Real-Time Magnetic Sensing for Soft 3-DoF Continuum Robots

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Why do we want Real-Time Sensing in Soft Robotics?

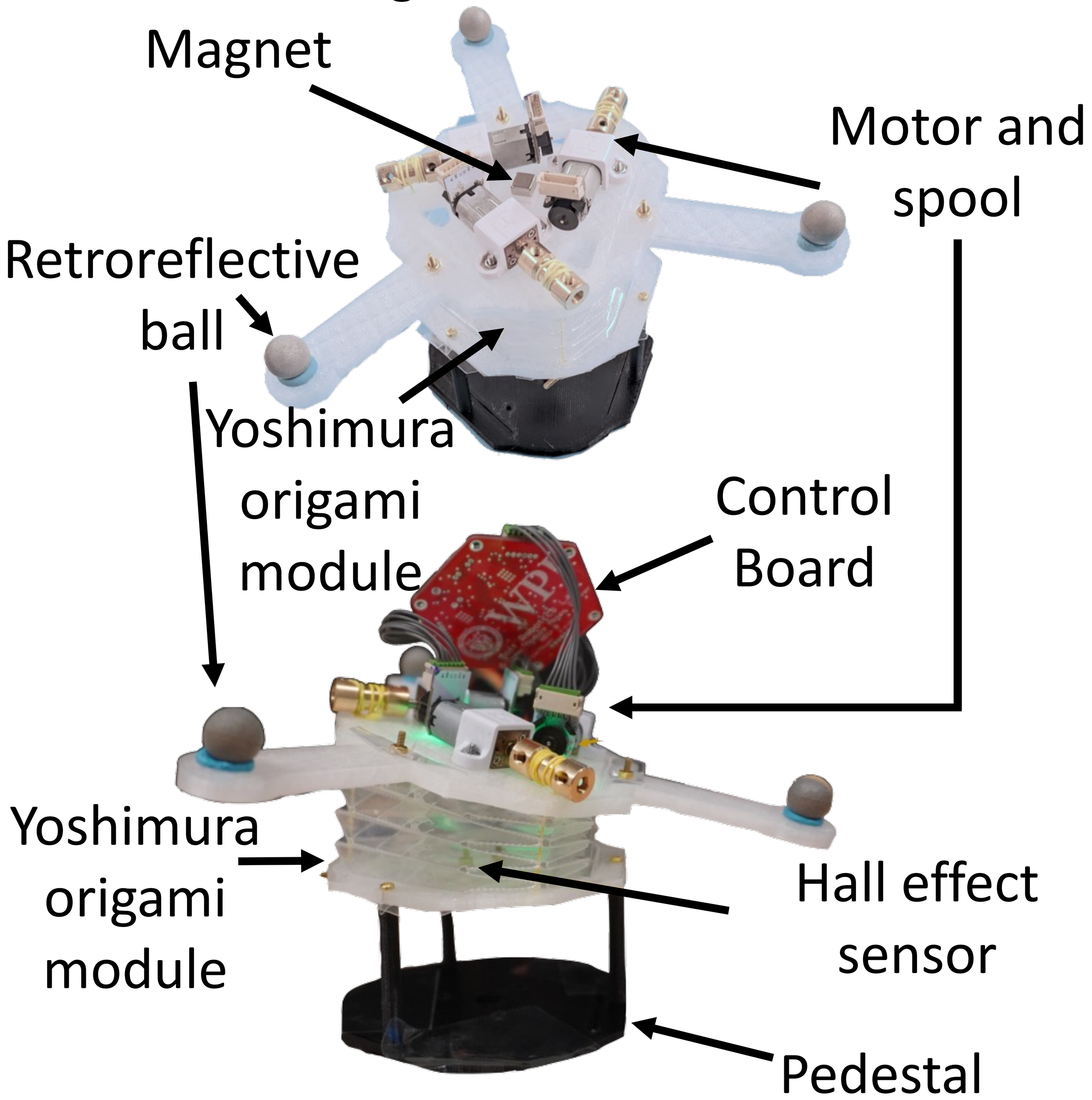
- Soft robotics has major implications in medical robotics, biological mimicry, and dexterous manipulation.
- Classical sensing techniques cannot handle the large DoF cleanly.
- This flexibility allows for more **adaptive** and **manipulatable** structures.

