A Physics-Informed Neural Network for the Calibration of Electromagnetic Navigation Systems

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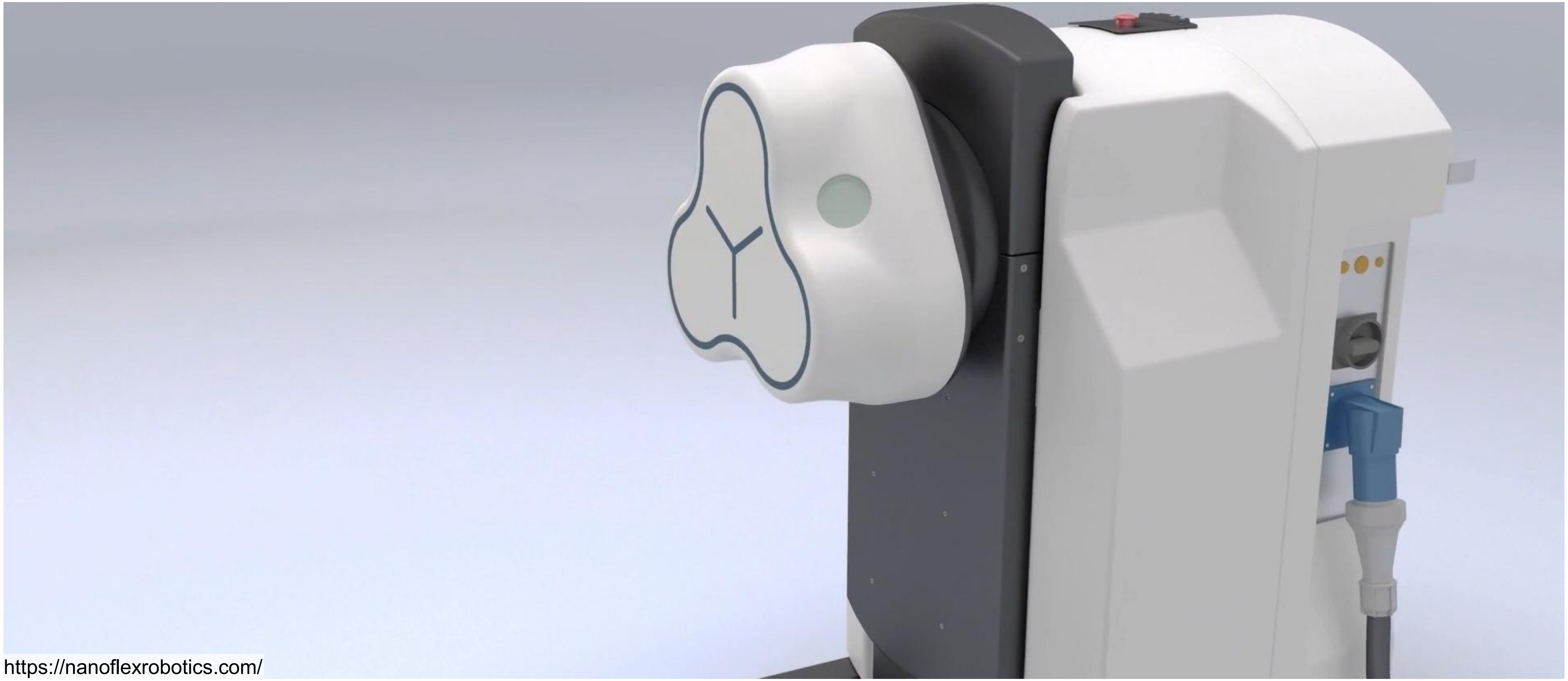
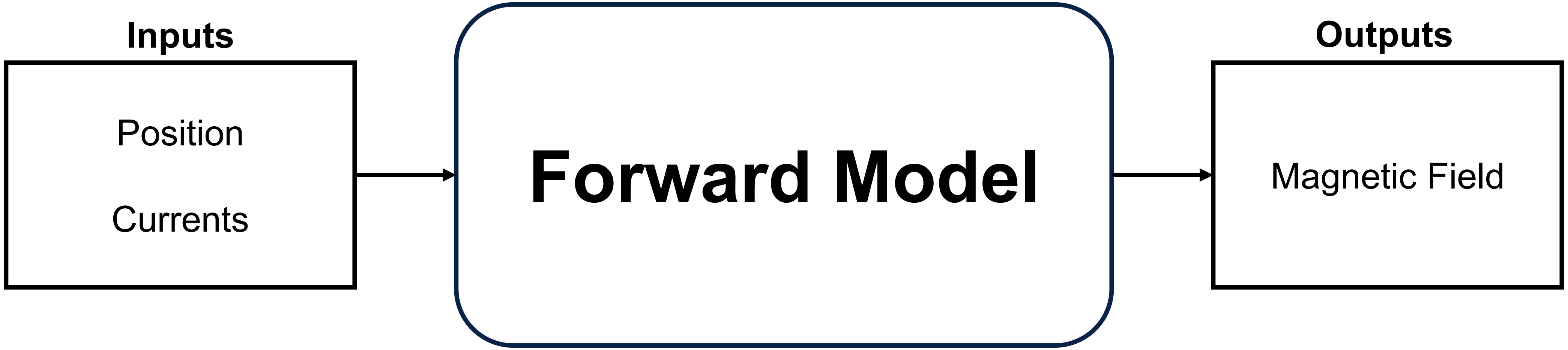
Electromagnetic Navigation Systems

