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

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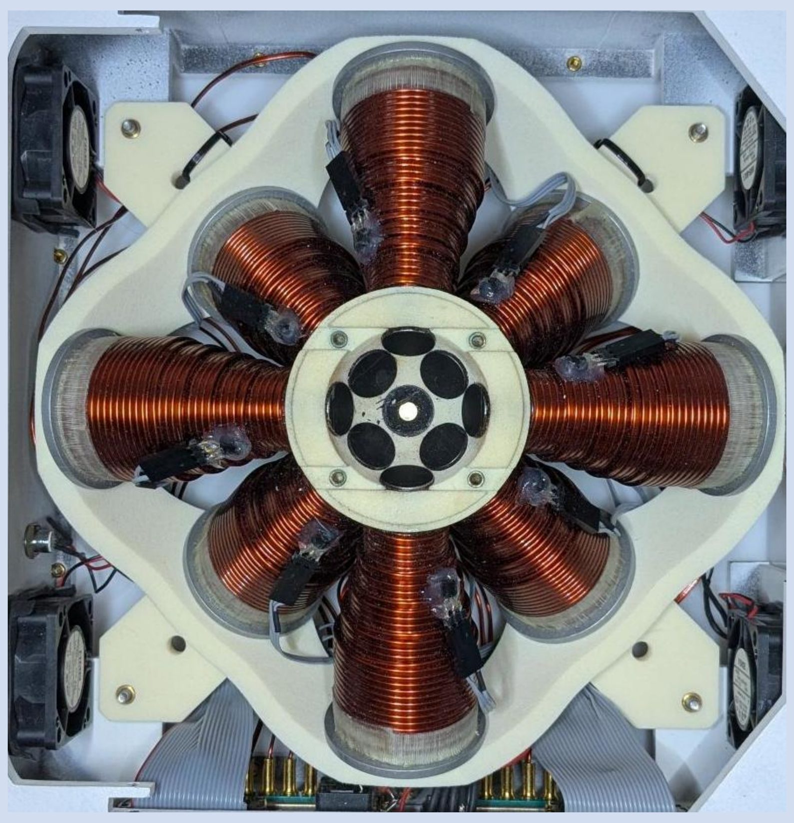
## Introduction

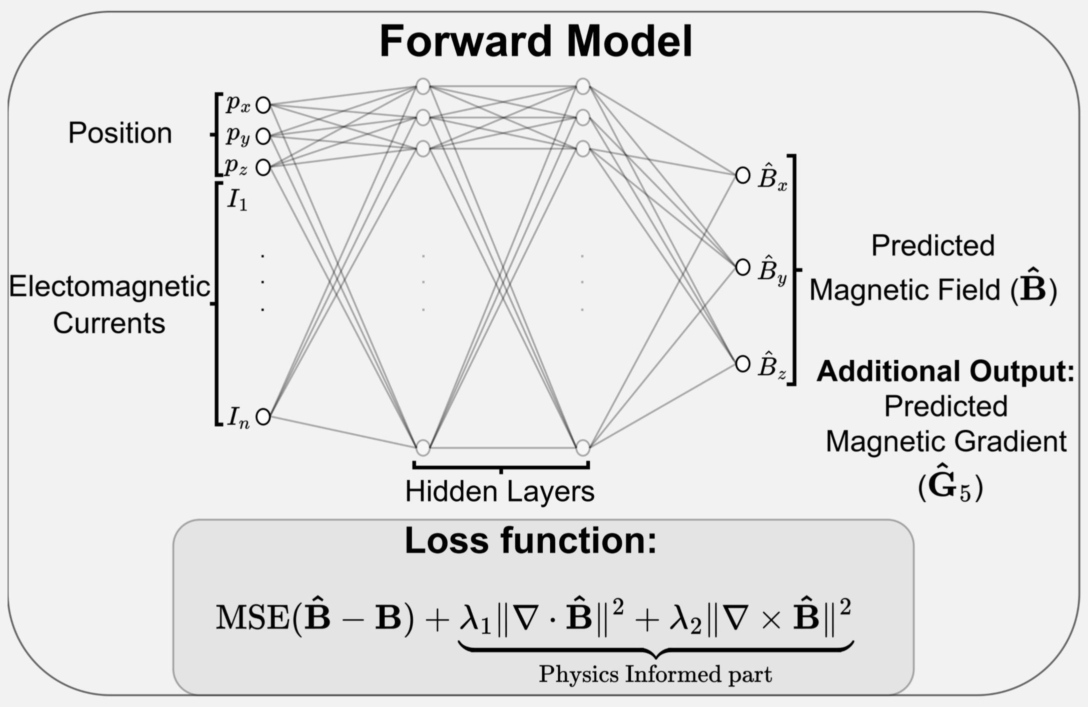
**Electromagnetic Navigation Systems** enable precise control of microrobots and magnetic tools in biomedicine.

