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Shape Sensing with Fiber Bragg Grating Sensors: A Realistic Model of Curvature Interpolation for Shape Reconstruction

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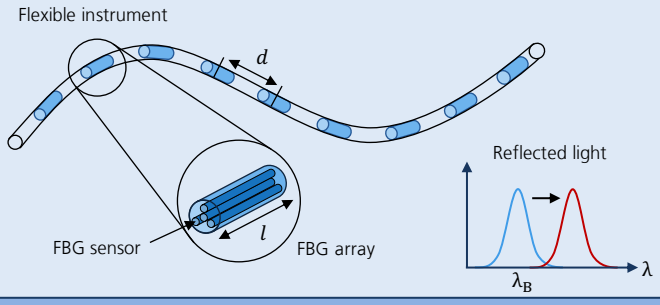
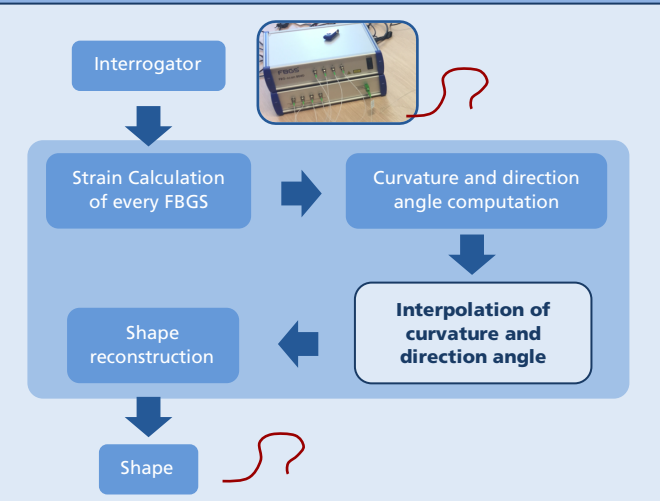
MOTIVATION



- Fiber Bragg Gratings (FBG) are reflectors which are constructed as short segments of an optical fiber and are able to reflect a specific Bragg-wavelength. Strain and temperature change cause a wavelength shift.
- By combining several FBGs into an array and by placing multiple arrays along a medical instrument (e.g. needle, catheter) its shape can be reconstructed by so-called shape sensing [1,2].
- In contrast to existing approaches, we take the physical extent of FBG into account. We consider measurements as a spatial average rather than pointwise values for a more realistic estimation of curvature and finally more accurate shape reconstruction.

SHAPE SENSING

- Fiber system of length $\boldsymbol{L}$ with $\boldsymbol{n}$ FBG arrays, each containing 3 FBGs in a triplet configuration and 1 FBG at the center and width length $\boldsymbol{l}$ and center-to-center distance $\boldsymbol{d}$.
- Workflow:



NEW INTERPOLATION MODEL

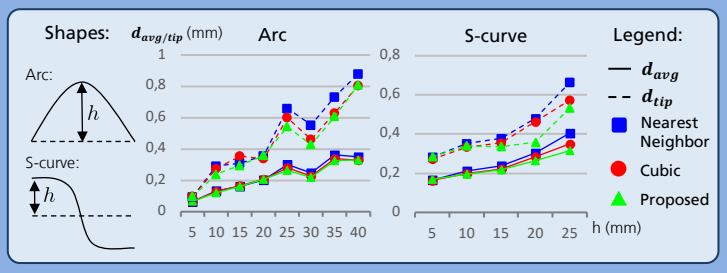
- Idea: $\boldsymbol{n}$ FBGs with length $\boldsymbol{l}$, center at $\boldsymbol{t_i} \coloneqq \boldsymbol{t_0} + \boldsymbol{d} \cdot \boldsymbol{i} \in [\frac{\boldsymbol{l}}{2}, \boldsymbol{L} - \frac{\boldsymbol{l}}{2}]$ and distance $\boldsymbol{d} = |\boldsymbol{t_{i+1}} - \boldsymbol{t_i}|$.
- Assumption: measured curvature is averaged curvature

$$\boldsymbol{C_i} = \frac{\boldsymbol{1}}{\boldsymbol{l}} \int_{\boldsymbol{t_i} - \frac{\boldsymbol{l}}{\boldsymbol{2}}}^{\boldsymbol{t_i} + \frac{\boldsymbol{l}}{\boldsymbol{2}}} \boldsymbol{c(t)}\, \boldsymbol{dt}$$

- Curvature function: $\boldsymbol{c(t)} = \sum_{\boldsymbol{j=0}}^{\boldsymbol{n-1}} \boldsymbol{w_j S_j(t)}$ with cubic b-splines $\boldsymbol{S_j(t)}$ centered at the $\boldsymbol{j}$th FBG sensor.

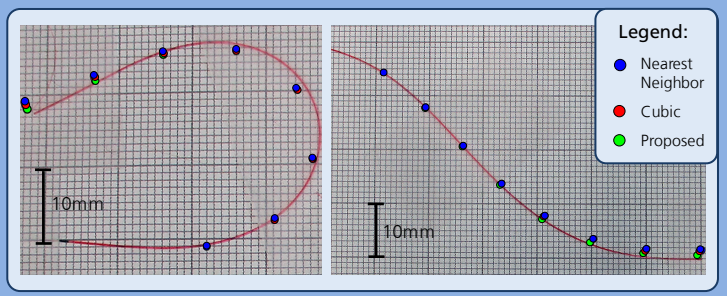
RESULTS

- Distances: $\boldsymbol{d_{avg}} = \frac{\boldsymbol{1}}{\boldsymbol{n}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \left\| \boldsymbol{x_i} - \boldsymbol{x_i^{gt}} \right\|_{\boldsymbol{2}}$, $\boldsymbol{d_{tip}} = \left\| \boldsymbol{x_n} - \boldsymbol{x_n^{gt}} \right\|_{\boldsymbol{2}}$
- Simulation study: shape distance to ground truth (in mm)



- Experiment study: shape distance to ground truth (in mm)

Shape	Distance	Nearest Neighbor	Cubic	Proposed
Arc	$\boldsymbol{d_{avg}}$	1.71	1.53	1.53
	$\boldsymbol{d_{tip}}$	3.37	2.84	2.66
S-curve	$\boldsymbol{d_{avg}}$	0.95	0.86	0.47
	$\boldsymbol{d_{tip}}$	2.18	2.04	1.10



CONCLUSION

- Our proposed method yields smaller reconstruction errors than the compared state-of-the art reference methods.
- In the next step the idea will be used for strain interpolation.
- Interpolation is one error source of the shape sensing workflow. Thus, the other calculation steps will be analyzed and optimized.

Full paper:

REFERENCES

[1] Park YL, Elayaperumal S, Daniel B, et al. Real-time estimation of 3-D needle shape and deflection for MRI-guided interventions. IEEE ASME Trans Mechatron. 2010; 15(6):906–915.

[2] Roesthuis RJ, Kemp M, van den Dobbelsteen JJ, et al. Three-dimensional needle shape reconstruction using an array of fiber bragg grating sensors. IEEE ASME Trans Mechatron. 2014;19(4):1115-1126.

[3] Jäckle, S., Strehlow, J., Heldmann, S.: Shape sensing with fiber bragg grating sensors. In: Bildverarbeitung für die Medizin 2019, pp. 258{263. Springer (2019)

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