Robot-Assisted FBG-based Sensorized Needle Calibration

Paper Presentation

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Project Summary

- **Objective:** to calibrate flexible needles with FBG-based shape-sensing capabilities
- **Current problem:** manual needle calibration is very time-consuming and prone to human error
- **Project aim:** to develop an automatic needle calibration process that can be both precise and efficient

Paper Selection

Improved FBG-Based Shape Sensing Methods for Vascular Catheterization Treatment

Omar Al-Ahmad, Mouloud Ourak, Jan Van Roosbroeck, Johan Vlekken, and Emmanuel Vander Poorten

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Summary

This paper mainly discusses the methods for fiber integration within catheters to improve shape estimation accuracy and repeatability. It also introduces a two-step calibration process for intrinsic twist compensation and a practical method for fiber parameter identification. An example calibration setup was then demonstrated and validated.

Overall Structure

- Section I: Introduction
- Section II: Basic Principles
- Section III: Contributors to Shape Accuracy
- Section IV: Experimental Setup
- Section V: Results
- Section VI: Conclusion

Section I: Introduction

- History and advantages of Fiber Optic Shape Sensing (FOSS)
- Fiber Bragg Gratings (FBGs) vs. Rayleigh scattering
- Optical Frequency Domain Reflectometry (OFDR) vs. Wavelength Division Multiplexing (WDM)
- Basis for Reconstruction methods
  - Frenet-Serret frames
  - Parallel transport frames
  - Constant curvature segmentation
  - Helical geometry

TABLE I
SHAPE SENSING EXAMPLES FROM PREVIOUS LITERATURE (ALL DIMENSIONS ARE IN MILLIMETRE)

Authors	Interrogation	Fibers & Cores	Conf.	Model	Length	#Grts	Spacing	Validation	Error	R_{min}
Abayazid *et al.* [11]	FBG / WDM	3 outer / no central	Straight	Constant curvature	90	4	30	2D / 3D	2.10 ± 1.10 (mean)	375
Henken *et al.* [12]	FBG / WDM	3 outer / no central	Straight	Frenet-Serret	70	2	70	2D	1.32 ± 0.48 (mean)	NA
Yi *et al.* [23]	FBG / WDM	4 outer / no central	Straight	Frenet-Serret	400	5	100	2D / 3D	4.10 (mean)	NA
Elayaperumal *et al.* [24]	FBG / WDM	3 outer / no central	Straight	Other	85	2	85	2D	4.20 (rms)	NA
Gander *et al.* [25]	FBG / WDM	4 (MCF) / no central	Straight	Other	NA	NA	NA	2D	2.00 (max)	20
Van de Berg *et al.* [13]	FBG / WDM	3 outer / no central	Straight	Frenet-Serret	120	4	40	3D	2.60 ± 1.10 (mean)	71.4
Parent *et al.* [26]	OFDR	3 outer / no central	Straight	Other	NA	NA	NA	2D	≈1.00 (rms)	17.5
Sefati *et al.* [14]	FBG / WDM	3 outer / no central	Straight	Constant curvature	NA	NA	NA	3D	0.62 (max)	101.6
Ryu *et al.* [17]	FBG / WDM	3 outer / no central	Straight	Other	NA	NA	NA	2D	0.84 ± 0.62 (mean)	NA
Leyendecker *et al.* [27]	FBG / WDM	3 (MCF) / central	Straight	Constant curvature	250	6	50	2D / 3D	15.40 (max)	NA
Lally *et al.* [28]	OFDR	3 (MCF) / central	Helical	Other	30000	NA	NA	3D	210 (max)	NA
Klute *et al.* [1]	OFDR	3 outer / no central	Straight	Constant curvature	2000	NA	NA	3D	42.9 (max)	14
Duncan *et al.* [10]	OFDR	3 (MCF) / no central	Straight	NA	1100	110	10	2D	22.50 ±0.5 (max)	667
Khan *et al.* [29]	FBG / WDM	4 (MCF) / no central	Straight	Frenet-Serret	108	6	18	2D / 3D	1.05 (max)	NA
Roesthuis *et al.* [18]	FBG / WDM	3 outer / no central	Straight	Frenet-Serret	90	4	3	2D	1.14 (mean)	30
Kim *et al.* [15]	FBG / WDM	3 outer / no central	Straight	Constant curvature	150	NA	NA	3D	0.53 (max)	NA
Wang *et al.* [30]	FBG / WDM	4 outer / no central	Straight	Frenet-Serret	200	5	50	3D	15.00 (mean)	NA
Moore *et al.* [2]	FBG / OFDR	3 (MCF) / no central	Straight	Frenet-Serret	1100	111	10	3D	31.06 (max)	14.3
Roesthuis *et al.* [4]	FBG / WDM	3 outer / no central	Straight	Constant curvature	90	4	30	2D / 3D	1.66 (max)	15

