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An optical fiber and deep neural network-based method to estimate the 3D position of endovascular devices in autonomous endovascular robot control

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April 3rd 2025 - A.Y. 2024/2025

» Introduction

State of the Art

Materials and Methods

Results and Conclusion

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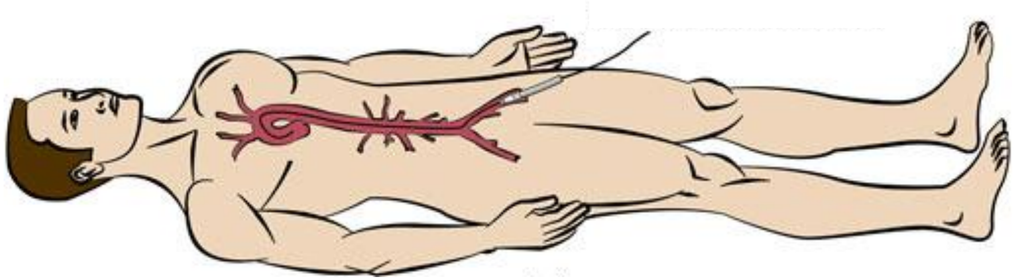
Medical Scenario

Endovascular interventions



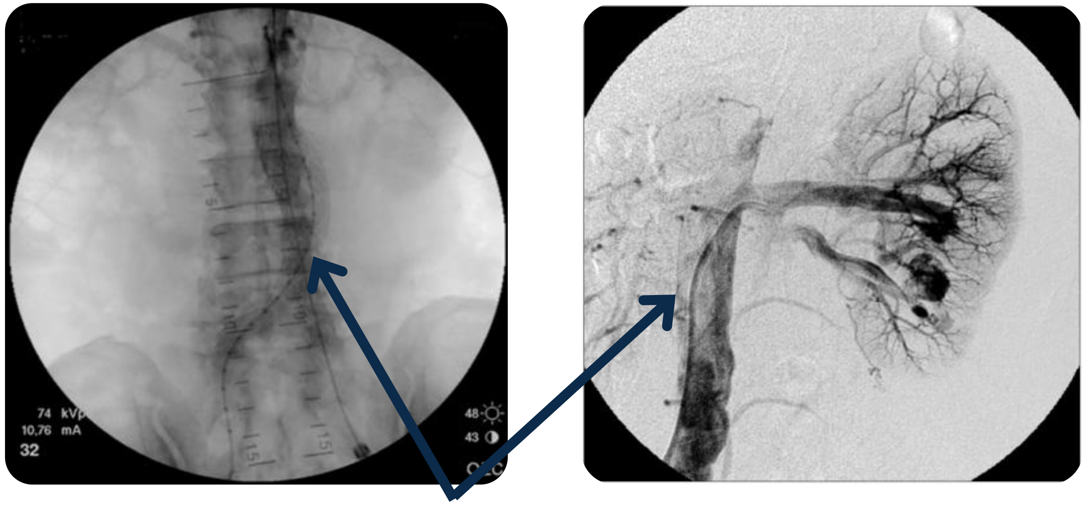
Catheters and guidewires navigated into blood vessels to the target location.

- Minimally invasive [1]
- Quick patient recovery [1]
- Reduced complications [1]

[1] – Alsawas et al. (2017)

Critical points [1]

- Radiation exposure
- Contrast agent injection
- Device control limitations



Guidewire and catheter in real fluoroscopic images.

Trend in Robotics

Objectives of research field

- *Minimizing X-ray exposure* for patient and clinician
- *Reducing use of contrast agent*
- Making the guidance *faster and safer*

Autonomous endovascular robotic navigation

?

Device 3D shape »

Anatomy »

Robot controller [2]

» Control action

[2] – Scarponi et al. (2024)

Goal Definition

?