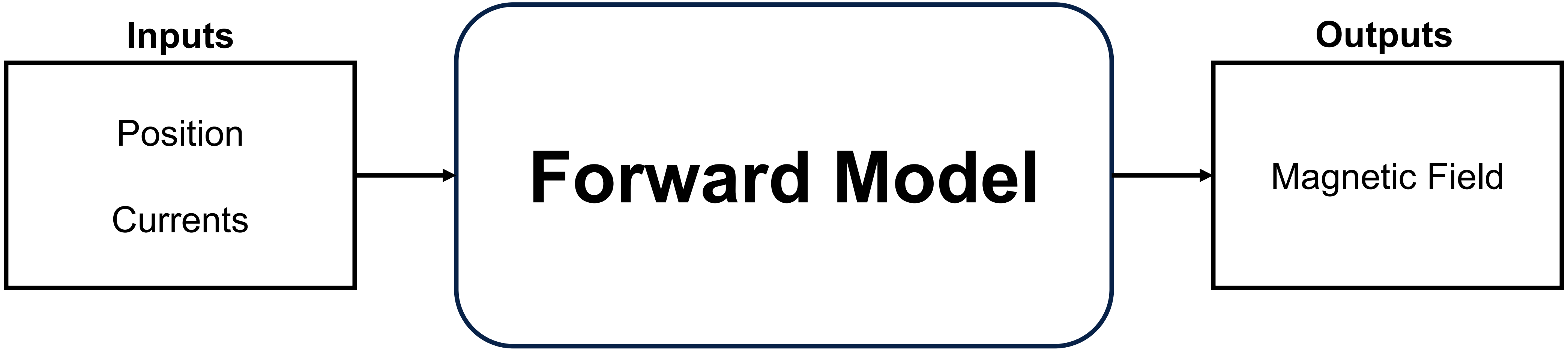

https://nanoflexrobotics.com/

- Used to navigate Microrobots & Surgical Tools
- Precise Torque & Force Control requires Field and Gradient models