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Section I: Introduction

- Major factors on reconstruction accuracy
- Contributions in this paper
  - Fiber integration approach into a catheter
  - Two-step calibration method for intrinsic twist
  - Approach for spatial curve reconstruction
  - Parameter identification method
  - Validation process of all the methods

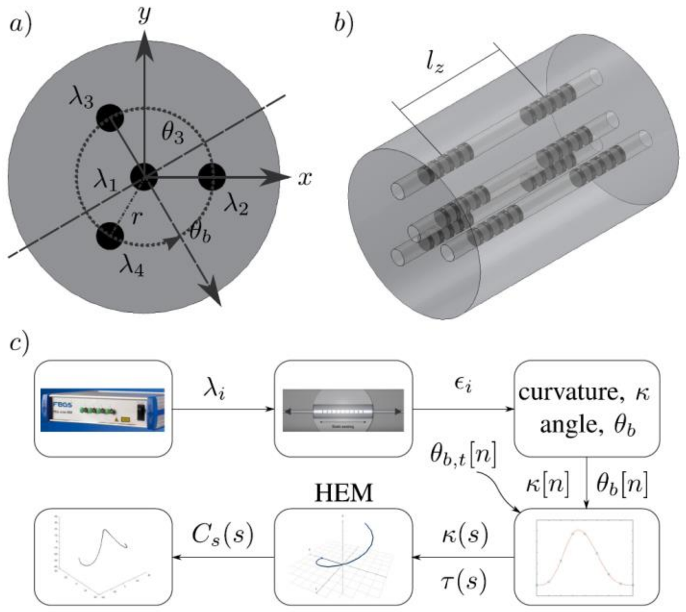
Section II: Basic Principles

1. Principles behind FBG sensors

$$\epsilon = -\kappa y$$

$$\frac{\lambda_B - \lambda_{B_0}}{\lambda_{B_0}} = \frac{\Delta\lambda_B}{\lambda_{B_0}} = S_\epsilon \Delta\epsilon + S_T \Delta T$$

$$\Delta\epsilon_i = \frac{\Delta\lambda_{B,i}}{S_\epsilon \lambda_{B_0,i}} - \frac{\Delta\lambda_{B,1}}{S_\epsilon \lambda_{B_0,1}}$$



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Section II: Basic Principles

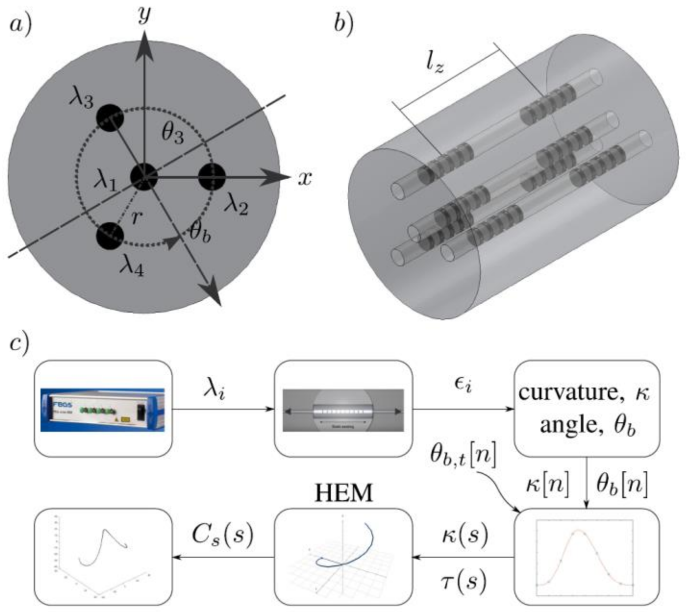
2. Strain, curvature and Bend Angle

$$\epsilon_i = -\kappa r \sin(\theta_b - 3\pi/2 - \theta_i)$$

$$\boldsymbol{\kappa}_{app} = -\sum_{i=1}^{N} \frac{\epsilon_i}{r} \cos\theta_i \hat{\boldsymbol{i}} - \sum_{i=1}^{N} \frac{\epsilon_i}{r} \sin\theta_i \hat{\boldsymbol{j}}$$