Device 3D shape »

Anatomy »

Robot controller

» Control action

Project goal: Reconstruct the 3D shape of endovascular devices

Explore different solutions » Define the method » Validate it

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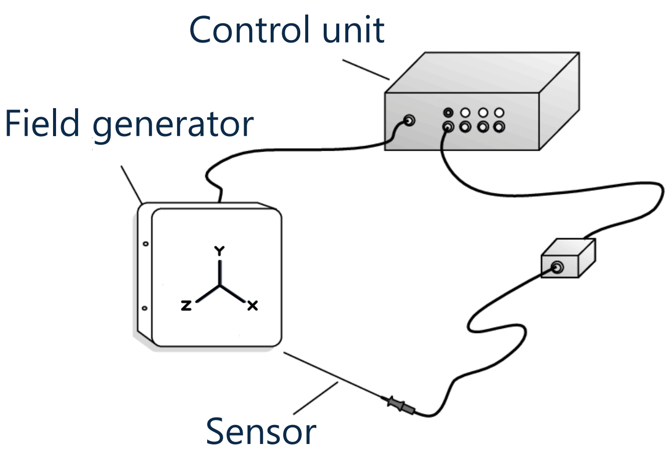
3D Shape Reconstruction

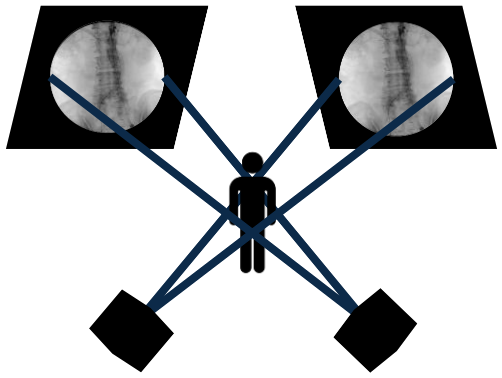
Electromagnetic (EM) tracking



- ✓ *Small dimensions*
- ⚠ *Accuracy* [3]
- ⚠ *Electro-magnetic interferences* [3]

[3] – Ha, X. et al. (2021)

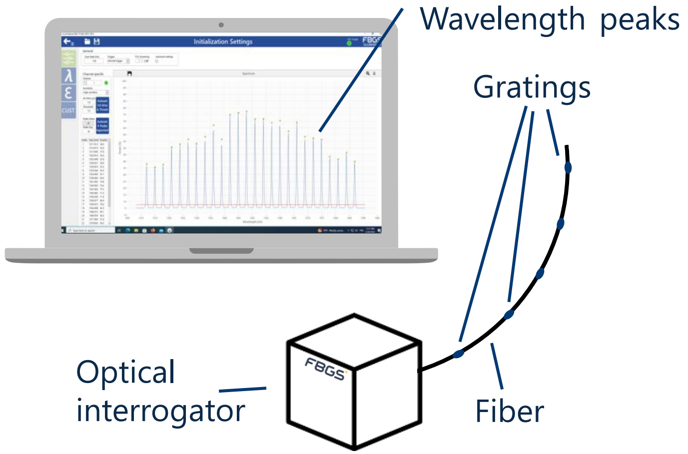
Biplane fluoroscopy



- ✓ *Accuracy* [4]
- ⚠ *X-rays exposure*
- ⚠ *Contrast agent*

[4] – Sadick, V. et al. (2021)

Fiber Bragg Grating (FBG) sensor

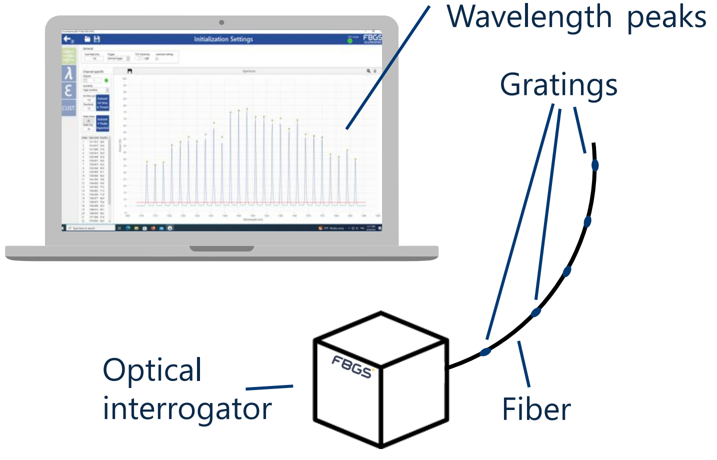


- ✓ *Incorporable in catheters* [5]
- ✓ *No X-Rays needed*
- ✓ *Biocompatible* [5]

