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Hybrid Physics-Informed Neural Network Inverse Hysteresis Compensation for Precision Piezoelectric Positioning Systems

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INTRODUCTION & AIM

Piezoelectric actuators enable high-precision positioning in applications such as semiconductor manufacturing, microscopy, and robotics; however, their performance is limited by hysteresis, a nonlinear and history-dependent effect that introduces 10–15% positioning error . Existing compensation methods including PID control, analytical inverse models, and purely data-driven approaches often lack robustness and generalization under varying conditions. This work proposes a hybrid hysteresis compensation method that combines analytical inverse modeling with a neural network–based residual compensation to improve tracking accuracy, robustness, and generalization.

METHOD

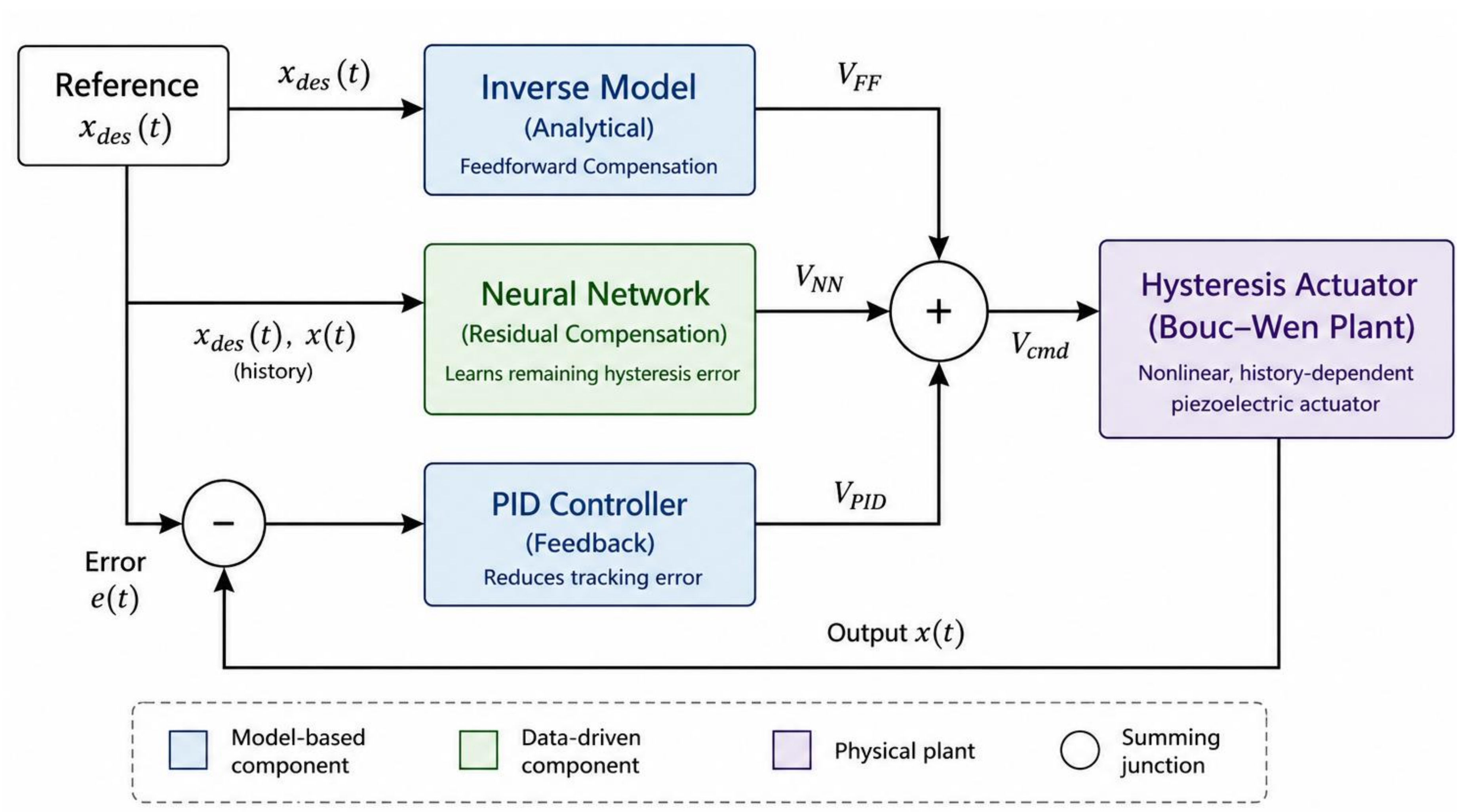

Figure 1: Hybrid feedforward–feedback control architecture combining analytical inverse modeling, neural network–based residual compensation, and PID feedback for hysteresis compensation in piezoelectric actuators.