$$\kappa = \frac{2|\boldsymbol{\kappa}_{app}|}{N},$$

$$\theta_b = \angle \boldsymbol{\kappa}_{app},$$



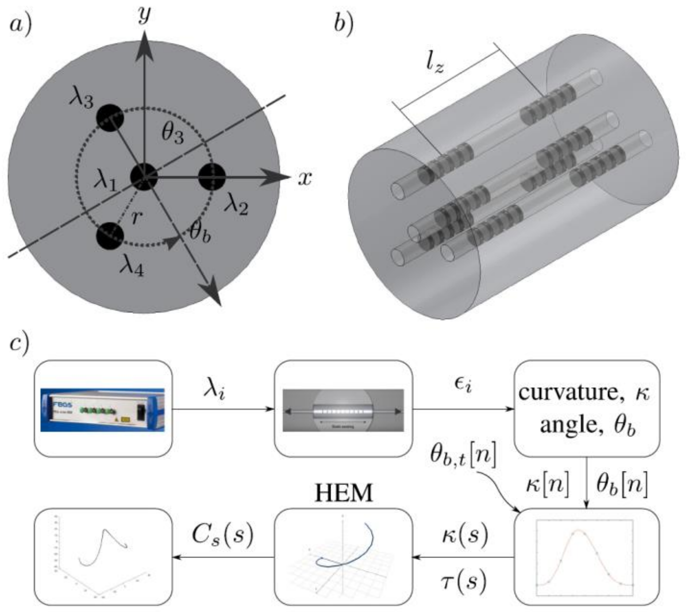
Section II: Basic Principles

3. Shape Reconstruction

- Frenet-Serret formula

$$\frac{d\mathbf{T}}{ds} = \kappa \mathbf{N},$$
$$\frac{d\mathbf{N}}{ds} = -\kappa \mathbf{T} + \tau \mathbf{B},$$
$$\frac{d\mathbf{B}}{ds} = -\tau \mathbf{N},$$

$$C_s(s) = C_{s,0} + \int_0^l \boldsymbol{T}(s) ds$$



Section III: Contributors to Shape Accuracy

- interrogation method
- fiber integration method
- presence of twist compensation
- calibration for twist compensation
- parameter identification
- reconstruction algorithm

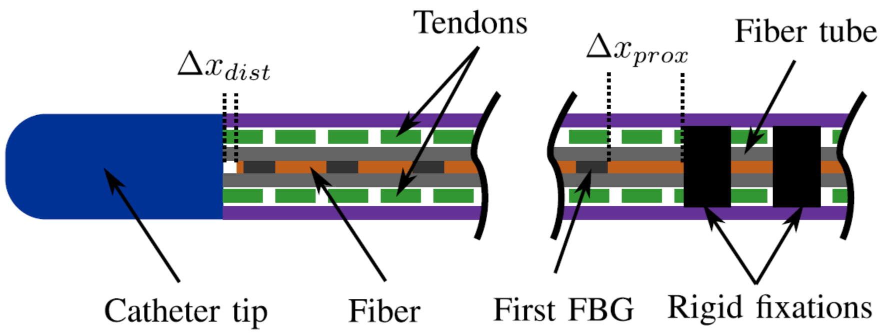
Section III: Contributors to Shape Accuracy

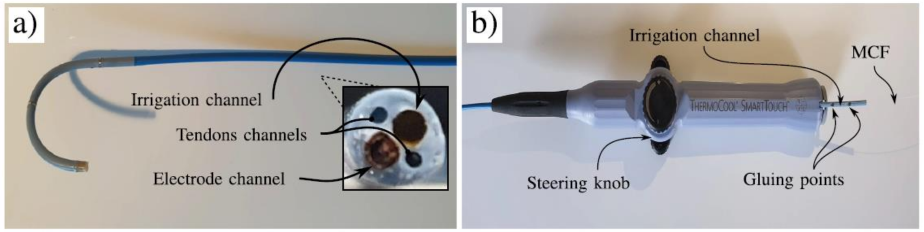
- **interrogation method**: WDM vs. OFDR

	WDM	OFDR
Spatial resolution	Lower (~1mm)	Extremely high (~10µm)
Refresh rate	High	Not as high
SNR	High	Not as high
Cost	Cheaper	More expensive
Wavelength measurement accuracy	More accurate	Less accurate

Section III: Contributors to Shape Accuracy

- **fiber integration method**
- 3 guidelines:
  - reducing the spacing between the multiple-core fiber (MCF) and the inner lumen of the catheter
  - including one or two rigid fixations at the base of the MCF with distance Δx_prox to the closest FBG grating
  - attaching the MCF at a location where its tip is at distance Δx_dist away from the tip of the catheter





Section III: Contributors to Shape Accuracy

- **presence of twist compensation**
- Fiber is more sensitive in sensing the strain caused by the twist
- Intrinsic twist is present in FBG fibers even when they are not externally loaded. Mechanical design is necessary to reduce the twist.

Section III: Contributors to Shape Accuracy

- **calibration for twist compensation**
- 2-step procedure proposed

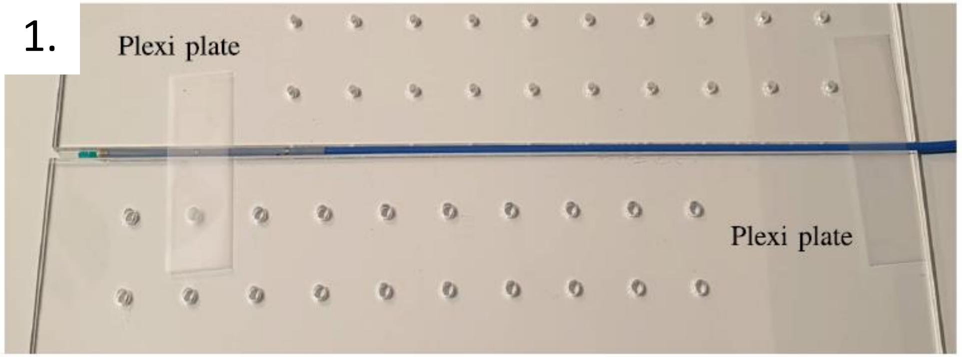
$$\Delta\epsilon_i = \frac{\Delta\lambda_{B,i}}{S_\epsilon \lambda_{B_0,i}} - \frac{\Delta\lambda_{B,1}}{S_\epsilon \lambda_{B_0,1}}$$