[5] – Floris, I. et al. (2021)

3D Shape Reconstruction

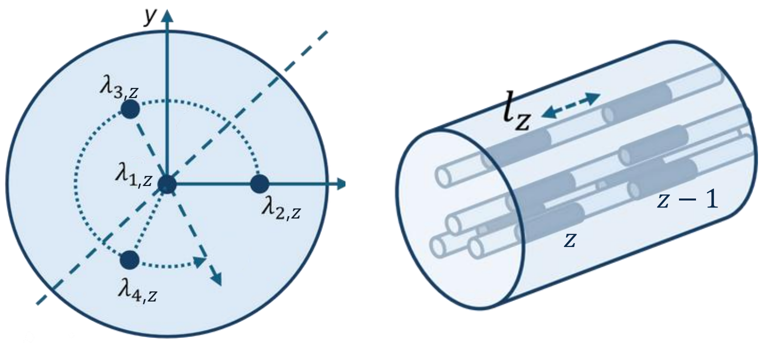
Fiber Bragg Grating (FBG) sensor



- *Incorporable in catheters*[5]
- *No X-Rays needed*
- *Biocompatible*[5]

[5] – Floris, I. et al. (2021)

The Technology



4-cores FBG sensor cross-section

$\lambda_{i,z}$ – Bragg wavelength of core i in plane z

l_z – Distance between acquisition planes z and $z-1$

$$strain_z = f(\lambda_{Bragg,z})$$ [6]

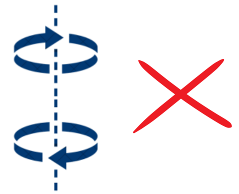
Integration of strains to reconstruct the 3D shape

[6] - Ha, Xuan Thao et al. (2022)

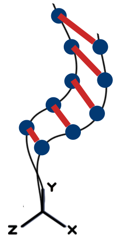
Related Works

All that glitters is not gold!

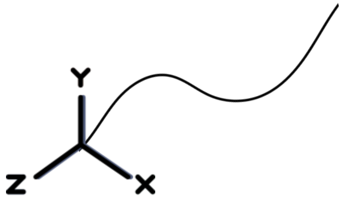
Fiber twist error [5]



Error propagation [5]



Relative reference system [5]



Solutions in literature

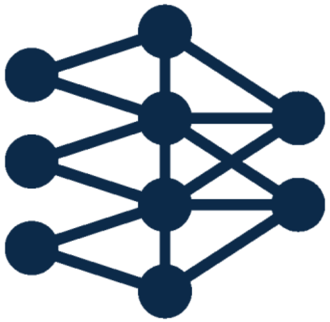
FBG shape (analytical) »

Other sensor »

» Fused shape [7], [8], [9]

X-Ray exposure - electromagnetic interferences

Bragg wavelengths »



» Shape [10] / Strains [11]

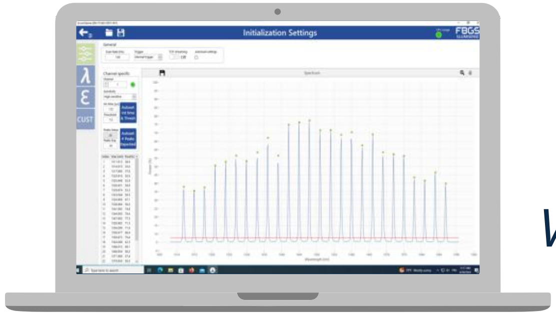
Accuracy needs improvements

[5] – Floris, I. et al. (2021)
[7] - Ha, Xuan Thao et al. (2023)
[8] - Ha, Xuan Thao et al. (2021)
[9] - Ourak, M. et al. (2021)
[10] - Roodsari, S. et al. (2024)
[11] - Han, Fei et al. (2023)

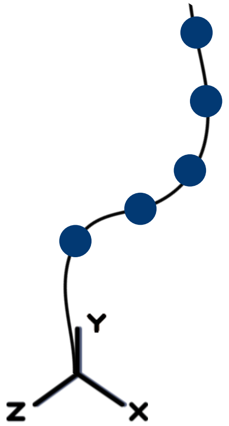
Workflow

» *Acquire Inputs and Ground Truth (GT)* » *Define input and output* » *Assess performances*