Calibration



Calibration

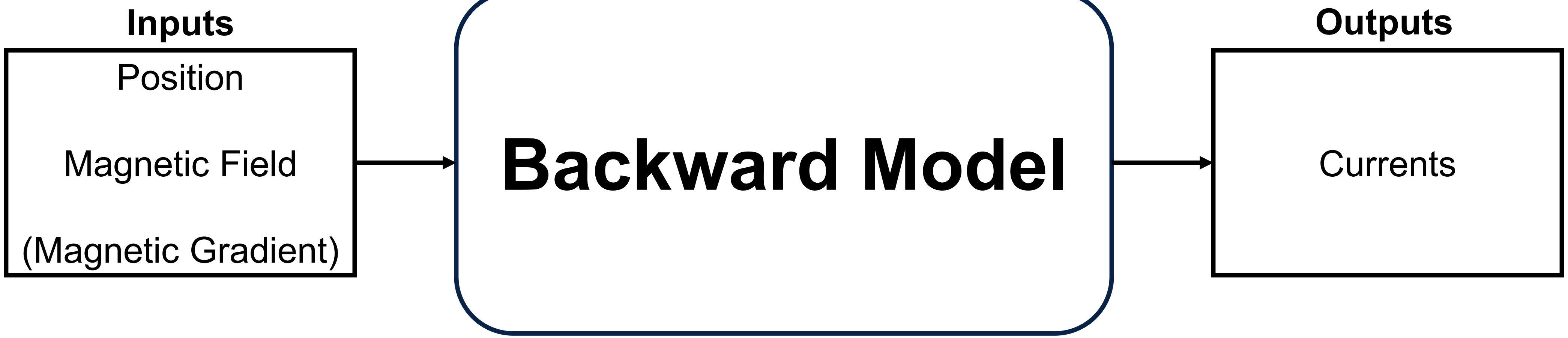


- **Additional Output:**
  Analytical derivation of magnetic gradient

- **Dataset:**
  Forward Model is fitted to a system with dataset

Calibration

Calibration



- **Physics Consistency:**
  Inverse of the fitted Forward Model

- **Control:**
  Can be used for control tasks

Existing Methods

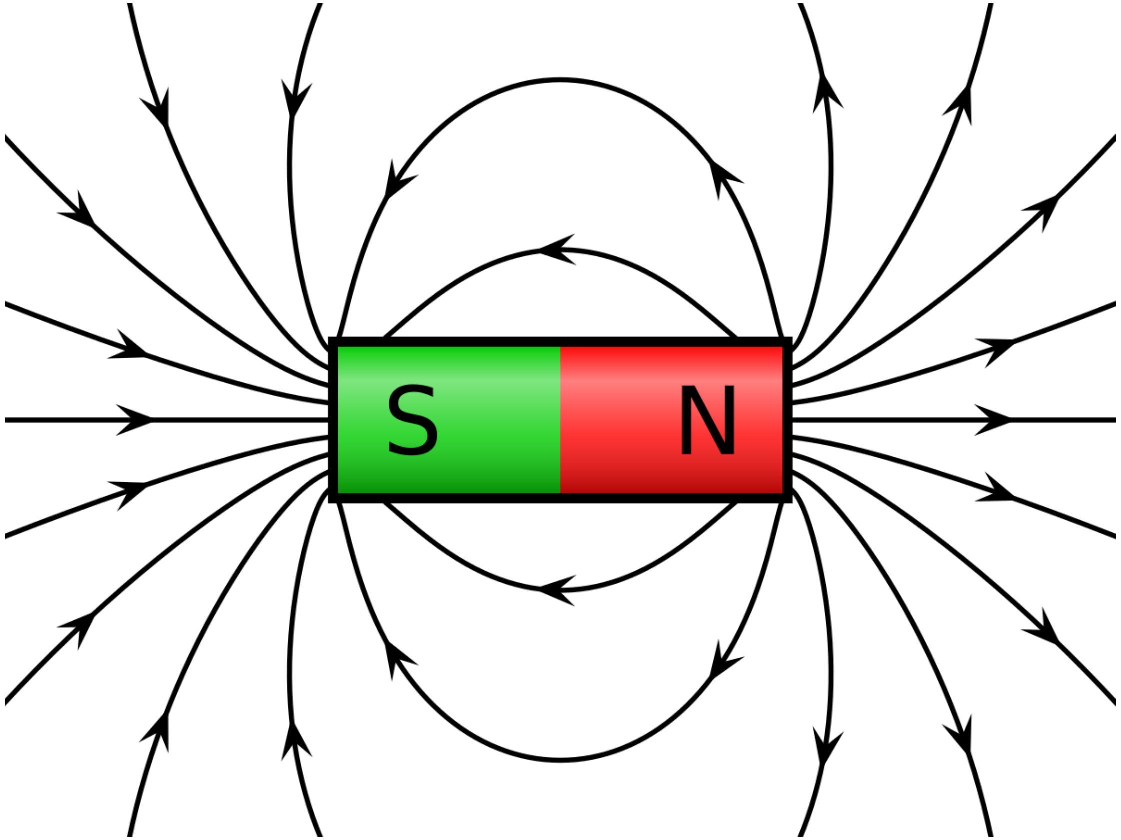
Classical Methods

Multipole Electromagnet Model (MPEM) [1]

