PHI LAB

NEURAL INFORMATION PROCESSING SYSTEMS

Input-to-State Stable Coupled Oscillator Networks for Closed-form Model-based Control in Latent Space

Maximilian Stölzle and Cosimo Della Santina

TU Delft Delft University of Technology

EMERGE

Problem setting: Learning Latent-space Dynamics

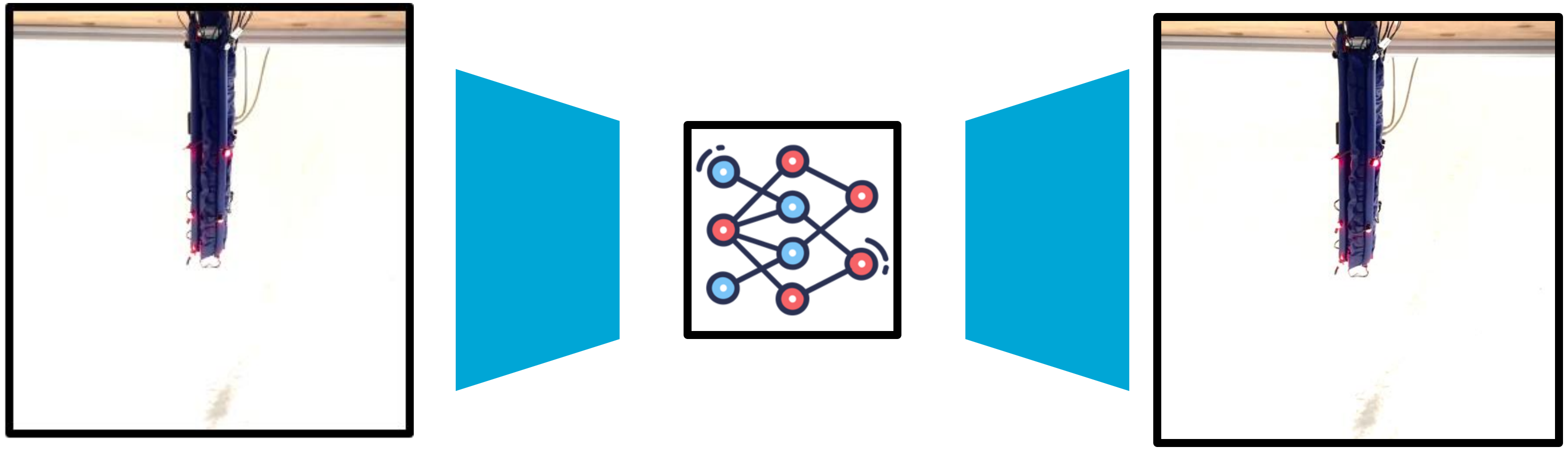
High-dimensional observation

Latent dynamics (e.g., MLP, RNN)

Future observations

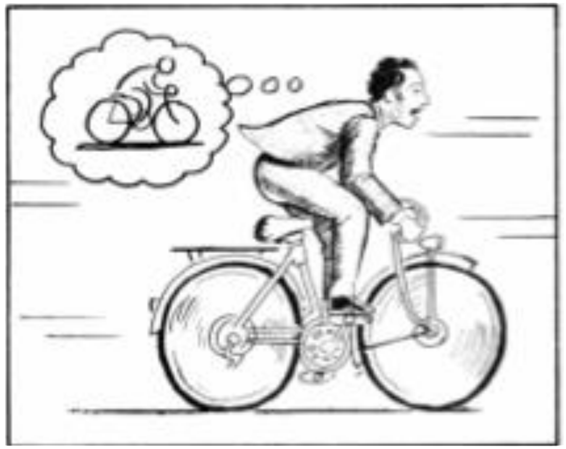
Encoder

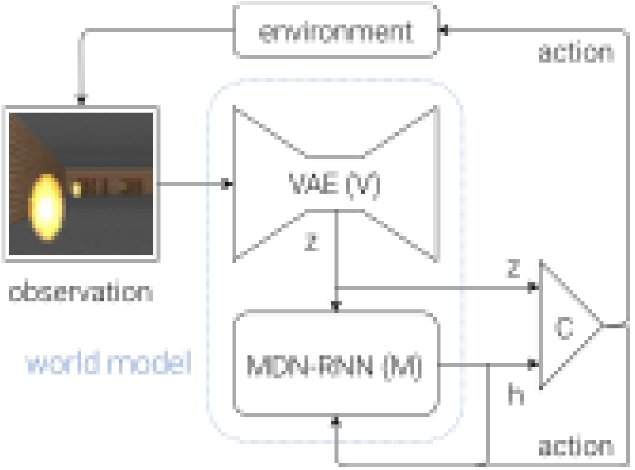
Decoder



Haggerty, D. A., Banks, M. J., Kamenar, E., Cao, A. B., Curtis, P. C., Mezić, I., & Hawkes, E. W. (2023). Control of soft robots with inertial dynamics. Science robotics, 8(81).