Design and train the Neural Network



Bragg Wavelengths » *Neural Network* » *3D positions of sensor's points*



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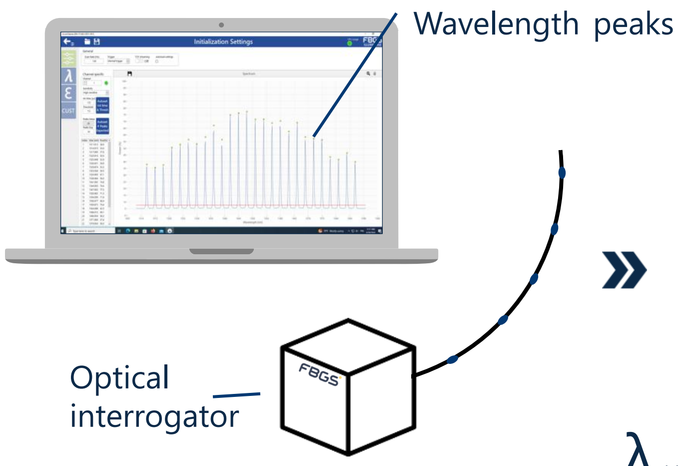
Input and Output

Input definition



$$\begin{array}{c} \text{4 cores} \\ \begin{bmatrix} \lambda_{1,1} & \cdots & \lambda_{1,4} \\ \vdots & \ddots & \\ \lambda_{29,1} & & \lambda_{i,j} \end{bmatrix} \end{array} \ \text{29 planes}$$

$\lambda_{i,j}$ - Bragg Wavelength of ith core and jth plane

Pre-processing

Computation of

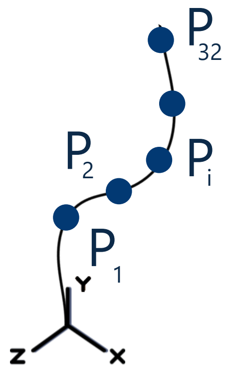
- μ_k - mean
- σ_k - std deviation

For each sample k

z-standardization of wavelengths

$$z_{ijk} = \frac{\lambda_{ijk} - \mu_k}{\sigma_k}$$

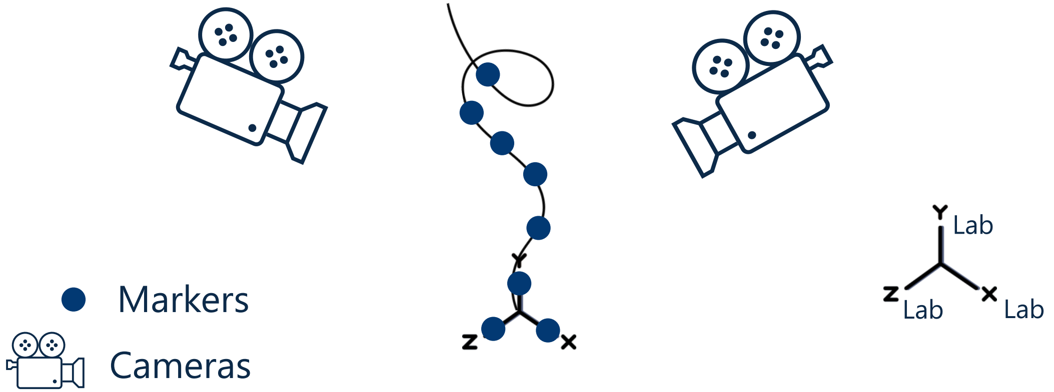
Output definition



$$\begin{array}{c} \text{3 coordinates} \\ \begin{bmatrix} P_{1,1} & \cdots & P_{1,3} \\ \vdots & \ddots & P_{i,j} \\ P_{32,1} & & \end{bmatrix} \end{array} \ \text{32 points}$$