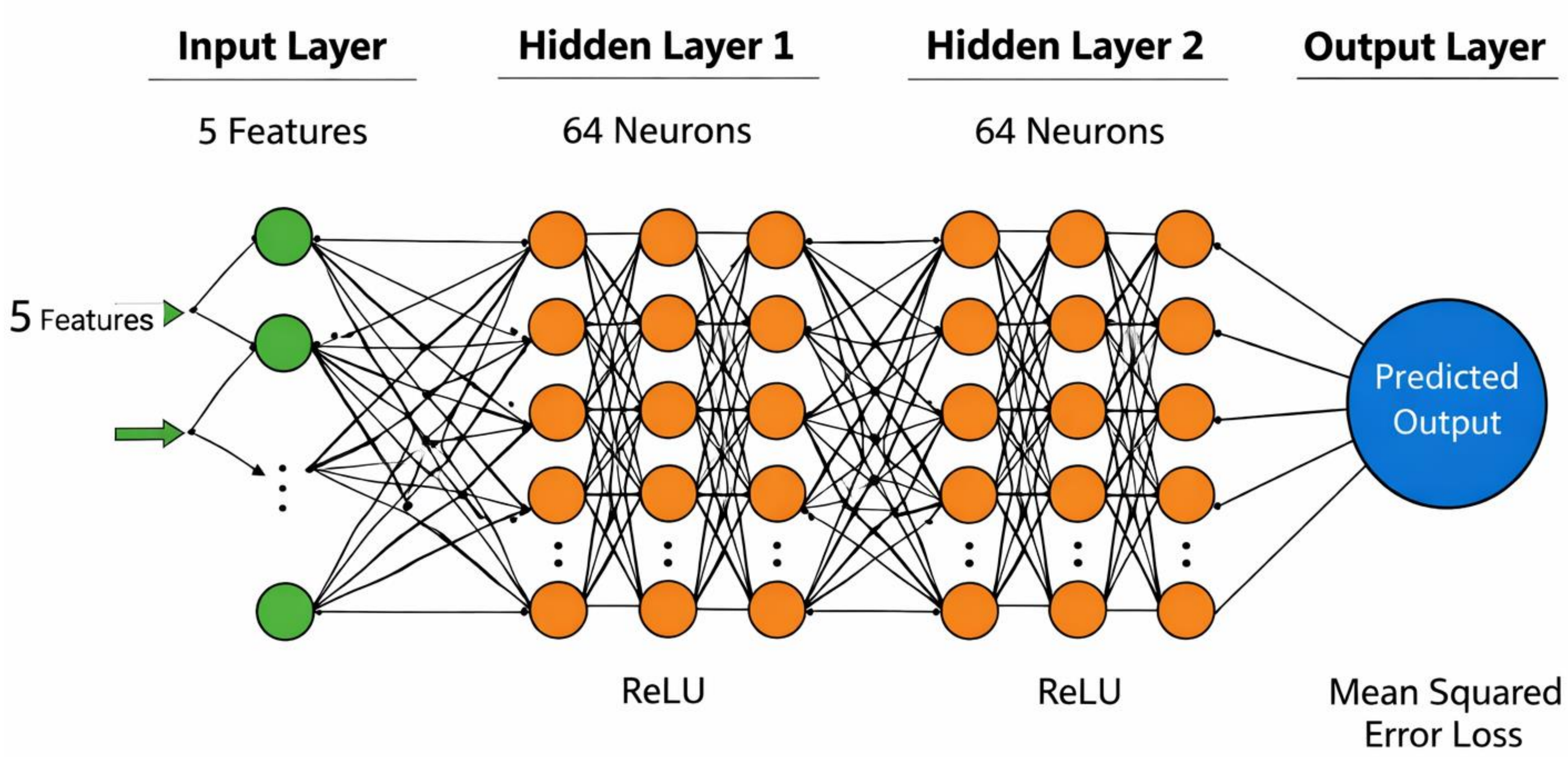

Figure 2: Feedforward neural network architecture used for residual hysteresis compensation, learning the discrepancy between the analytical inverse model and the actuator response to improve tracking accuracy and robustness in the hybrid control framework.

RESULTS & DISCUSSION

Frequency-Domain Performance (1–10 Hz):

- Inverse + PID controller reduces RMS tracking error
- Hybrid controller maintains low RMS errors.