World models





Ha, D., & Schmidhuber, J. (2018). World models. arXiv preprint arXiv:1803.10122.

Limitations of Existing Latent-space Dynamic Models

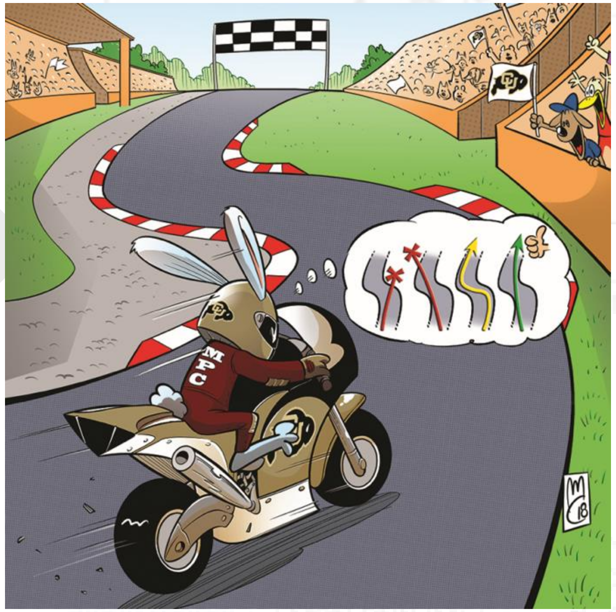
NEURAL INFORMATION PROCESSING SYSTEMS

❌ No (global) stability guarantees

❌ No interpretation as a mechanical system

❌ No closed-form control policy → only RL, MPC, etc.

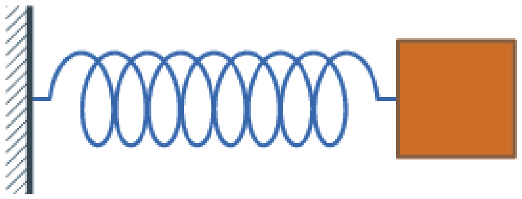
© Engineering Mechanics: by Knowledge flow