$$\boldsymbol{\kappa}_{app} = -\sum_{i=1}^{N} \frac{\epsilon_i}{r} \cos\theta_i \hat{\boldsymbol{i}} - \sum_{i=1}^{N} \frac{\epsilon_i}{r} \sin\theta_i \hat{\boldsymbol{j}}$$

$$\kappa = \frac{2|\boldsymbol{\kappa}_{app}|}{N},$$

$$\theta_b = \angle \boldsymbol{\kappa}_{app},$$

1.



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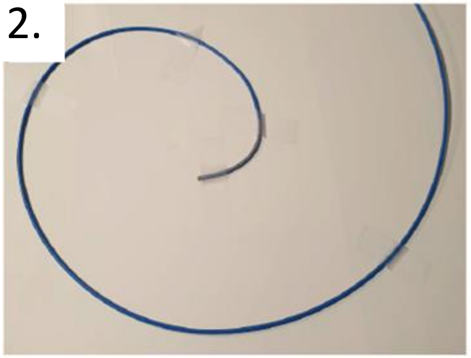

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Section III: Contributors to Shape Accuracy

- **parameter identification**
- Procedure proposed
    1. Position in various ground-truth scenarios
    2. Minimize the cost function:

$$\boldsymbol{C}(\boldsymbol{\Theta}) = \sum_{i=1}^{k} \max(\ \boldsymbol{d}(C_{s,gr}(s,k) - C_{s,rc}(s,k,\boldsymbol{\Theta})))$$

for $\boldsymbol{\Theta}$ subject to

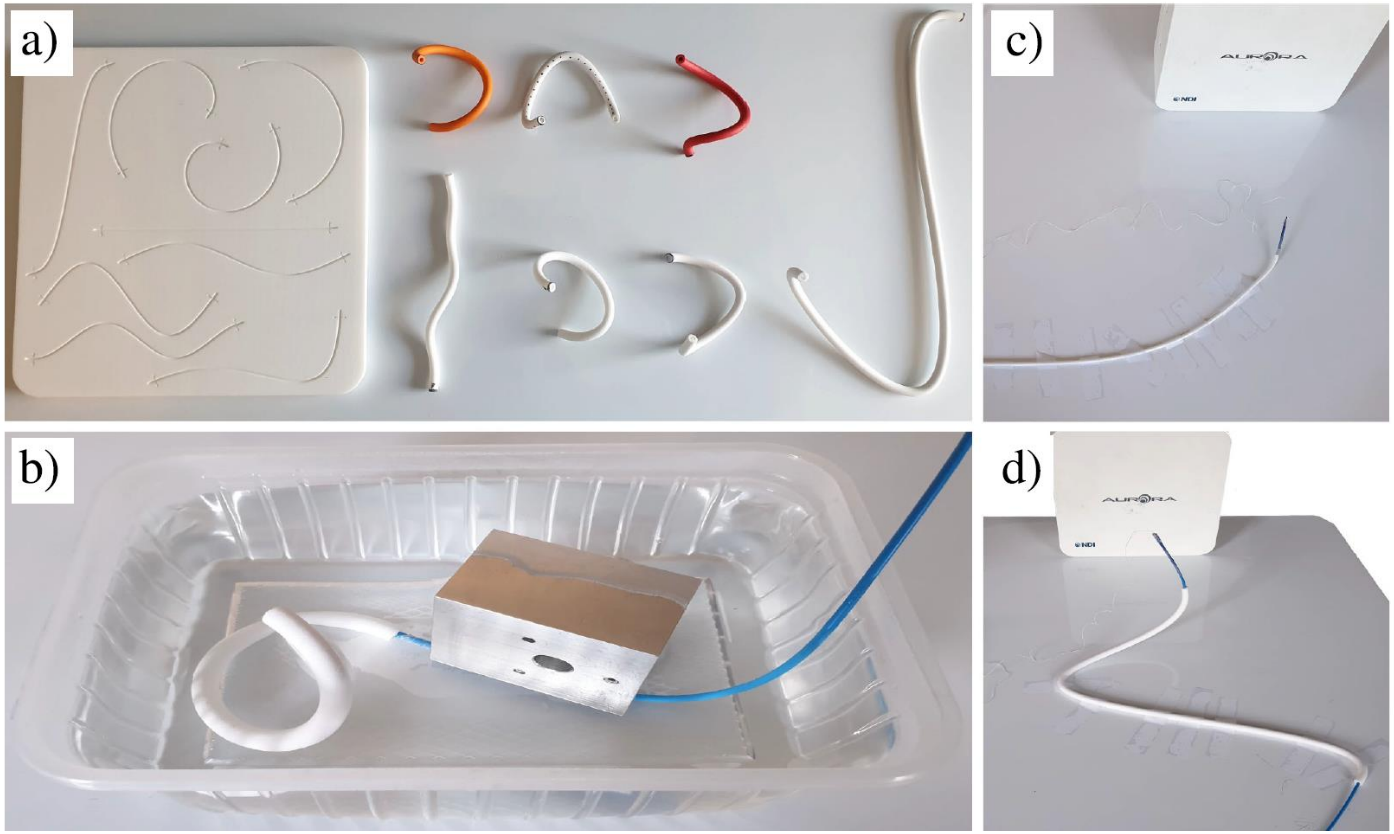
$$\begin{cases} \boldsymbol{\Theta} = [\Delta\theta,\ r,\ S_\epsilon], \\ \Delta\theta_{\min} \le \Delta\theta \le \Delta\theta_{\max}, \\ r_{\min} \le r \le r_{\max}, \\ S_{\epsilon,\min} \le S_\epsilon \le S_{\epsilon,\max}, \end{cases}$$