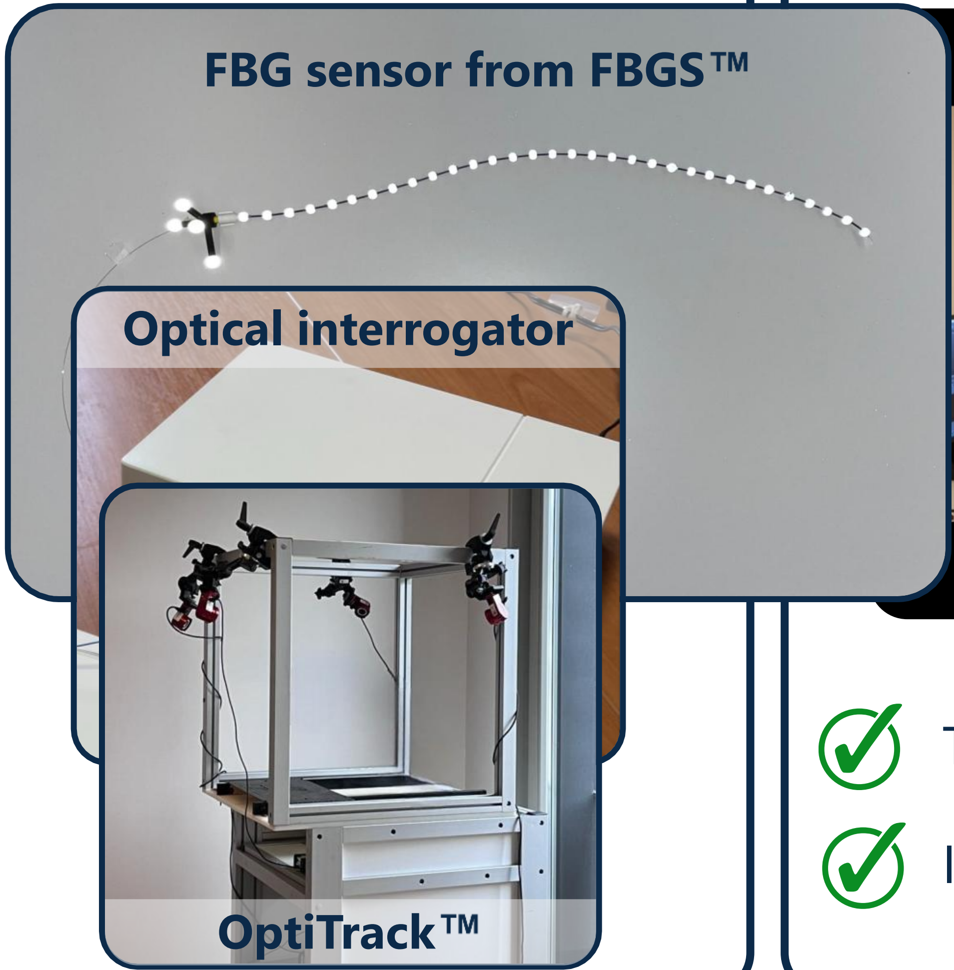
$P_{i,j}$ – coordinate j of point i

<u>Need of GTs to train the Neural Network!</u>

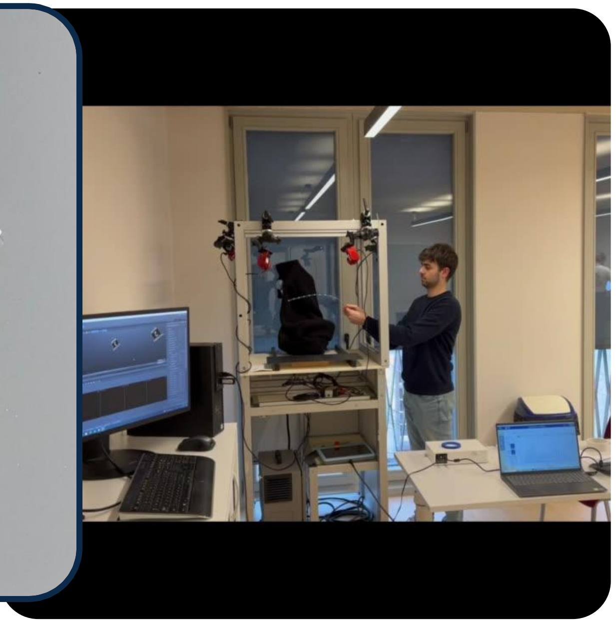


Data acquisition

Materials



Acquisition of inputs and GT