Fails under Magnetic Saturation

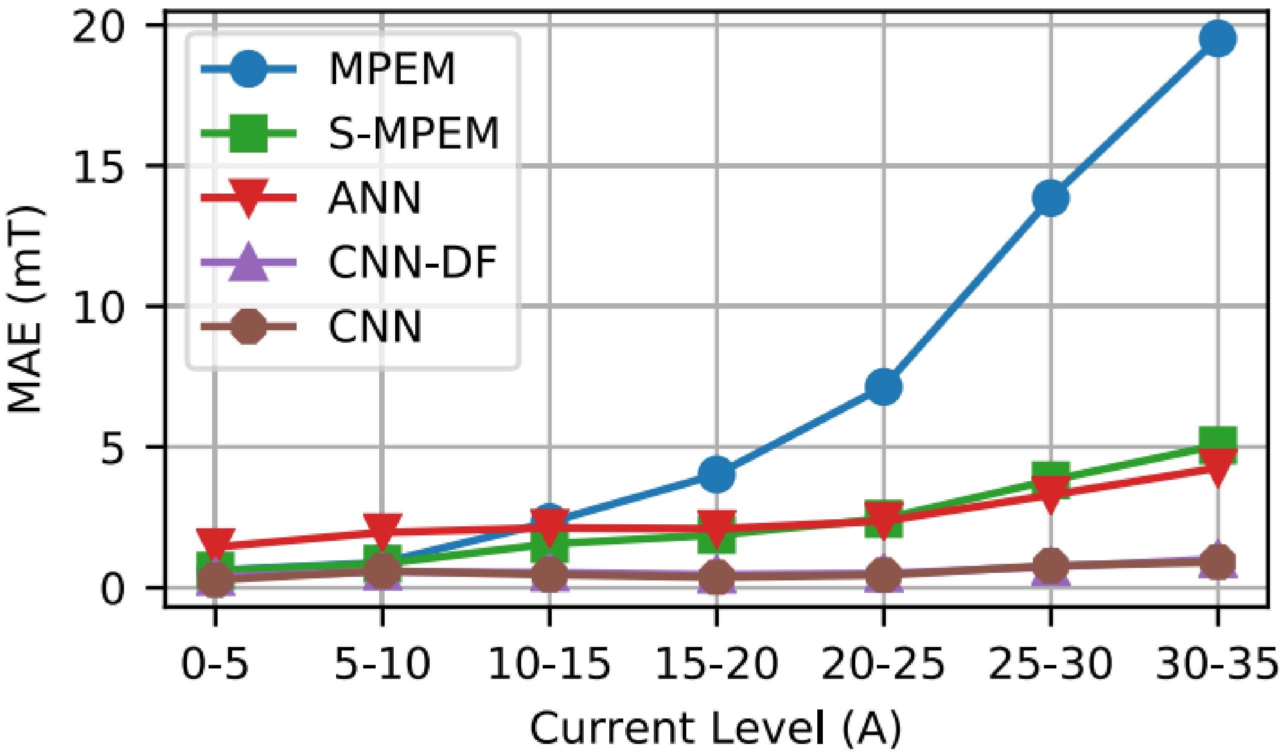
Guaranteed Maxwell consistency

$\nabla \cdot B = 0$ and $\nabla \times B = 0$



[1] Petruska, Andrew J., et al. "Model-based calibration for magnetic manipulation." IEEE Transactions on Magnetics 53.7 (2017): 1-6.

Existing Methods



Machine Learning Methods

Artificial Neural Network (ANN) [2]

Convolutional Neural Network (CNN) [2]

✓ Models Nonlinearity

✗ Violates Maxwell Equations

[2]Charreyron, Samuel L., et al. "Modeling electromagnetic navigation systems." IEEE Transactions on Robotics 37.4 (2021): 1009-1021.