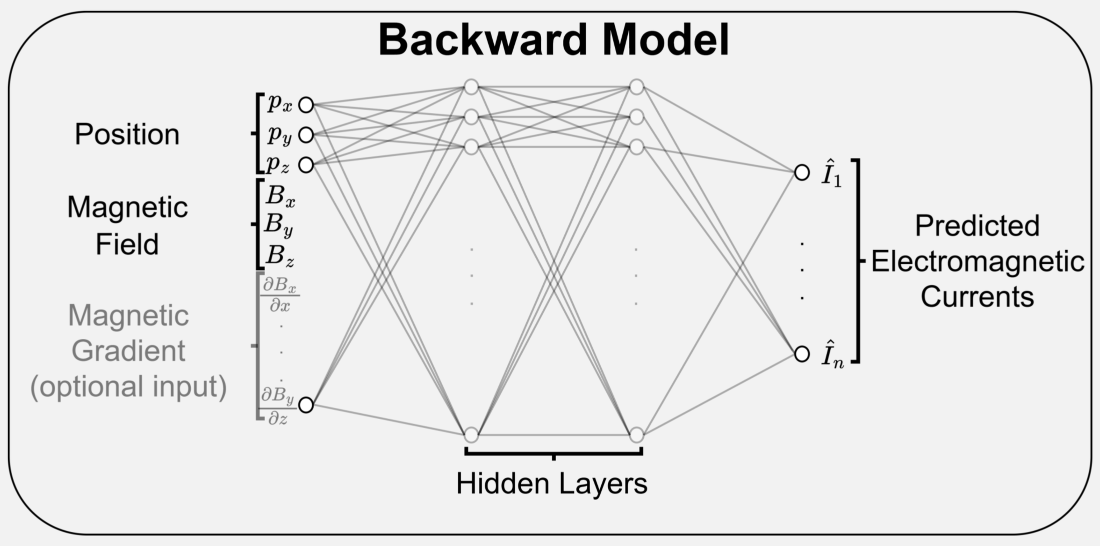
- **Accurate field and gradient models** are critical for force and torque control.
- **Conventional linear models** (e.g. Multipole Electromagnet Model) respect physics but do not capture saturation.
- **Data-driven models** (e.g. ANN, CNN) capture nonlinearities but violate Maxwell's equations, impeding accurate estimation of magnetic gradients.

**We introduce** a Physics-Informed Neural Network (PINN) that
- Embeds Maxwell's constraints,
- Predicts fields & gradients consistently,
- Enables reliable inverse models,
- Improves open-loop control performance.



