environmental changes.
- System design draws inspiration from neuromorphic principles, creating a feedback loop similar to how biological systems perceive, process, and react to dynamic environments.
- Spike-based sensing methods provide high efficiency ideal for closed-loop control systems that rely on rapid feedback.

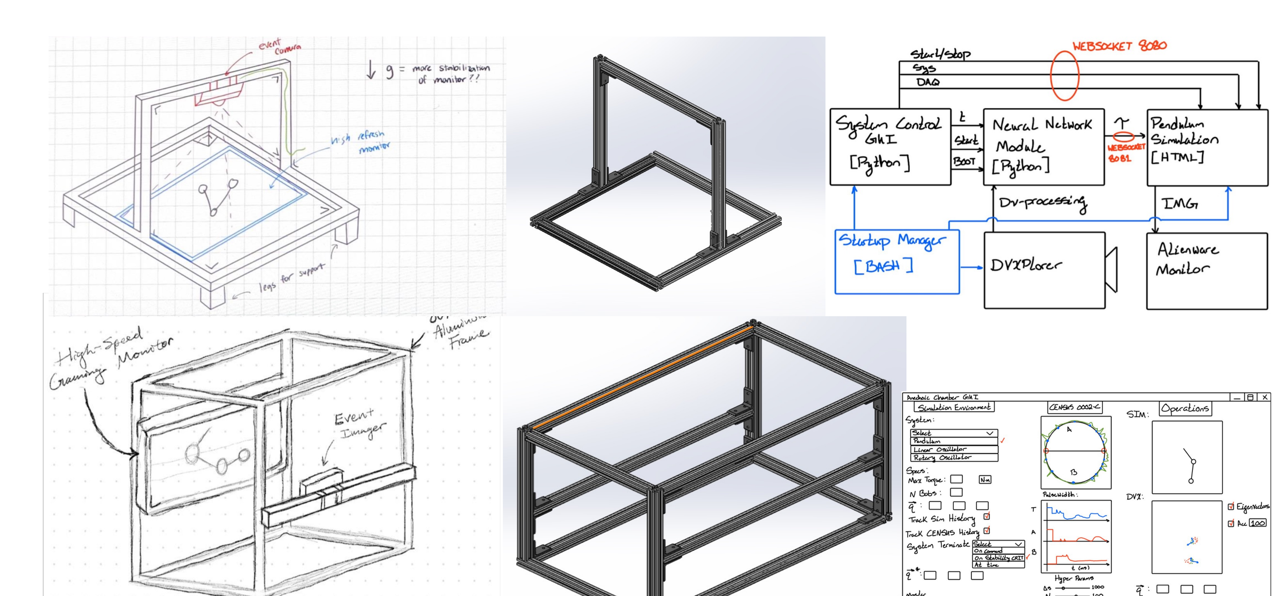




Concept Development

- Integrate simulation, event imaging, and neural network control for pendulum dynamics.
- Three key areas: pendulum system, observation system, and neural network.
- Stable environment crucial for event-based imaging.
- High-speed display critical for lifelike simulation.
- Enhance imaging contrast and reduce light exposure using dark backgrounds; “optical anechoic chamber.”
- Designed and evaluated frame concepts to securely position event camera and monitor.
- Compared frame materials, including 80/20 aluminum and 3D-printed mounts.
- Conducted preliminary software tests to integrate event camera data into simulations.
- Explored Principal Component Analysis to optimize neural network data processing.
- Evaluated multiple pendulum setups for simulations.
- Identified key hardware constraints and computational demands for real-time control.
- Plan to iteratively refine both the physical frame and software integration to enhance system accuracy.





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