Simultaneous Shape Reconstruction and Force Estimation of Soft Bending Actuators Using Distributed Inductive Curvature Sensor

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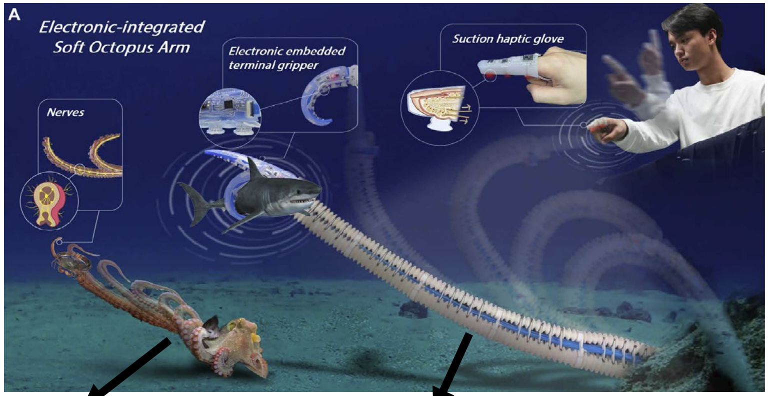
Background of Soft Robots

Research Trend

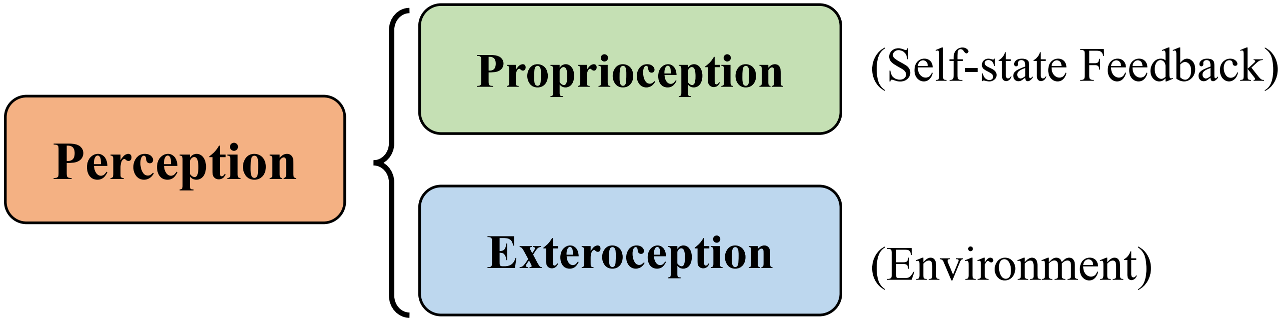
Equip soft robots with biological intelligence to interact with the environment.

Examples [1]



Octopus

Soft Manipulator



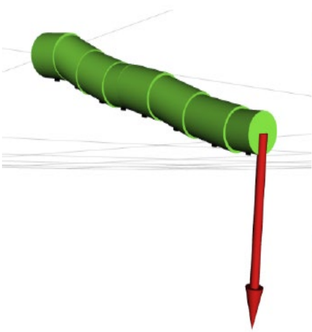
[1] Z. Xie et al., "Octopus-inspired sensorized soft arm for environmental interaction," *Science Robotics*, 2023.

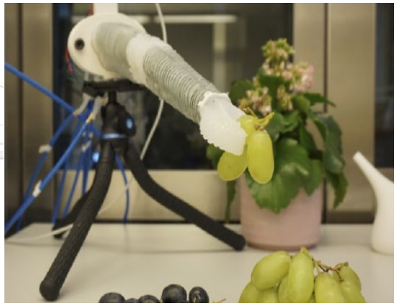
Perception System of Soft Robots

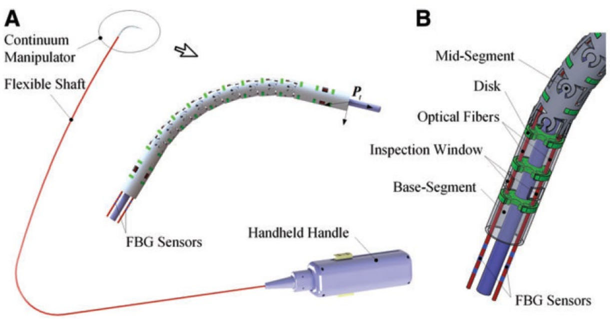
Challenges

- ❑ Flexible and Stretchable
- ❑ Infinite degrees of freedom
- ❑ Undesired external sensors