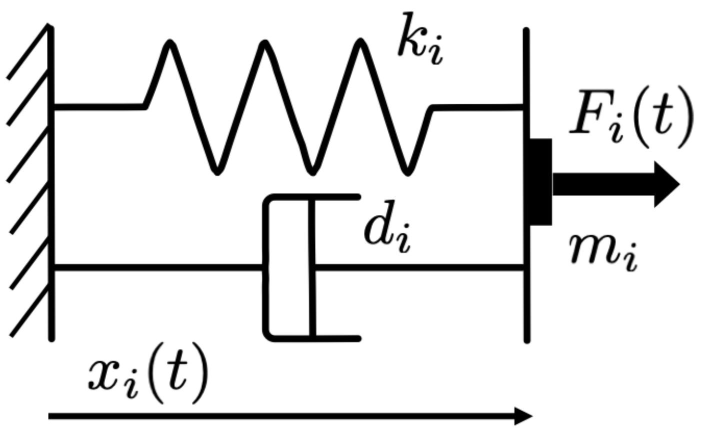
© Marco Nicotra

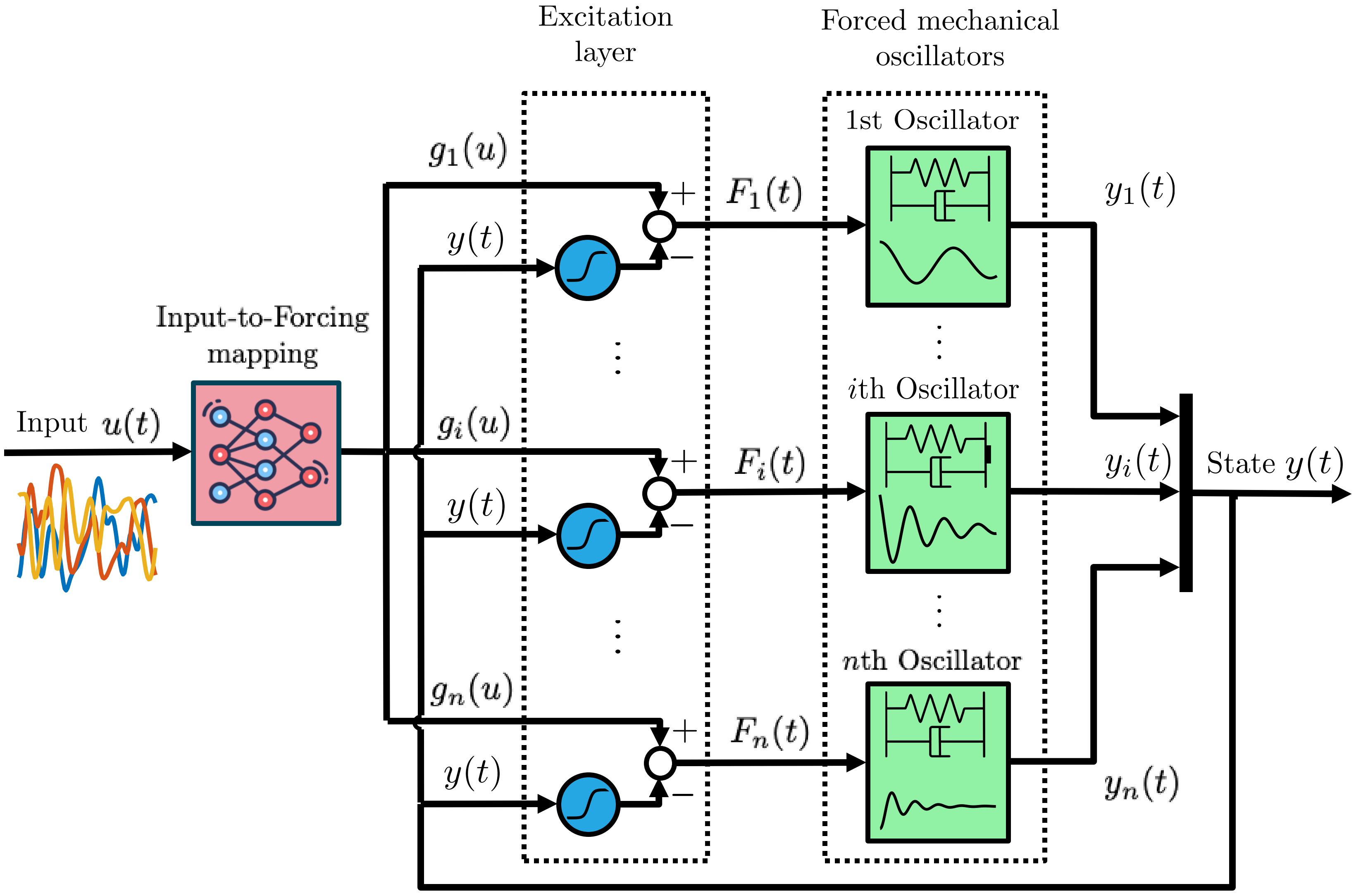
Coupling 1D Harmonic Oscillator Units via a Neuron-like Potential

Harmonic oscillator



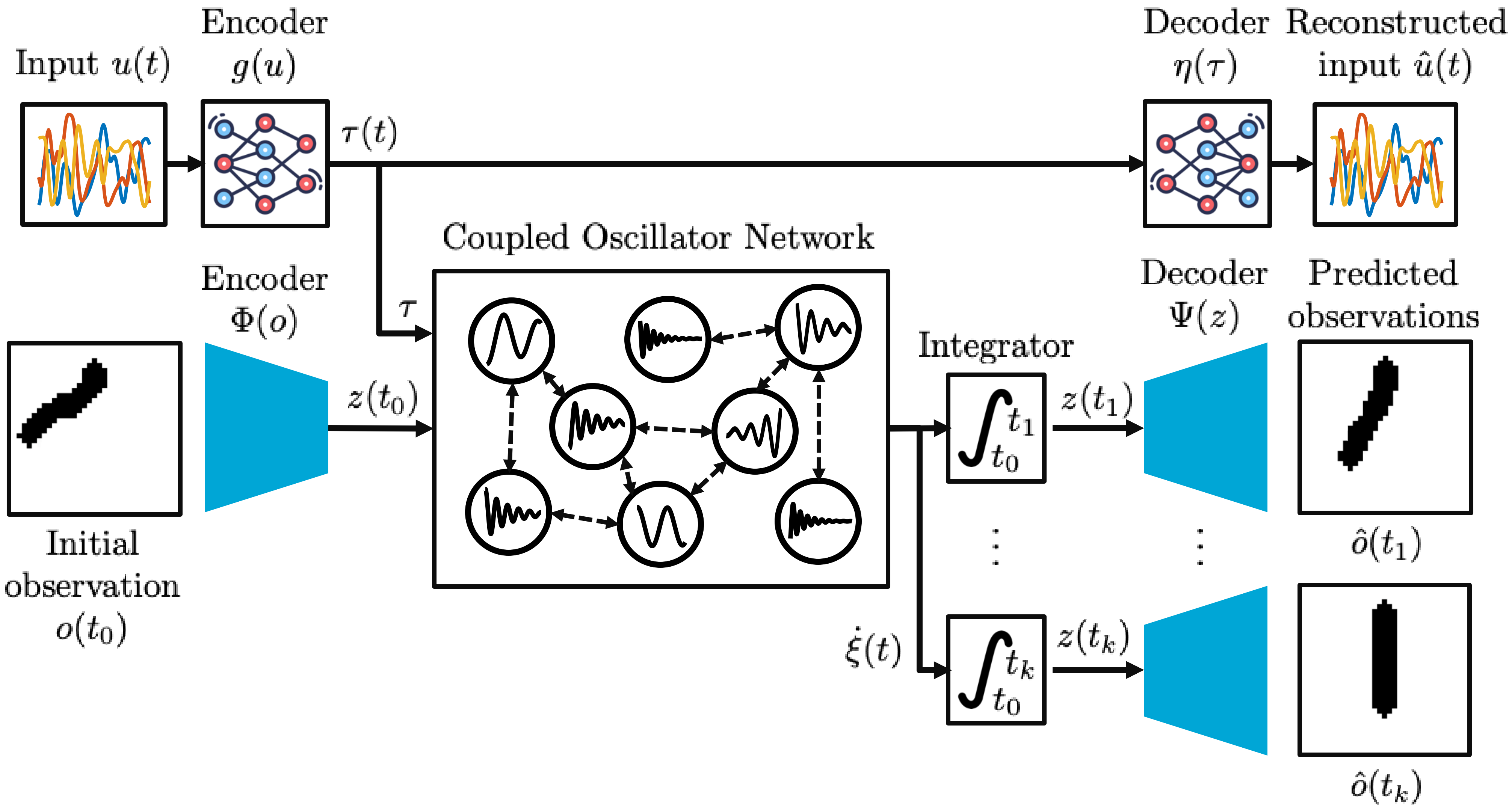
Parameters:





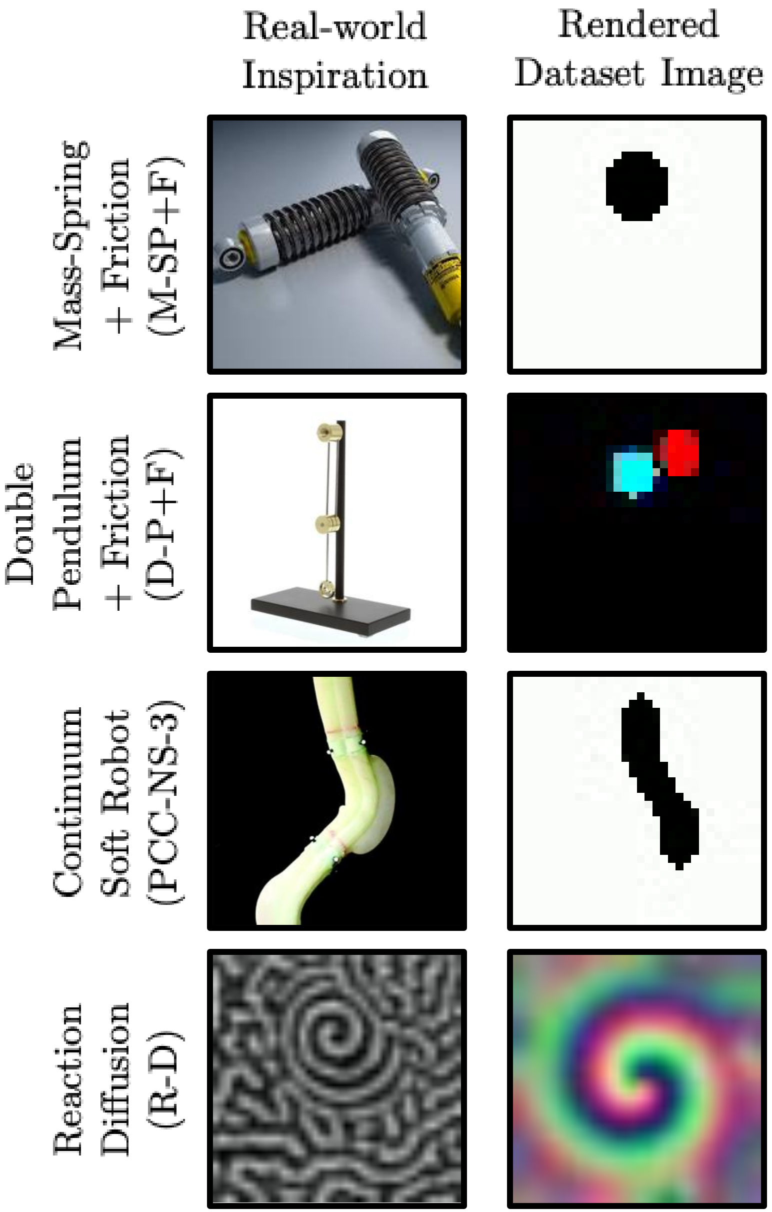
$$\ddot{x} + \kappa x + d\dot{x} + (K - \kappa)x + (D - d)\dot{x} + \tanh(Wx + b) = g(u)$$