Our Design

Soft sensors come in many forms such as

- Resistive & capacitive flexible circuits
- Fiber-Bragg grating
- Hall effect table lookups

We chose a magnetic solution

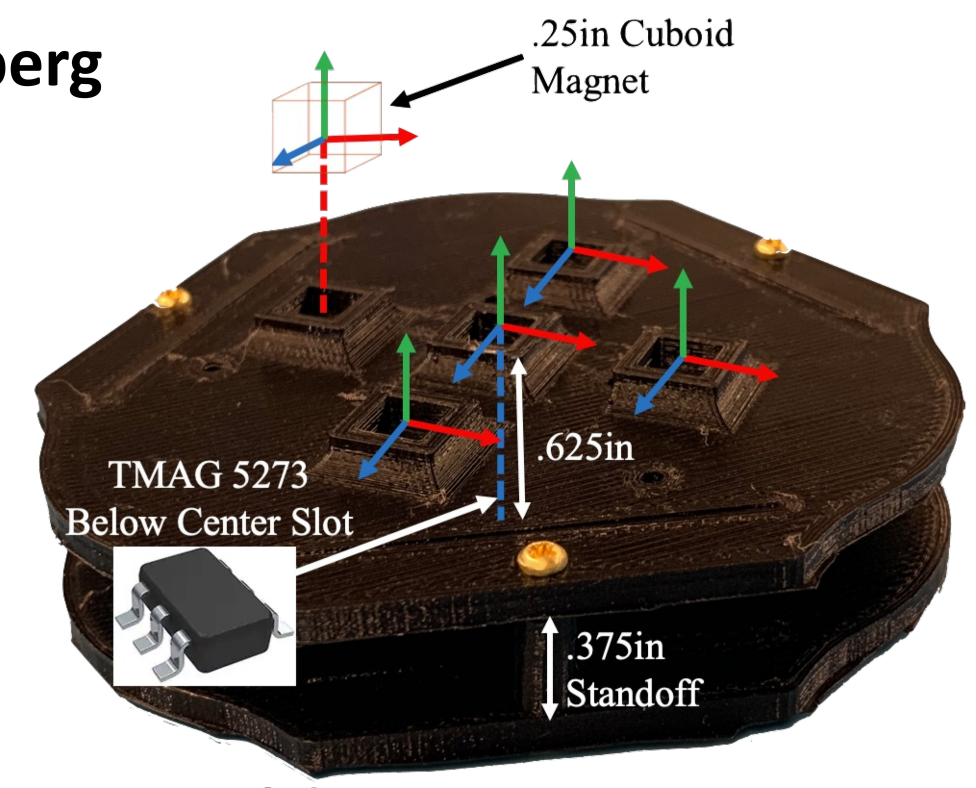


Design Advantages

- No contact between components
- Over 2 kHz speeds with 100 particles
- High accuracy at <1mm error
- Low cost & easy to integrate in existing robots

Magnetic Field Equations & Correction

We used **Levenberg Marquadt** optimization to solve the differences between our jig readings & magnetic simulation



Magnetic Field Equations

For 2kHz 100 particle custom magnetic simulation

$$B_x(x,y,z) = \frac{\mu_0 M}{4\pi} \ln\left(\frac{F_2(-x,y,z)F_2(x,y,z)}{F_2(x,y,z)F_2(-x,y,z)}\right) \quad (1)$$

$$B_y(x,y,z) = \frac{\mu_0 M}{4\pi} \ln\left(\frac{F_2(-y,x,-z)F_2(y,x,z)}{F_2(y,x,-z)F_2(-y,x,z)}\right) \quad (2)$$