Related Work [2-3]







Goal

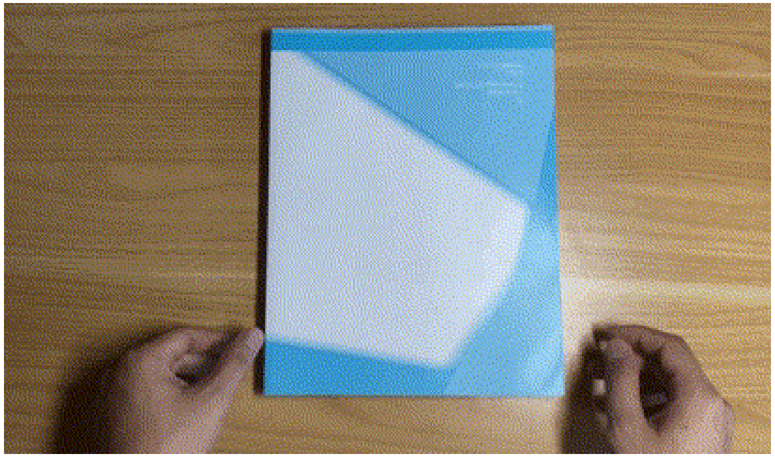
Simultaneous high-resolution shape sensing and accurate external force estimation using only a proprioceptive sensor.

[2] Y. Toshimitsu, K. W. Wong, T. Buchner, and R. Katzschmann, “SoPrA: Fabrication amp; Dynamical Modeling of a Scalable Soft Continuum Robotic Arm with Integrated Proprioceptive Sensing,” in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*.

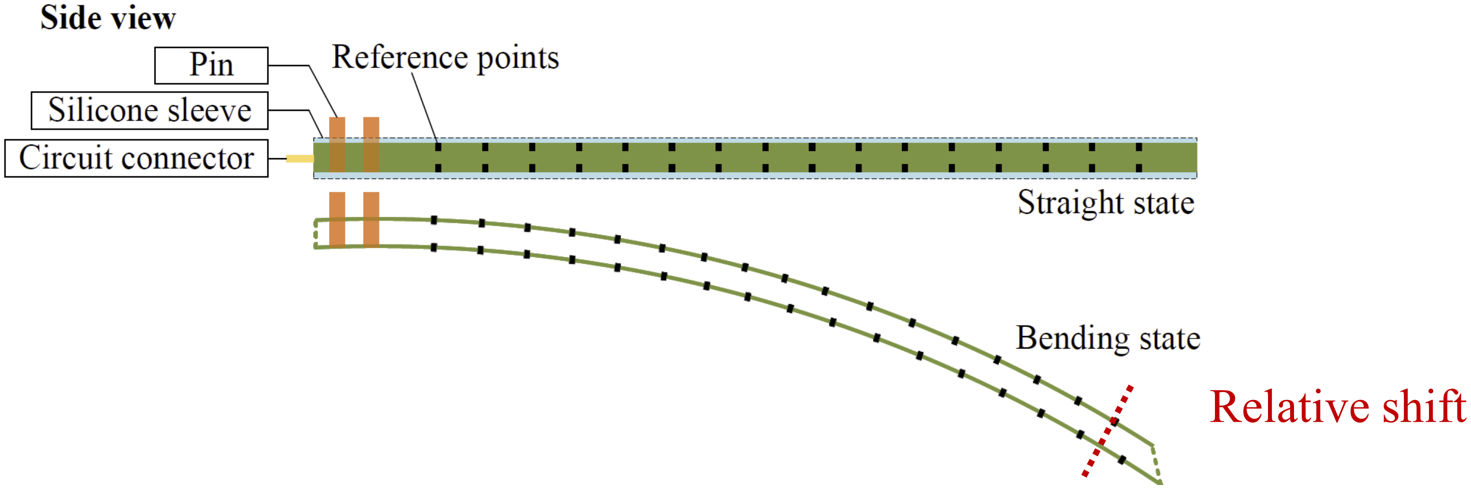
[3] A. Gao, N. Liu, M. Shen, M. E.M.K. Abdelaziz, B. Temelkuran, and G.-Z. Yang, “Laser-Profiled Continuum Robot with Integrated Tension Sensing for Simultaneous Shape and Tip Force Estimation,” *Soft Robotics*, vol. 7, no. 4, pp. 421–443, Aug. 2020.