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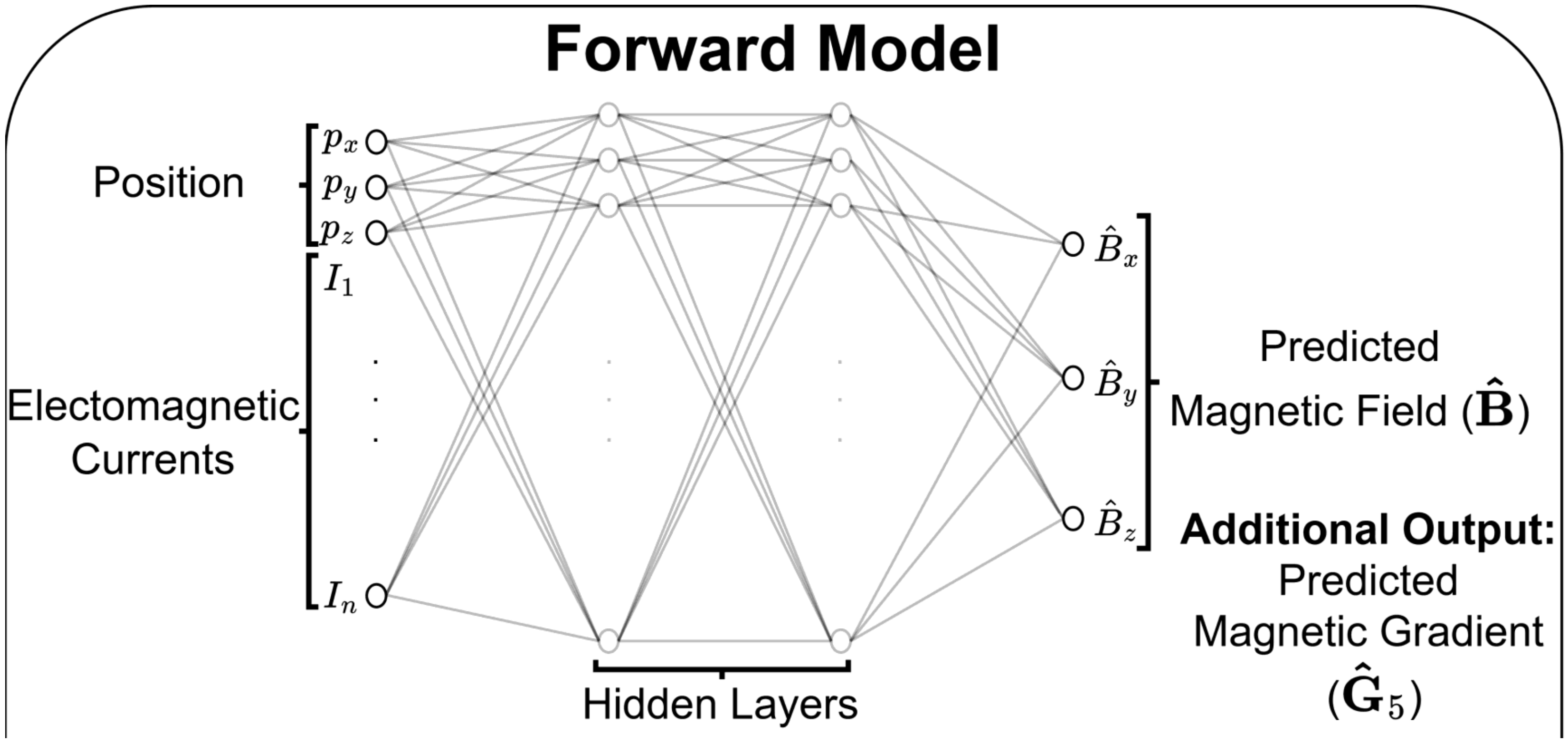
Approach – Forward Model