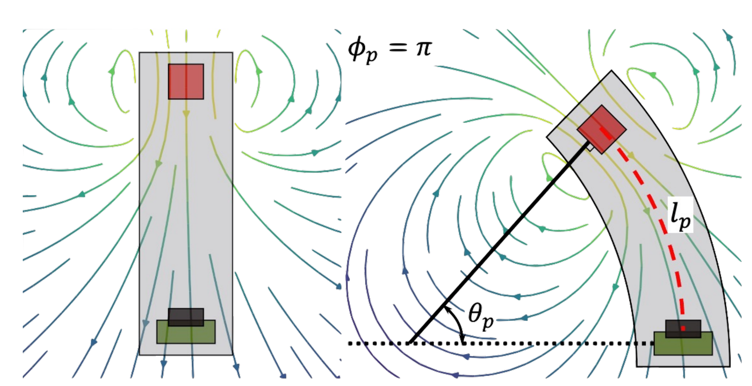
$$\begin{aligned} B_z(x,y,z) = -\frac{\mu_0 M}{4\pi}\Big[&F_1(-x,y,z) + F_1(-x,y,-z) \\ &+ F_1(-x,-y,z) + F_1(-x,-y,-z) \\ &+ F_1(x,y,z) + F_1(x,y,-z) \\ &+ F_1(x,-y,z) + F_1(x,-y,-z)\Big] \end{aligned} \quad (3)$$

With

$$F_1(x,y,z) = \arctan\left(\frac{(x+a)(y+b)}{(z+c)\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}}\right) \quad F_2(x,y,z) = \frac{\sqrt{(x+a)^2+(y-b)^2+(z+c)^2}+b-y}{\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}-b-y}$$

Particle Filtering Approach

By simulating the readings of 100 particles and comparing with the XYZ reading from the physical sensor, we can approximate the pose of the magnet.



The four main steps of our particle filter:

- Weighting

$$\mathcal{L}(\vec{x}_p \mid \vec{y}) = \exp\left(-\|\vec{x}_p - \vec{y}\|^2\right) \quad \& \quad \mathbb{P}(\vec{x}_p \mid \vec{y}) = \frac{\mathcal{L}(\vec{x}_p \mid \vec{y})}{\Sigma_{n\epsilon N}\mathcal{L}(\vec{x}_n \mid \vec{y})}$$