Sensor Concept

- Sensor principle



- Proposed shape sensor



Distributed Inductive Curvature Sensor

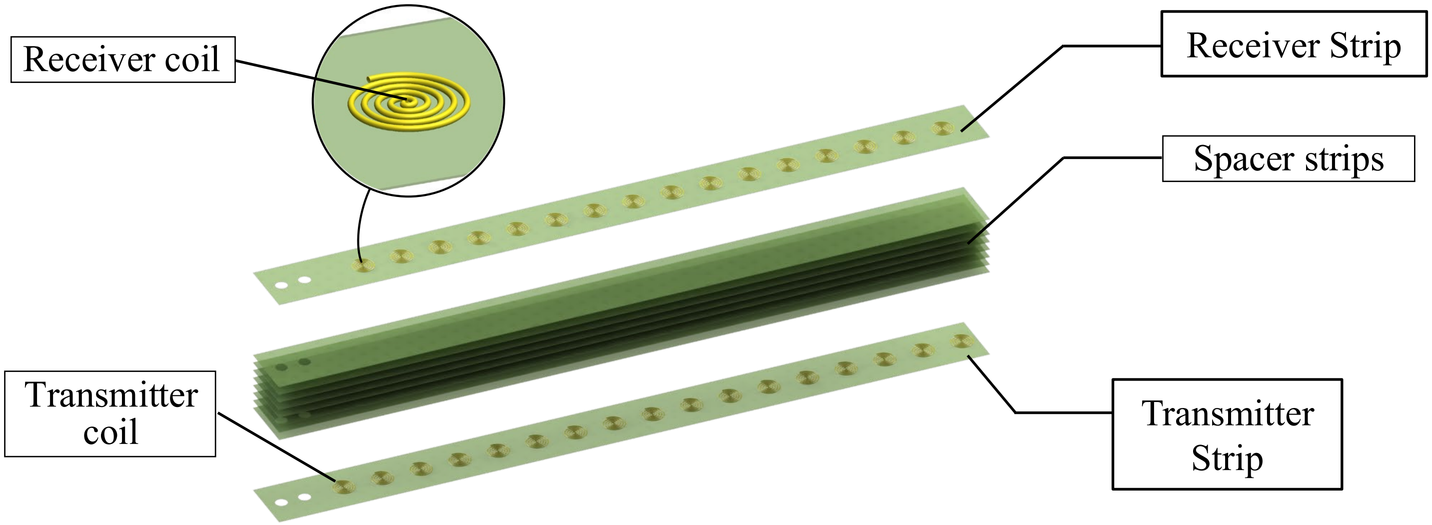
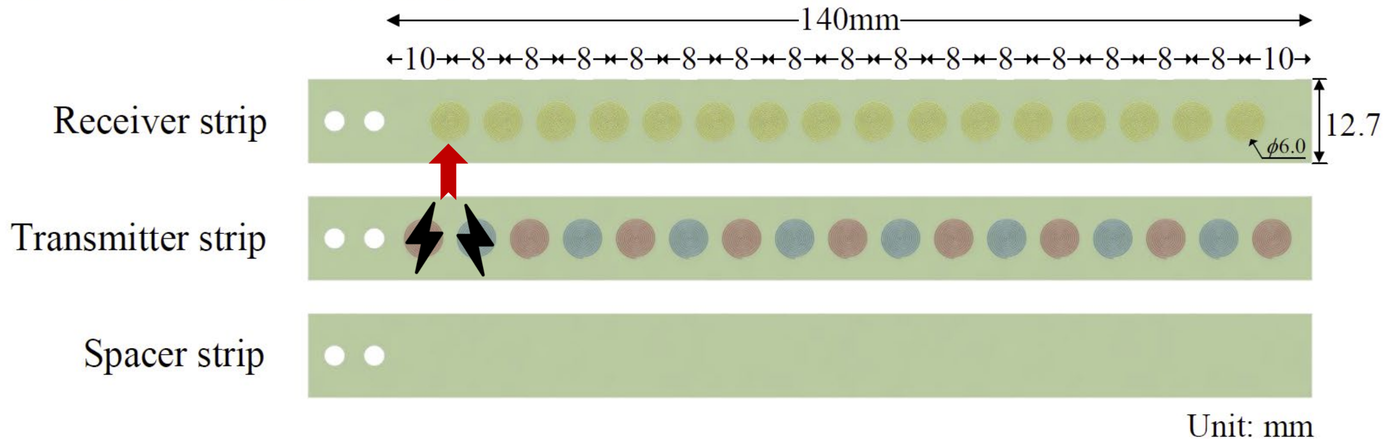