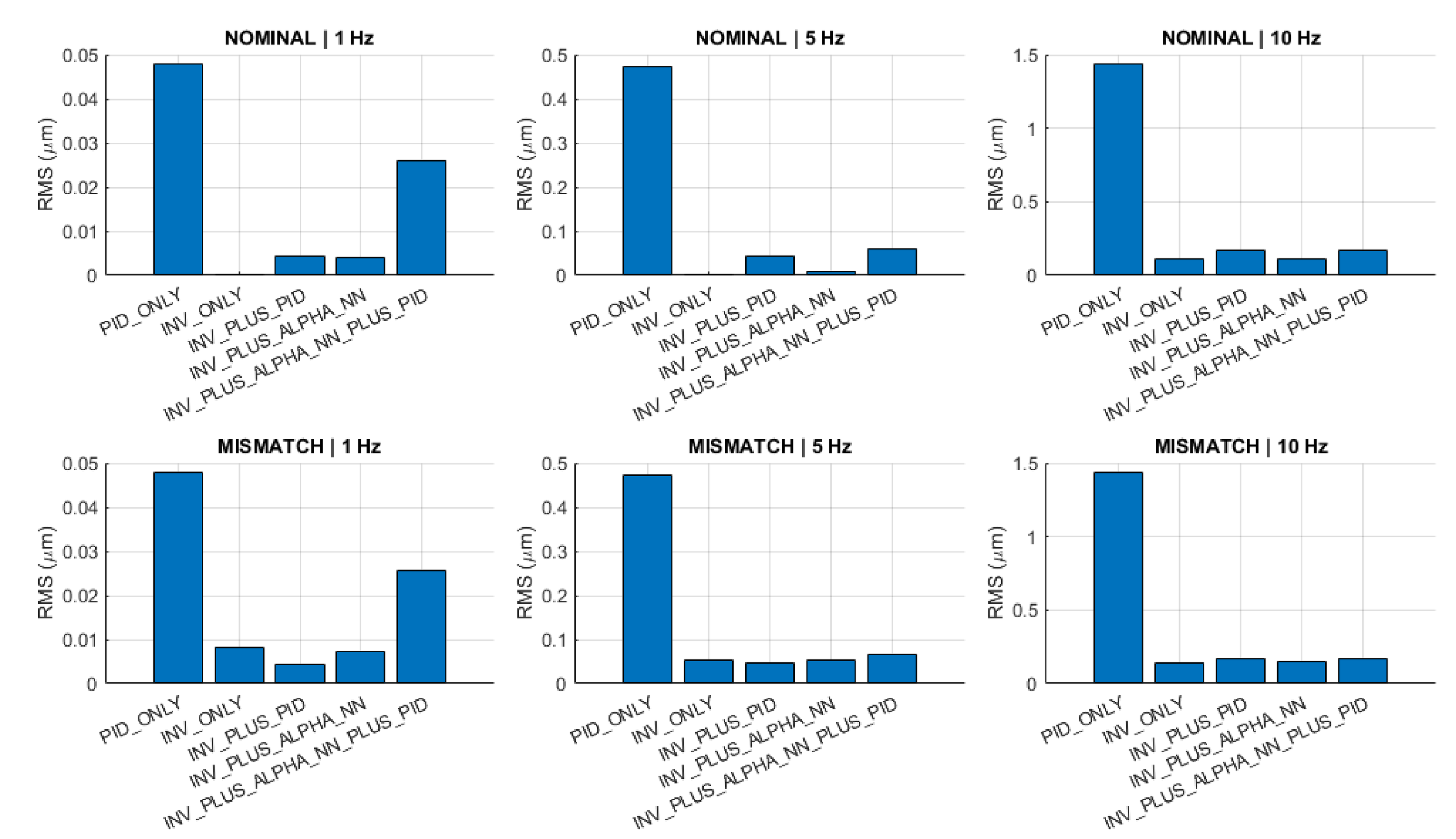

Figure 3: Feedforward control reduces RMS error by 88–91% vs. PID across 1–10 Hz. Hybrid variant adds robustness; analytical inverse drives performance.

Generalization to Unseen Frequencies:

- Performance degradation remains <10%
- Degradation increases at 7–9 Hz near the upper bound of the quasi-static regime

Freq.	Inv-Only	Hybrid (NN)	Degradation
2 Hz	0.274 µm	0.282 µm	**2.9%**
4 Hz	0.149 µm	0.157 µm	**5.0%**
6 Hz	0.127 µm	0.139 µm	**9.5%**
7 Hz	0.123 µm	0.139 µm	**12.7%**
9 Hz	0.119 µm	0.143 µm	**19.8%**

CONCLUSION

The proposed hybrid approach, combining analytical inverse modeling with neural network–based residual learning, significantly improves tracking accuracy in piezoelectric positioning systems. It achieves substantial error reduction across the 1–10 Hz range while maintaining robustness under model mismatch, demonstrating the effectiveness of integrating physics-based and data-driven methods for high-precision control.

FUTURE WORK / REFERENCES

Future work: Augment NN inputs beyond [u_inv, u̇_inv] for better dynamic regime conditioning

- Sabarianand D., et al. Control strategies for hysteresis compensation. Mechanical Systems and Signal Processing, 2020.
- Bahiuddin I., et al. Hybrid residual compensation neural networks. Results in Engineering, 2025.