Section III: Contributors to Shape Accuracy

- **reconstruction algorithm**
- 3 modifications:
  - code for twist compensation
  - construct the spatial curve using the Helical Extension Method
  - compare different interpolation techniques and employ one with the best performance

Section IV: Experimental Setup

- Static tests (left)
- Dynamic tests(right)



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Section IV: Experimental Setup

- **Static tests**

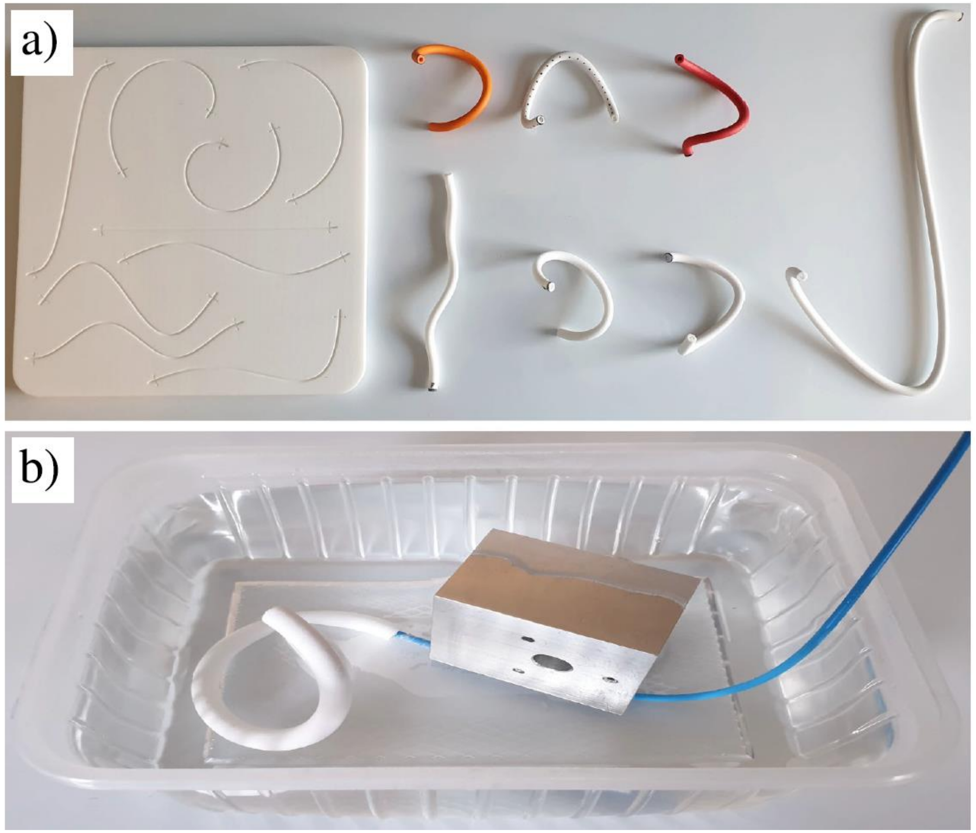