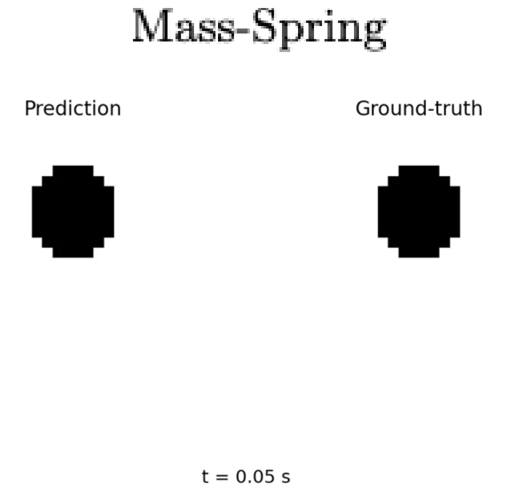
Learning Latent-space Dynamics with Coupled Oscillator Networks

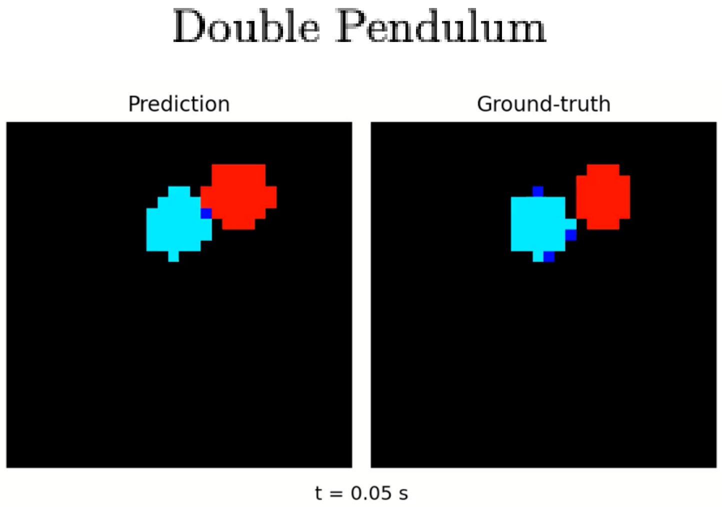


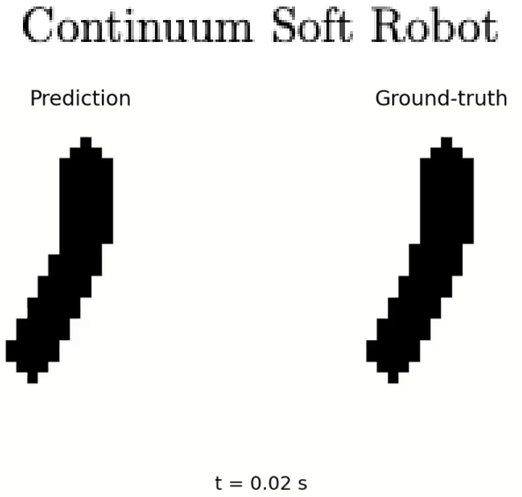
Results for Learning Latent Dynamics from Pixels