- ✓ Twist imposition
- ✓ Input-GT synchronization

General Dataset

- ✓ Generalization
- ⚠ Range of shapes to be covered

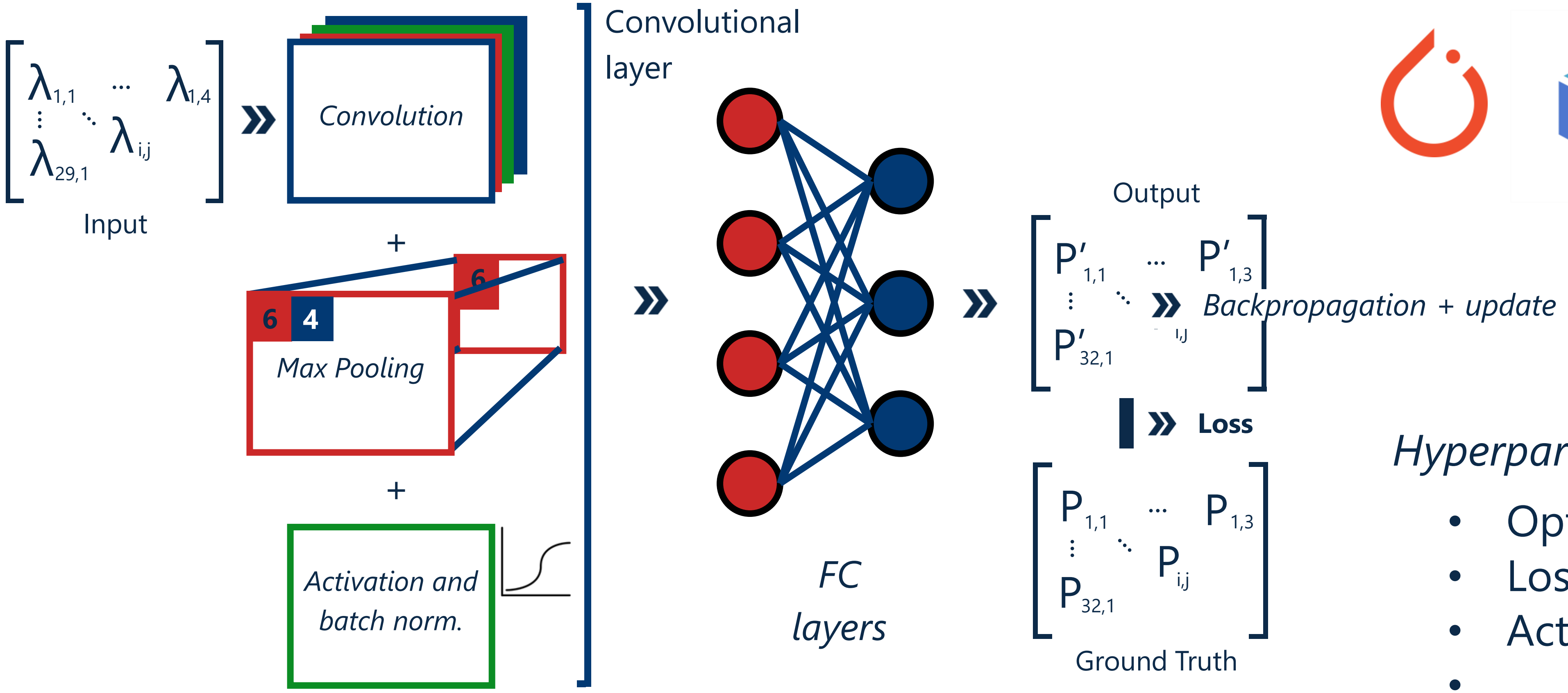
Training: ~230k samples
Validation: ~12k samples
Testing: ~9k samples