1. Parameter optimization

   12 shapes x 5 insertions each

   Half for optimization, half for validation

2. Temperature variation

   Submerge catheter in hot water bath



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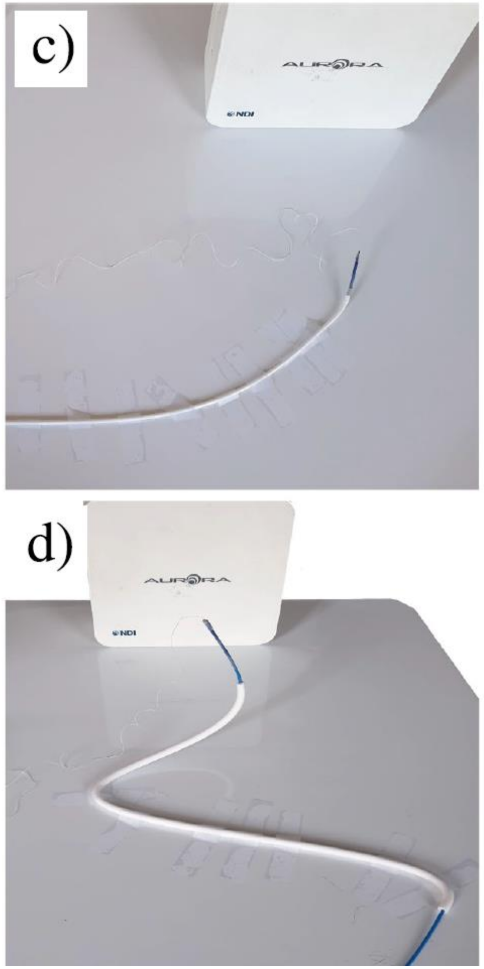
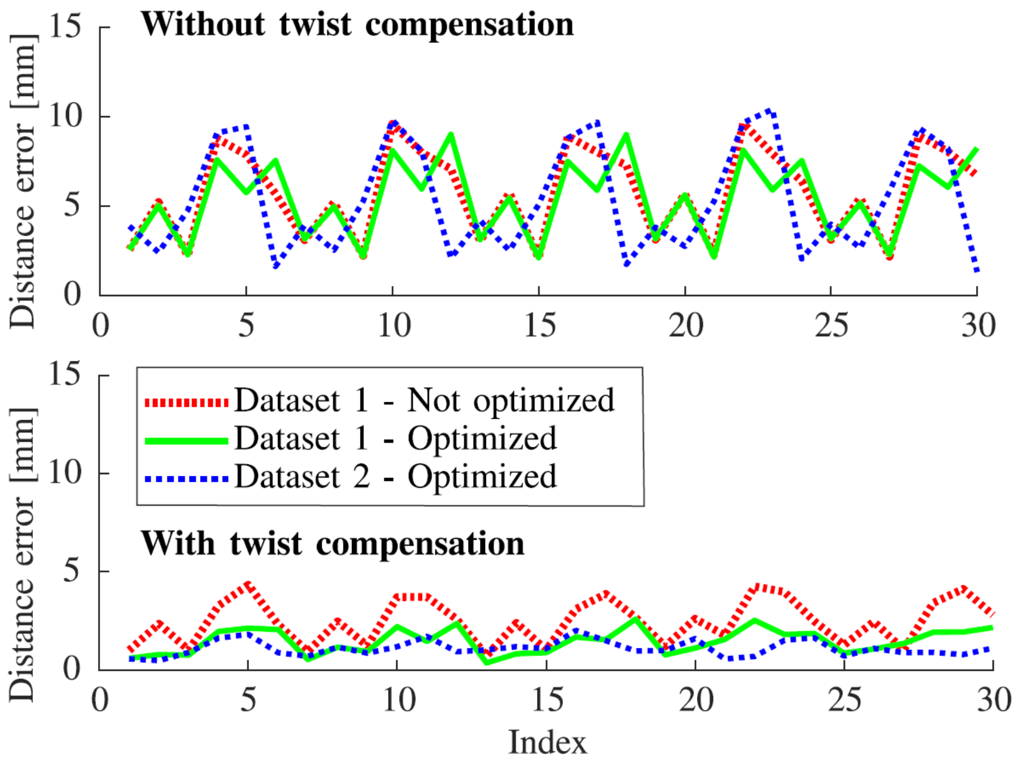
Section IV: Experimental Setup

- **Dynamic tests**
- EM sensor fixed at the tip
- 4 effects to be tested
    - Longitudinal catheter rotation
    - Repeatability
    - Tendon actuation
    - Dynamic catheter movement