Figure: Sensor structure

Top view of each type of strip



Distributed Inductive Curvature Sensor

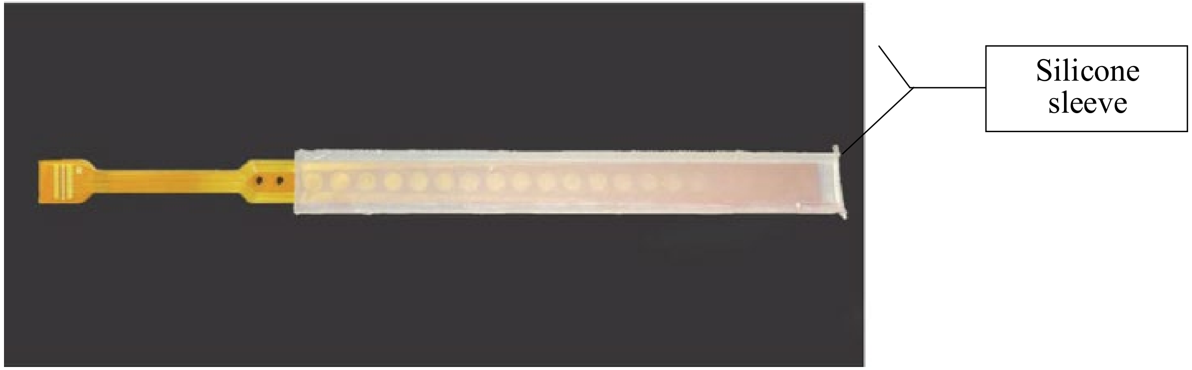


Figure: Sensor Prototype

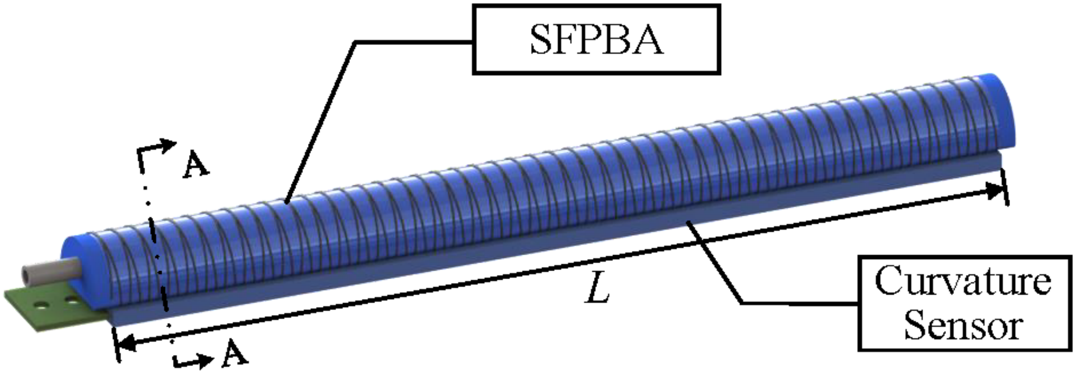
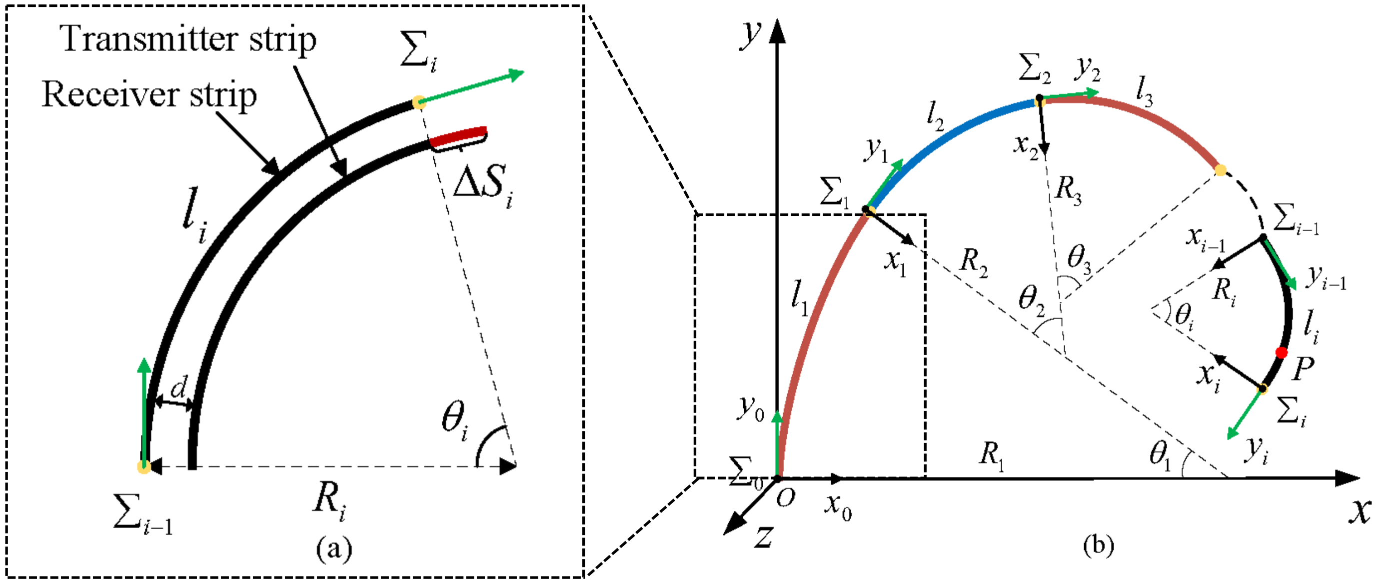