Application-specific Dataset

- ✓ Range of shapes to be covered
- ⚠ Generalization

Training: ~227k samples
Validation: ~10k samples
Testing: ~6k samples

Neural Network training



Libraries

Hyperparameters tuning *

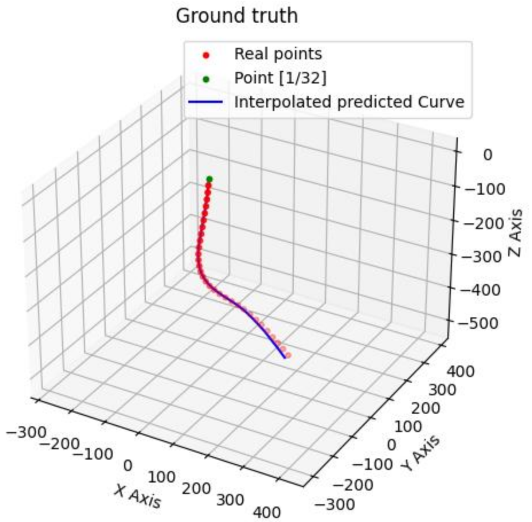
- Optimizer
- Loss function
- Activation function
- …

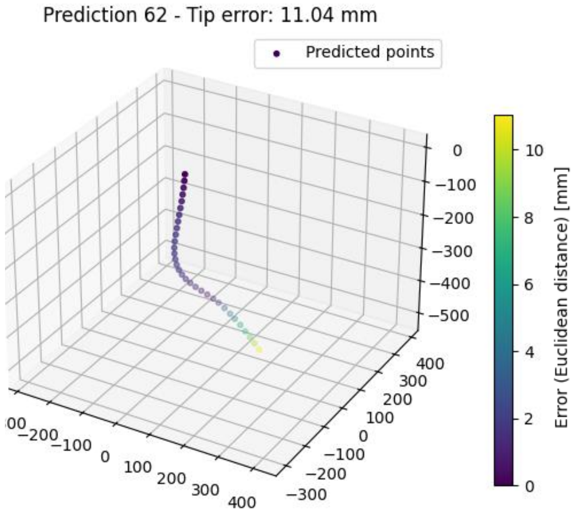
* - Details in the appendix

Neural Network training and testing

General Model

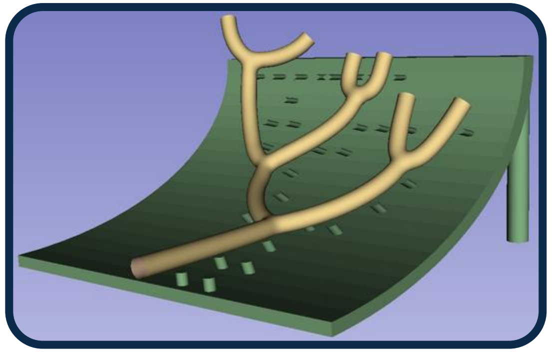
- Generalization
- Range of shapes to be covered
- Tested on acquired test-set (~9k samples)
- Compared against the literature





Application-specific Model

- Range of shapes to be covered
- Generalization
- Tested on 15 shapes on a vascular phantom
- Compared against FBGS™ commercial system on the same shapes



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General model against Literature

Evaluation Metrics

$$RMSE_i \; [mm] = \sqrt{\frac{1}{N}\sum_{j=1}^{N} ||\widehat{p_{i,j}} - p_{i,j}||}$$

N: number of markers

$\widehat{p_{i,j}}$: predicted position of marker j for sample i

$p_{i,j}$: ground truth position

$$Average\ RMSE \; [mm] = \frac{1}{M}\sum_{i=1}^{M} RMSE_i$$

M: number of samples

$$Tip\ error \; [mm] = ||\widehat{p_{32}} - p_{32}||$$

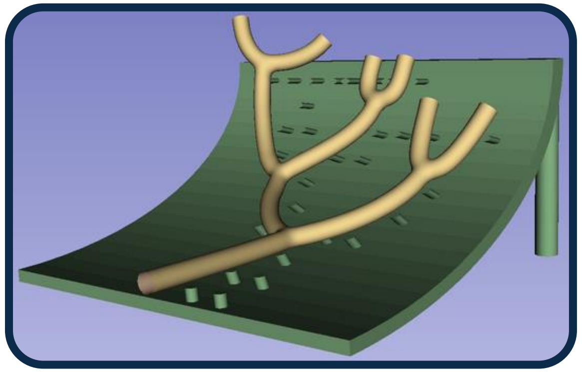
Comparison

	Roodsari, S. et al. (2024)	*General Model*	*Difference*
Avg RMSE	9.8 mm	5.7 mm	-41.8%
Median Tip Error	17.1 mm	9.1 mm	-46.8%
Fiber's length	300 mm	640 mm	+113%