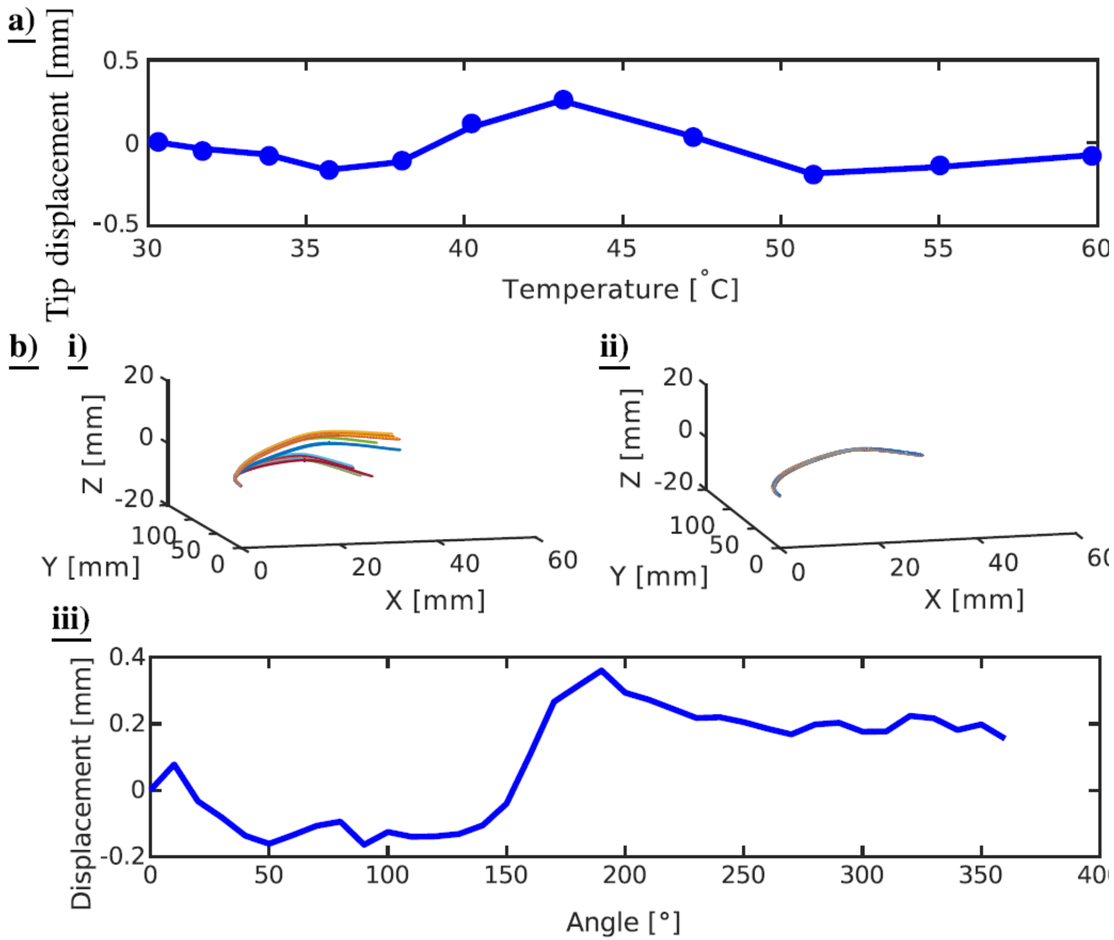
Section V: Results

- Parameter optimization improves accuracy
- Twist compensation improves accuracy
- Optimized parameters perform well for shapes excluded from optimization (data2)



Section V: Results

- variation caused by temperature is mostly uniform and are almost negligible
- rotation induces negligible twist and has no major effect on shape accuracy