- Predicting

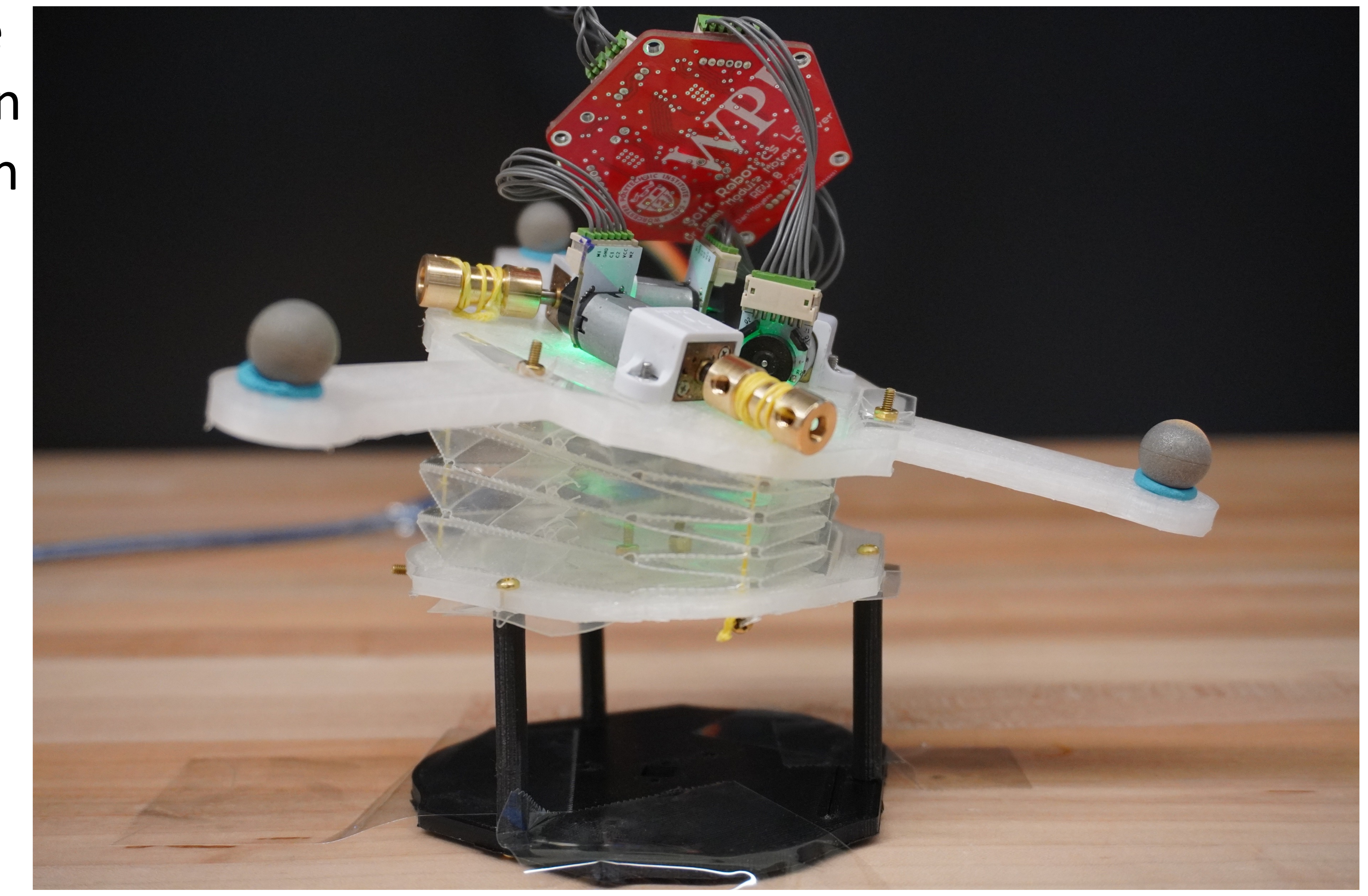
$$\hat{\phi} = \operatorname{atan2}\left(\sum_{s\in S}\sin(\phi_s), \sum_{s\in S}\cos(\phi_s)\right) \quad \& \quad \hat{\theta} = \frac{\sum_{s\in S}\theta_s}{|S|} \quad \hat{l} = \frac{\sum_{s\in S} l_s}{|S|}$$

- Resampling
  - Random sampling with replacement
- Updating
  - Particle update with rejection sampling

Continuum Robot Use Cases

Our proprioceptive origami module can

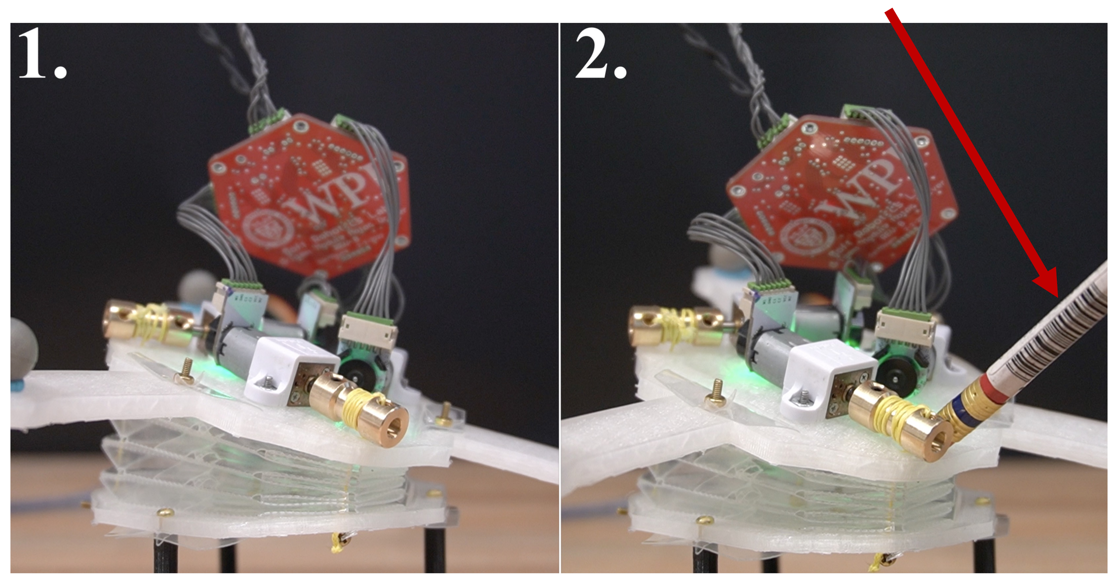
- Sense bending in any direction at any angle at <1mm accuracy
- Predict position under external force loads
- Enable complex control systems on mobile soft robots