Figure: Assembling with soft fiber-reinforced pneumatic bending actuator (SFPBA)

Shape Reconstruction Algorithm



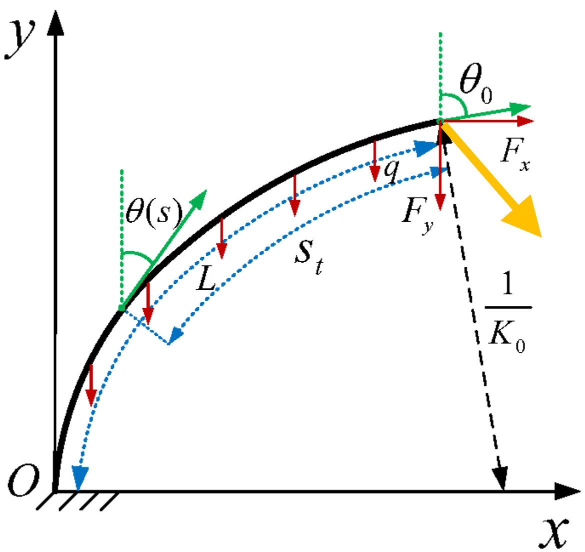
Induced AC Voltage ΔA_i → Polynomial Fitting → **Local Relative Shift** ΔS_i → Geometry Relationship → **Local Curvature** κ_i