## Methods



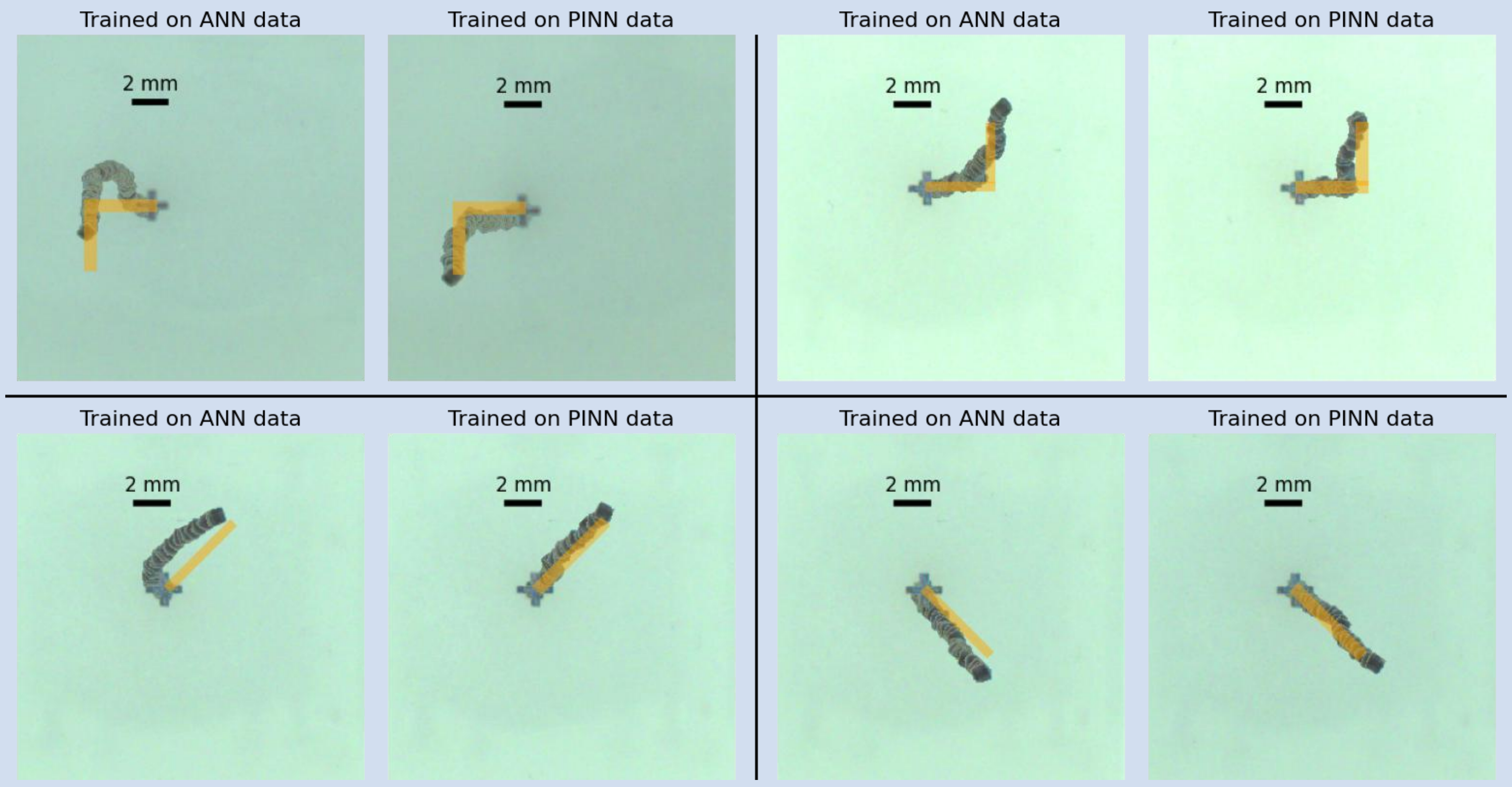

- **Forward Model (PINN):** promotes $\nabla\cdot\mathbf{B} = 0$ and $\nabla\times\mathbf{B} = \mathbf{0}$.
- **Backward Models:** w/o $\nabla\mathbf{B}$; efficient current sets (low norm), w/ $\nabla\mathbf{B}$; precise force control.
- **Consistency:** backward models use the trained PINN, ensuring physics compliance.

## Results

### Prediction Accuracies

| Model | RMSE | $R^2$ | Curl (T/m) | Div. (T/m) |
|---|---|---|---|---|
| **Forward Model** | | | | |
| ANN | 1.88 | 0.993 | 20.9 | 33.9 |
| PINN | 3.24 | 0.981 | 12.5 | 6.1 |
| **Backward Model w/o $\nabla\mathbf{B}$** | | | | |
| ANN | 0.7 | 0.999 | | |
| PINN | 0.6 | 0.999 | | |
| **Backward Model w/ $\nabla\mathbf{B}$** | | | | |
| ANN | 0.785 | 0.884 | | |
| PINN | 0.567 | 0.936 | | |

### Open-loop Control Experiment




## Conclusion

- PINN **balances accuracy and physics consistency**.
- PINN-trained backward model lead to **better inverse solution**.
- Introduced model leads **to improved open-loop control**.

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