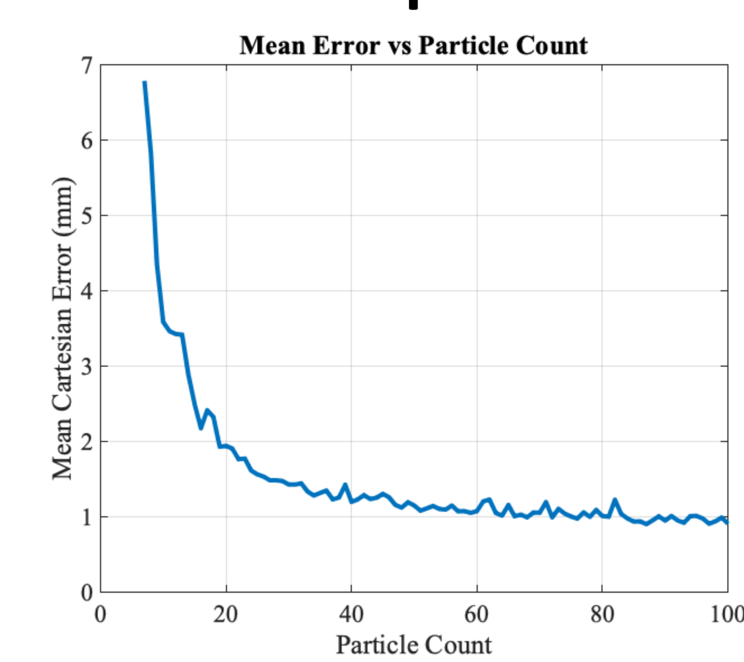
Model Verification & Testing

Experimental Setup

No external force — External force

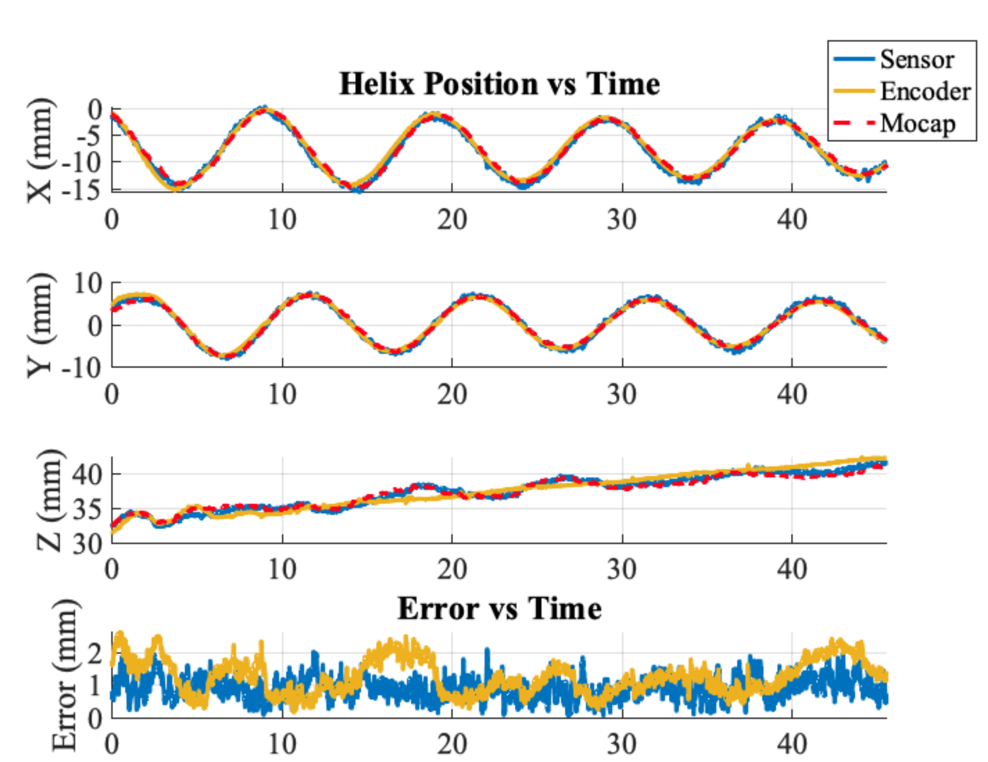


Diminishing reduction in error with more particles



Sensor validation results using Motion Capture ground truth

1.



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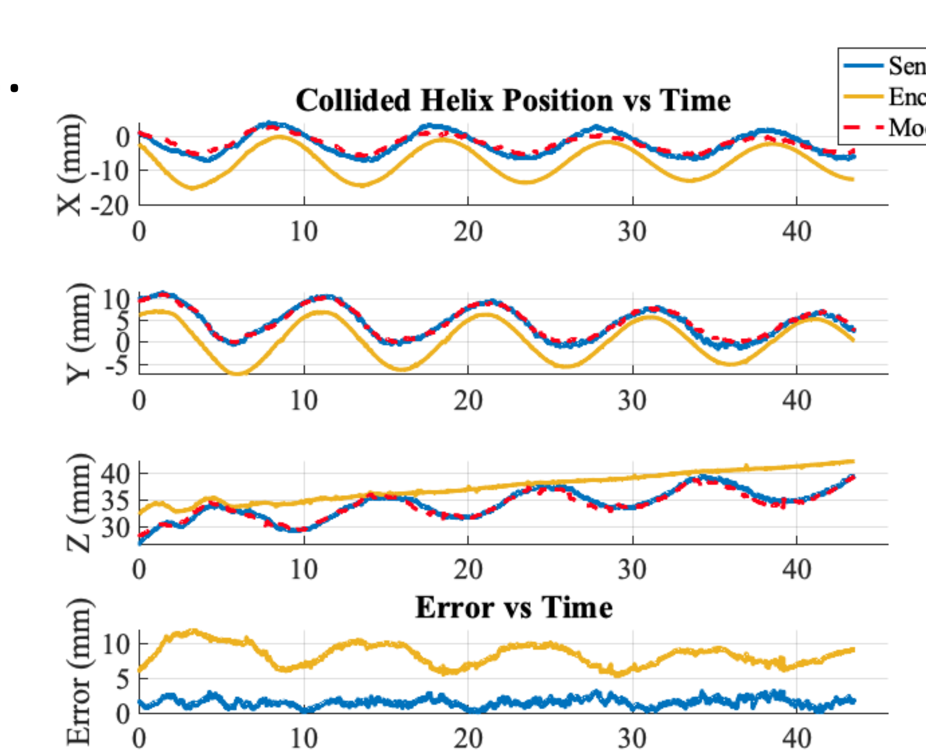

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References:

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M. Mitchell, K. Bonofiglio, C. DeMaio, L. Fichera and C. Onal, "Real-Time Magnetic Sensing for Soft 3-DoF Continuum Robots," 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Detroit, Michigan, 2023. **(Under Review)**

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