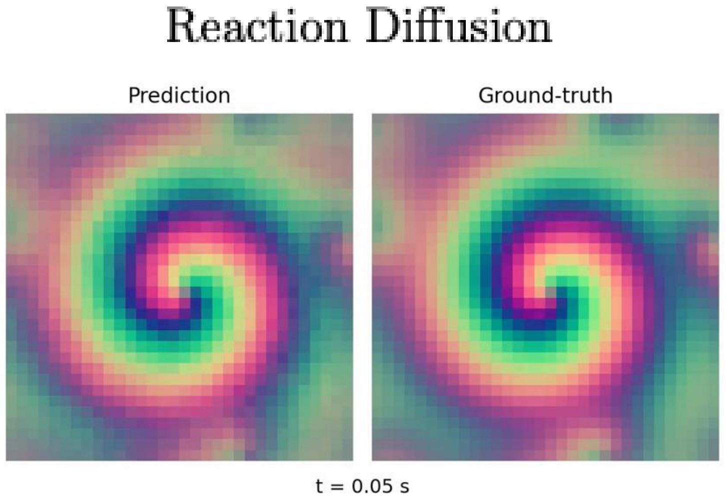
NEURAL INFORMATION PROCESSING SYSTEMS







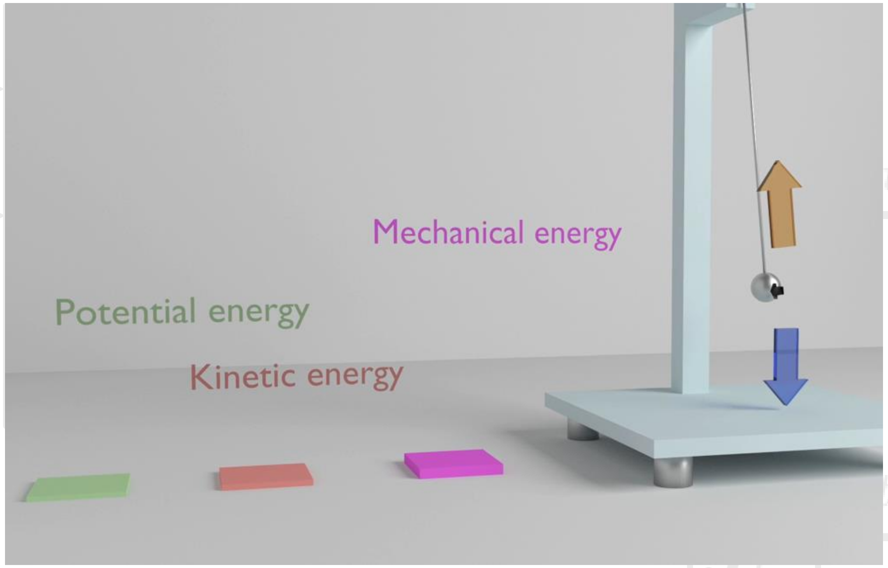




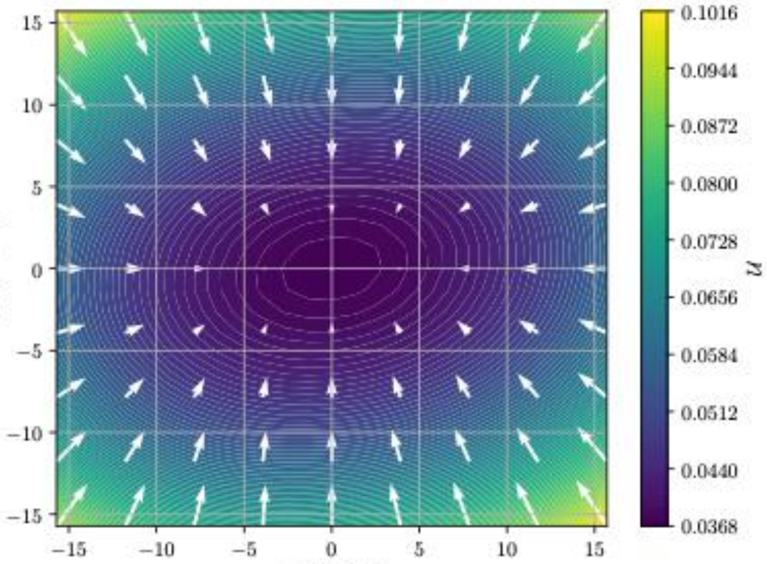
Priors to the Rescue:
Benefits of Coupled Oscillator Networks

- ✅ Latent dynamics have mechanical interpretation
- ✅ Shared stability characteristics between the original and latent system (GAS / ISS)
- ✅ Allows for closed-form model-based control in latent-space through potential shaping

Lee, R. H., Mulder, E. A., & Hopkins, J. B. (2022). Mechanical neural networks: Architected materials that learn behaviors. Science Robotics, 7(71).