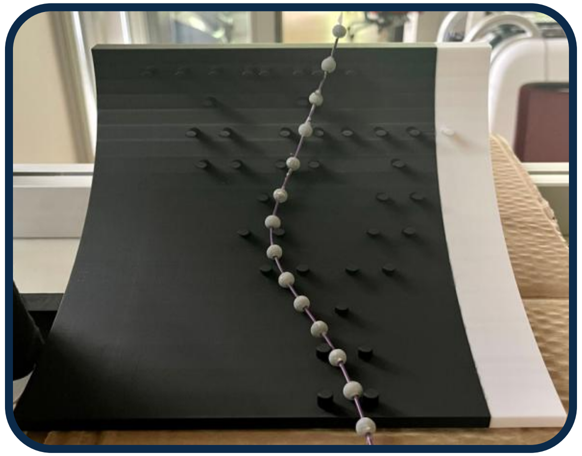
Test against FBGS™ commercial system

		App.-Specific Model	FBGS™
Without Twist	Avg RMSE	7.0 mm	9.4 mm
	Avg tip error	20.9 mm	17.0 mm
With Twist	Avg RMSE	5.9 mm	32.3 mm
	Avg tip error	23.6 mm	87.2 mm

Vascular phantom



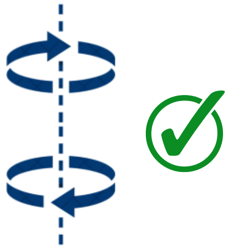
3D paths



Achievements and Perspectives

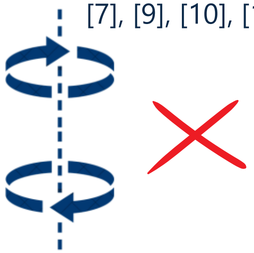
Twist imposition

This Project



Literature

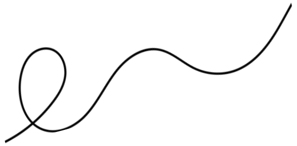
[7], [9], [10], [11]



Fiber length

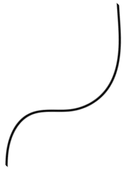
This Project

L = 640 mm



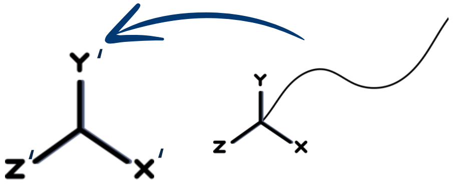
Literature

[7]	540 mm
[8], [9]	170 mm
[10]	300 mm
[11]	44 mm

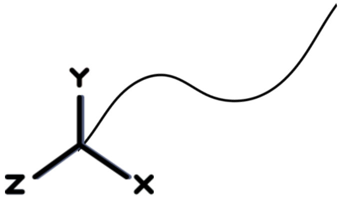


Reference frame adaptation

This Project

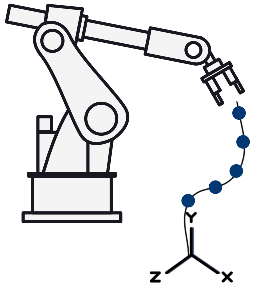


Literature

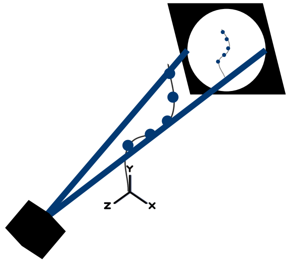


Perspectives

Automated data acquisition



Sensor fusion



[7] - Ha, Xuan Thao et al. (2023) [8] - Ha, Xuan Thao et al. (2021) [9] - Ourak, M. et al. (2021) [10] - Roodsari, S. et al. (2024) [11] - Han, Fei et al. (2023)

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Thank you for your *kind* attention!

And a special thank to my supervisors **Prof. Elena De Momi**, **Prof. Stéphane Cotin,** and **Prof. Florent Nageotte**, and co-supervisors **Anna Bicchi**, **Angela Peloso,** and **Phd Valentina Scarponi**