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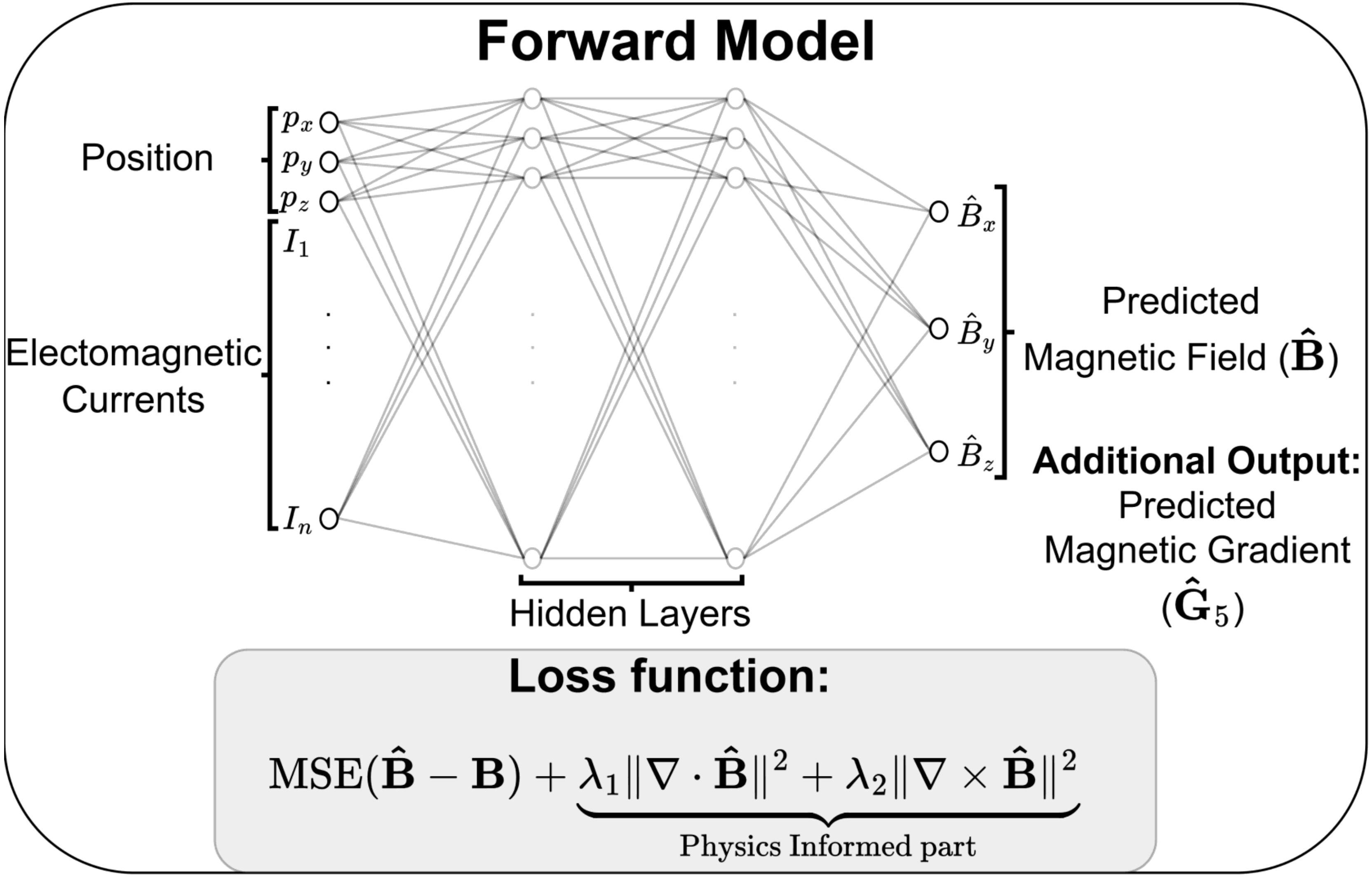
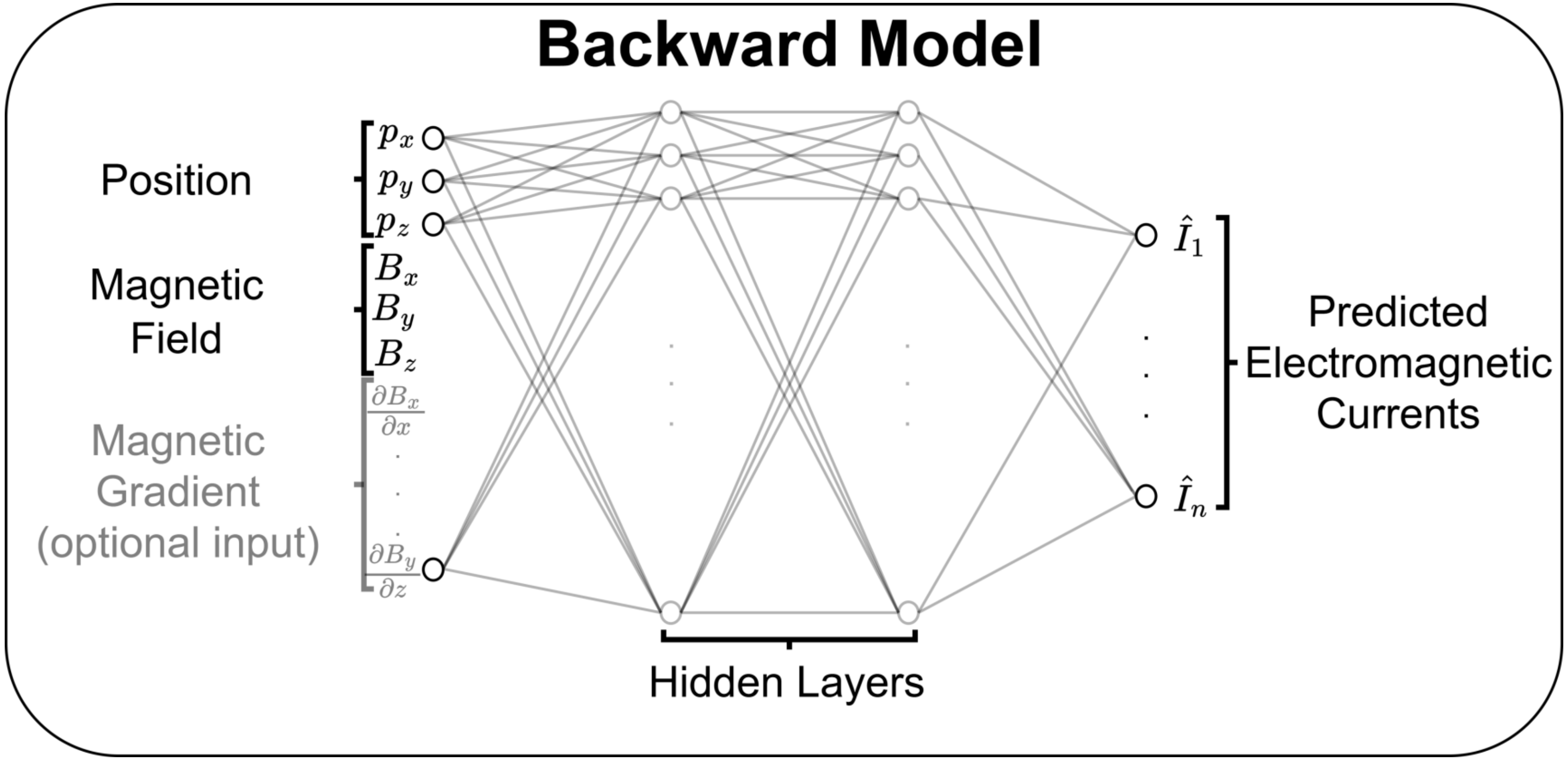