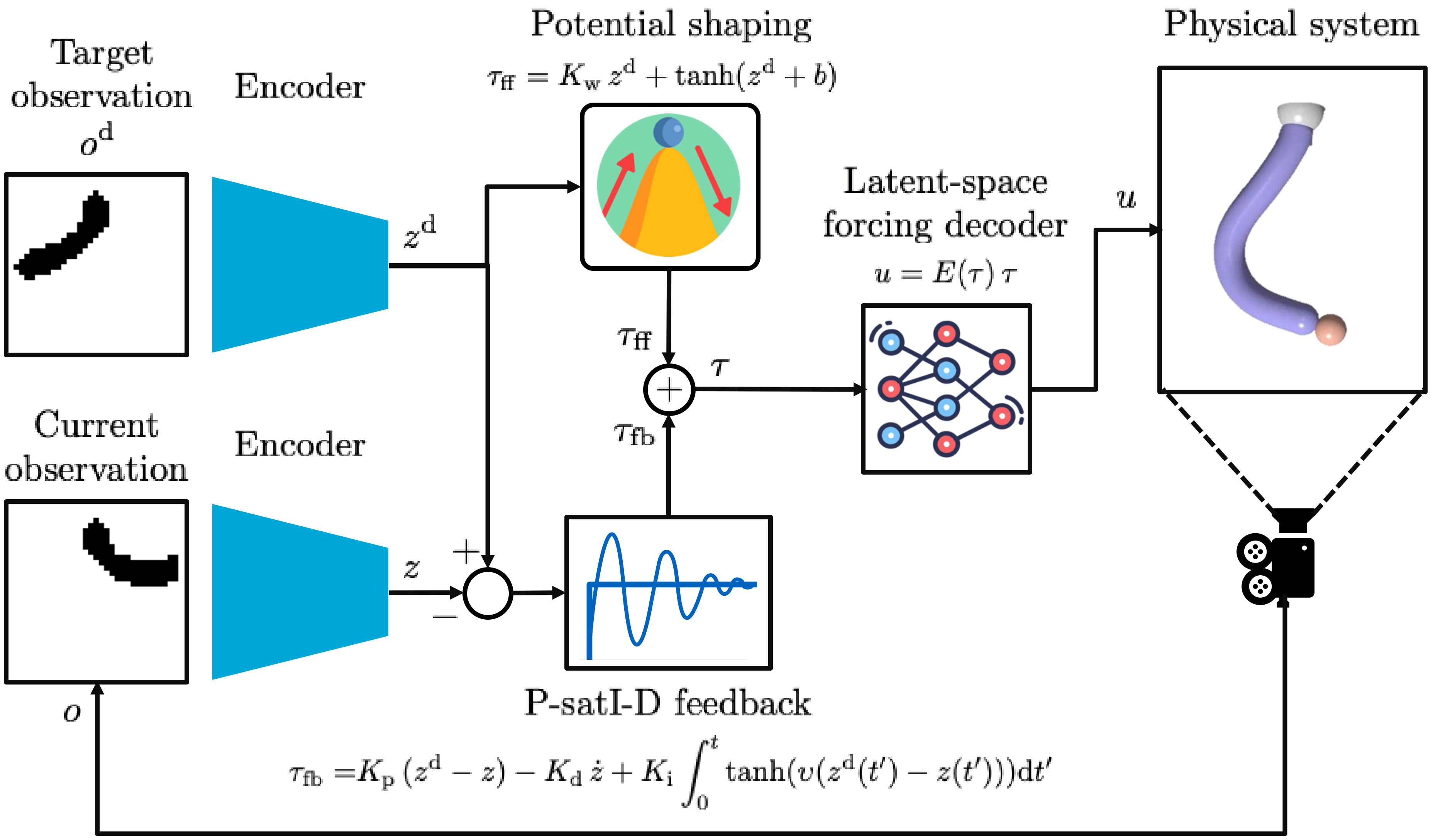


https://youtu.be/oWiuSp6qAPk

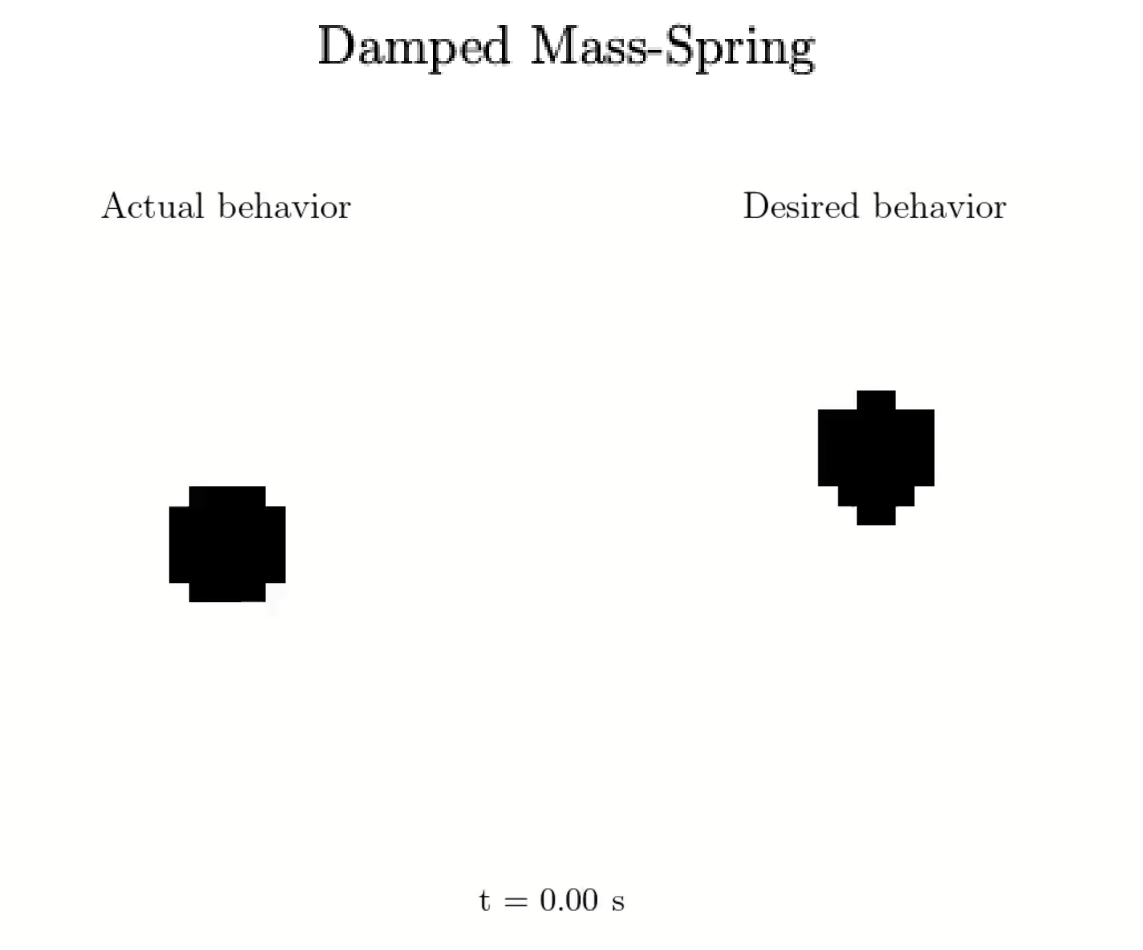


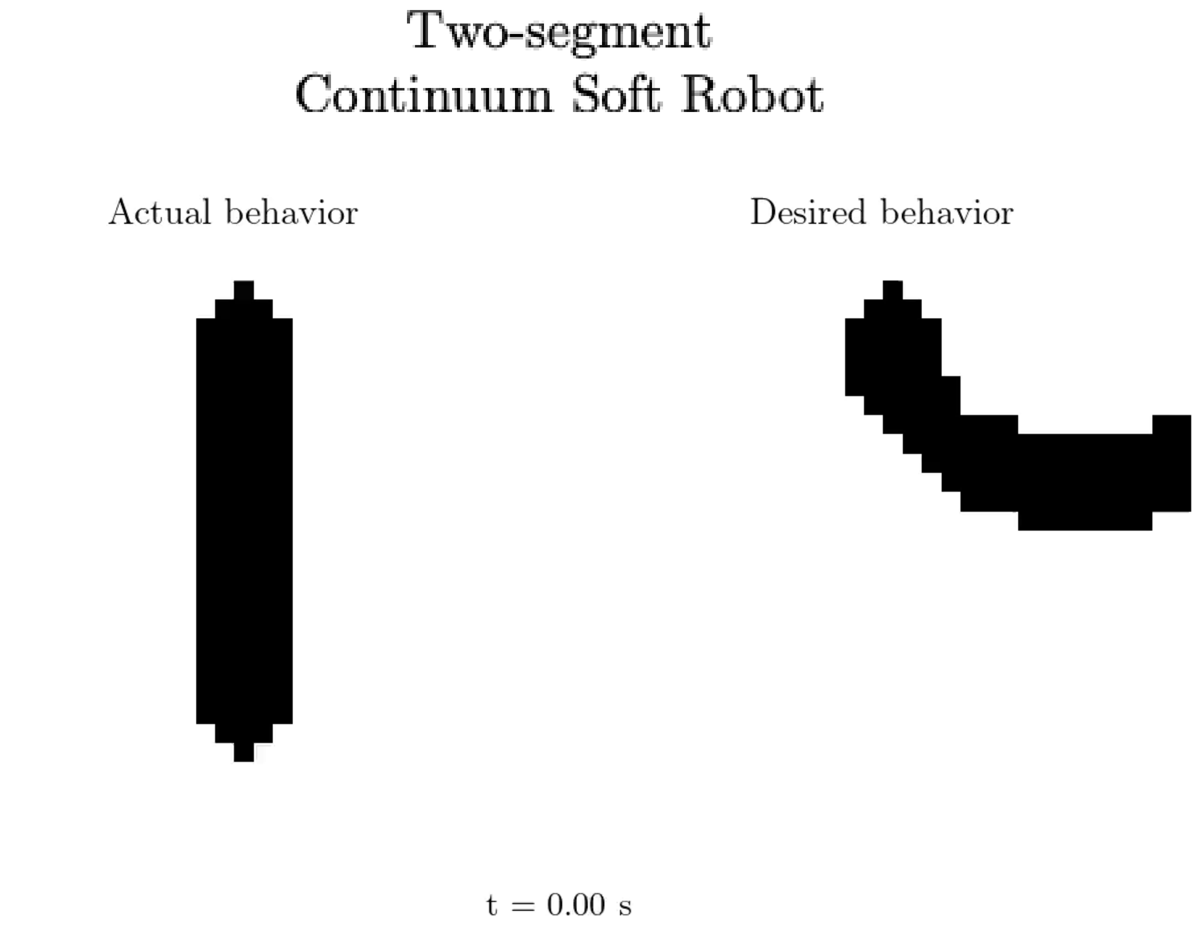
Exploiting Coupled Oscillator Networks for Control

NEURAL INFORMATION PROCESSING SYSTEMS



Results: Latent-space Control





Conclusion

NEURAL INFORMATION PROCESSING SYSTEMS

Summary:

- ☑ Proposed a new **oscillatory network** that is **Input-to-State (ISS) stable.**
- ☑ Leveraged the **Coupled Oscillator Networks** for learning latent dynamics from pixels.
- ☑ The **structure** of the latent dynamics can be exploited for **stability analysis** & **model-based control.**
- ☑ **Priors**: **shared characteristics** between **full- and reduced-order system**
  - Both systems are **mechanical** with **energy-like expressions.**
  - Both systems exhibit a **single, isolated equilibrium**.
  - Both systems **share stability guarantees**: Global Asymptotic Stability (GAS) & Input-to-State Stability (ISS).