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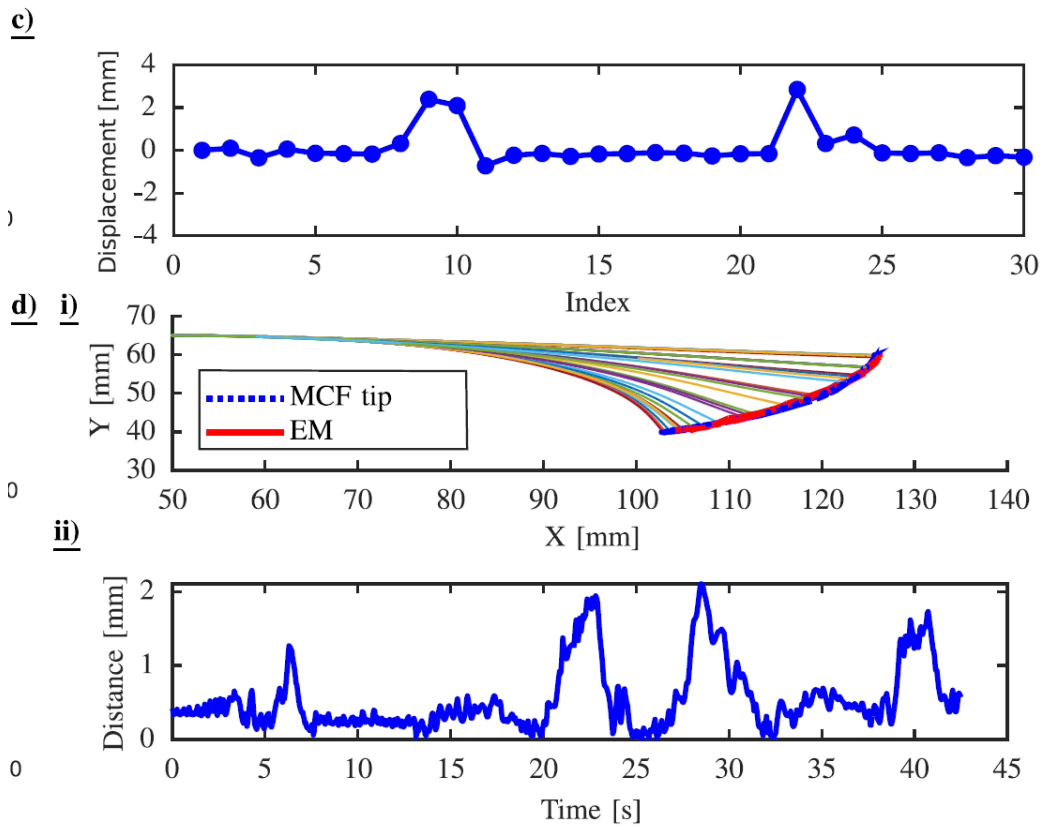
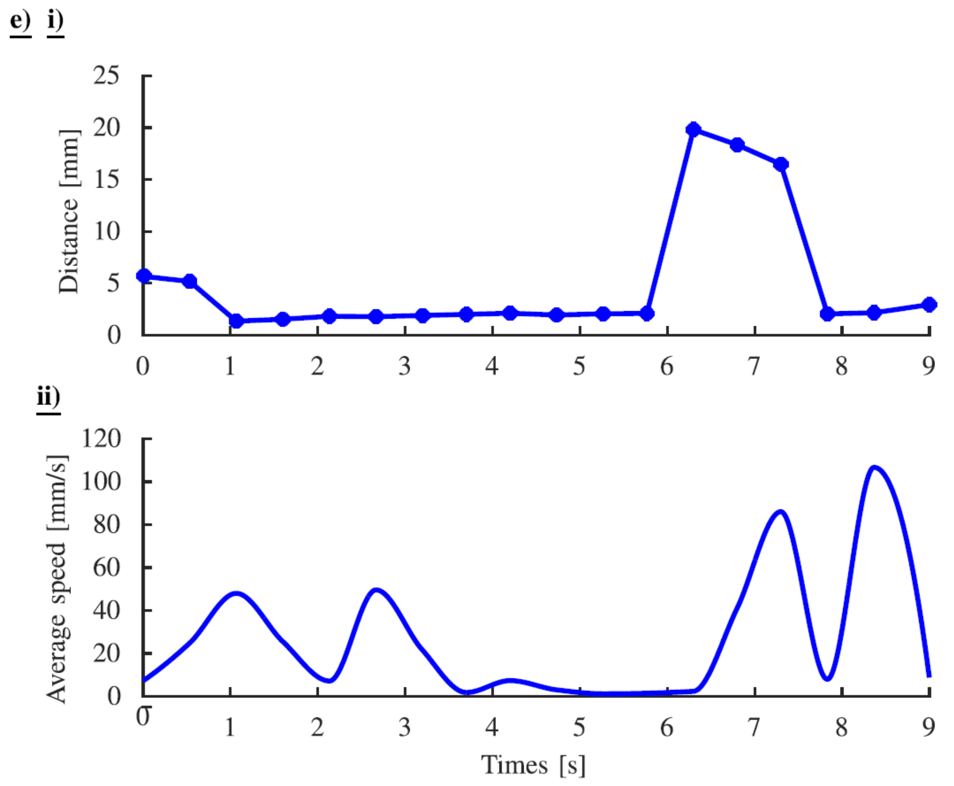
Section V: Results

- excellent repeatability, result will likely improve in real-life settings
- shape reconstruction is not affected by tendon actuation



Section V: Results

- distance error increases when there's sharp bends
- could be mitigated by applying lubrication in the sheath, and to use larger FBG spacing to avoid wavelength overlap in the spectrum



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Section VI: Conclusion

- This paper explored the effect of multiple factors on the accuracy of shape reconstruction of an FBG-based catheter. It also proposed several different algorithms to mitigate the possible errors. Through experiment, it shows that when applying these calibration algorithms, the FBG-based catheter is able to reconstruct the shape pretty accurately.

Critiques

Pros:

- Easy to follow
- Well structured
- Equations are clear
- Detailed explanation of the experiment

Cons

- No classification of good and bad FBG sensors

Takeaways

- Good general guidance
- Principles are applicable
- Good reference experiment

References

- Seifabadi, R., Iordachita, I., & Fichtinger, G. (2012, June). Design of a teleoperated needle steering system for MRI-guided prostate interventions. In 2012 4th IEEE Ras & Embs International Conference on Biomedical Robotics And Biomechatronics (Biorob) (pp. 793-798). IEEE.

- Al-Ahmad, O., Ourak, M., Van Roosbroeck, J., Vlekken, J., & Vander Poorten, E. (2020). Improved FBG-Based Shape Sensing Methods for Vascular Catheterization Treatment. IEEE Robotics and Automation Letters, 5(3), 4687-4694.