Approach – Backward Model



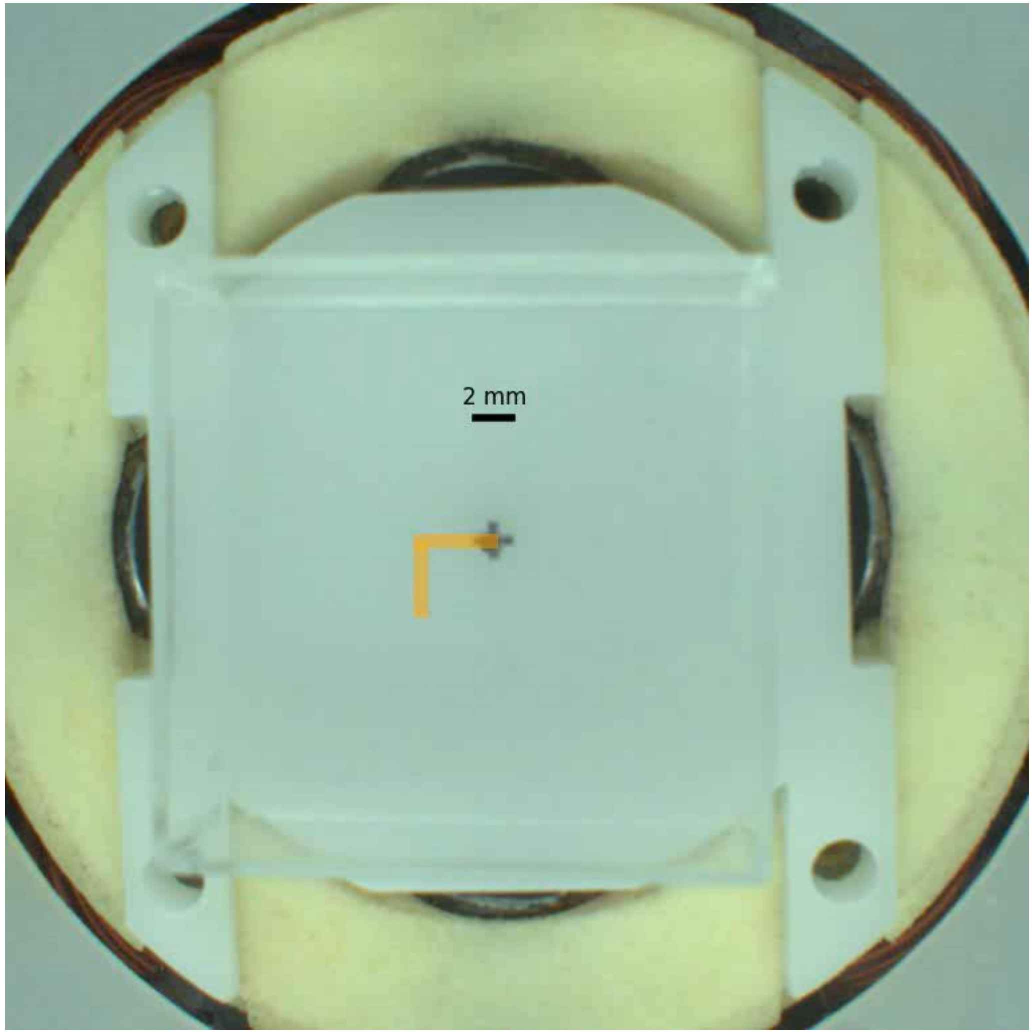
Without Magnetic Gradient: **Unsupervised Learning**

With Magnetic Gradient: **Supervised Learning**

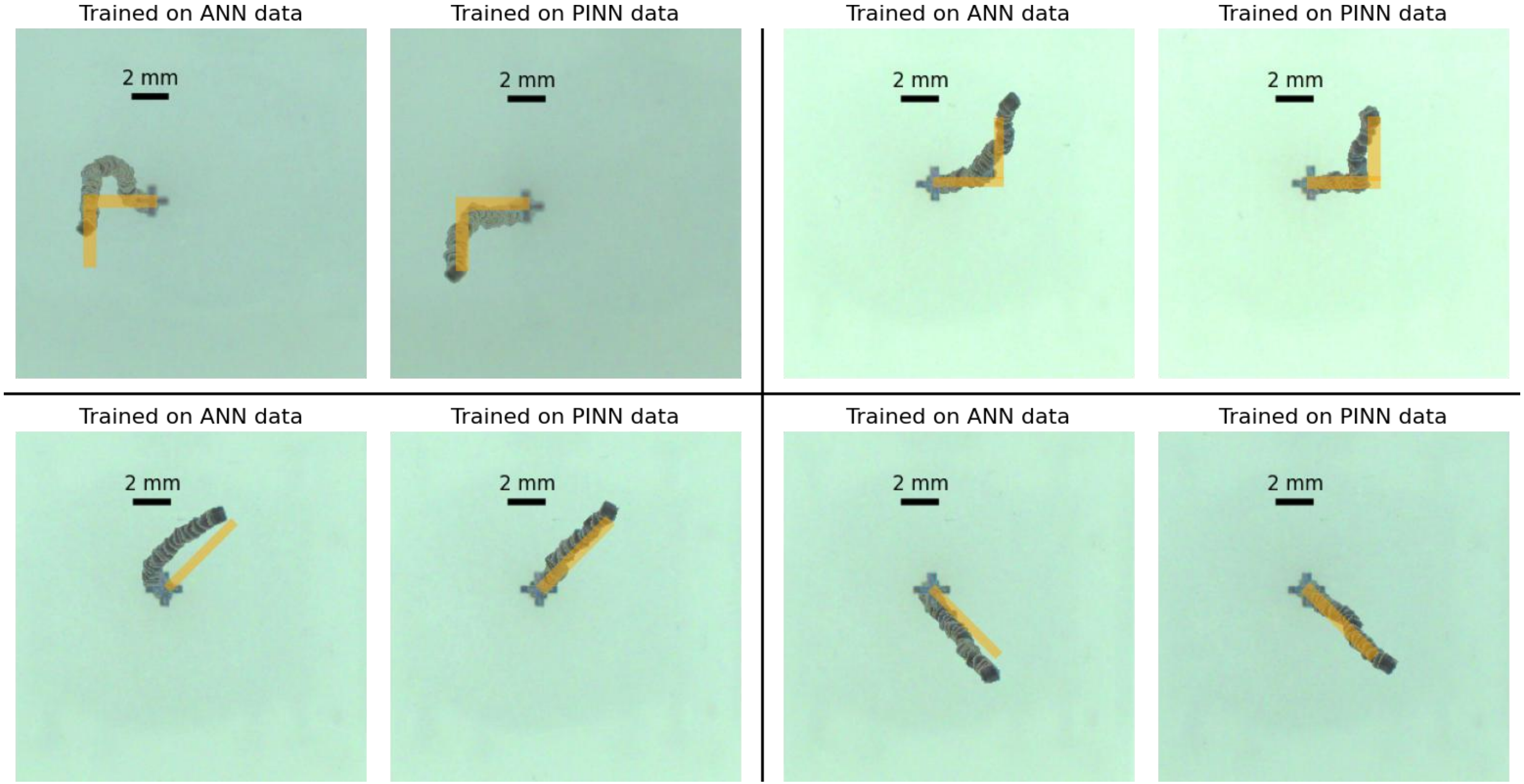
Results – Open-loop Control

Trained on ANN Data

Trained on PINN Data



Results – Open-loop Control



Implications

Balance:

- PINN balances accuracy & physics consistency

Inverse Solution:

- PINN leads to better inverse solution
- Inverse solution improves open-loop control