- P in the inertial frame Σ_0 :

$$\begin{bmatrix} p^0(s) \\ 1 \end{bmatrix} = T_1^0(\theta_1) \cdot T_2^1(\theta_2) \cdots T_{i-1}^{i-2}(\theta_{i-1}) \cdot \begin{bmatrix} p^{i-1}(s) \\ 1 \end{bmatrix} \quad (1)$$

Modeling of Bending Actuator with External Force

- Euler-Bernoulli beam theory for curved cantilever

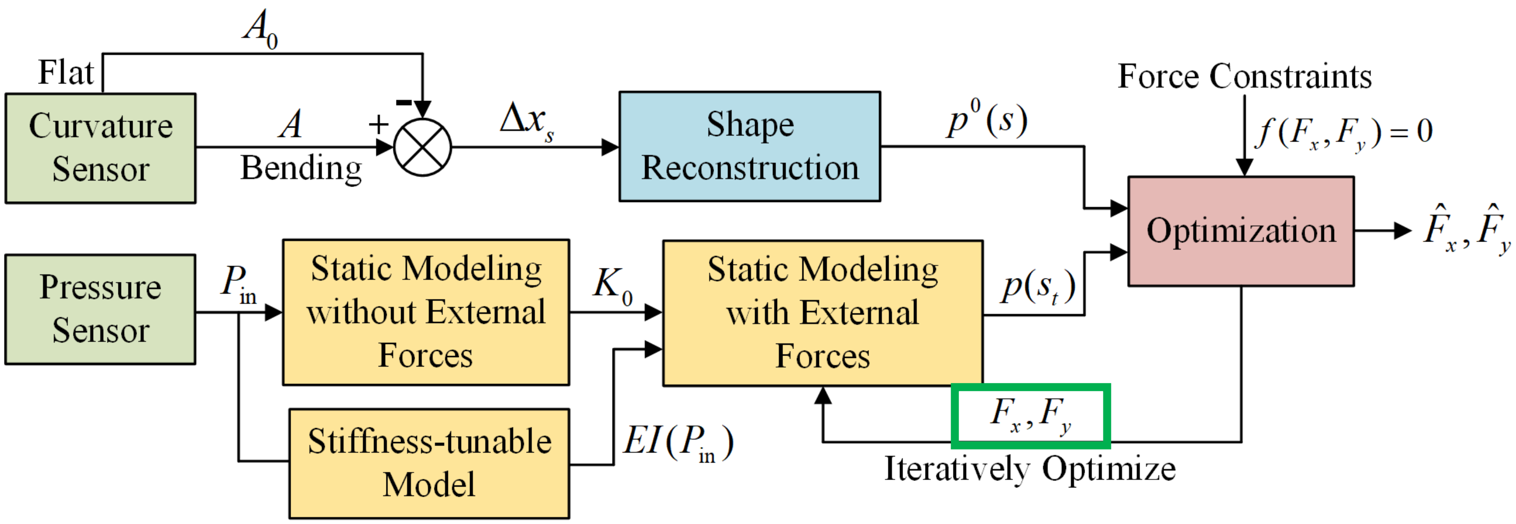


$$\begin{cases} EI\left(\dfrac{d^2(\theta(s_t))}{ds_t^{\,2}}\right) + F_x\cos(\theta(s_t)) + F_y\sin(\theta(s_t)) + qs_t\sin(\theta(s_t)) = 0 \\ B.C. \quad \theta(L) = 0,\ \dfrac{d\theta(0)}{ds_t} = -K_0 \end{cases} \tag{4}$$

Integrate for shape:

$$\begin{cases} x(s_t) = \int_L^{s_t} \sin(\theta(\tau))d\tau \\ y(s_t) = \int_L^{s_t} \cos(\theta(\tau))d\tau \\ p(s_t) = \begin{bmatrix} x(s_t) & y(s_t) & 0 \end{bmatrix}^T \end{cases} \tag{5}$$

Force Estimation Algorithm

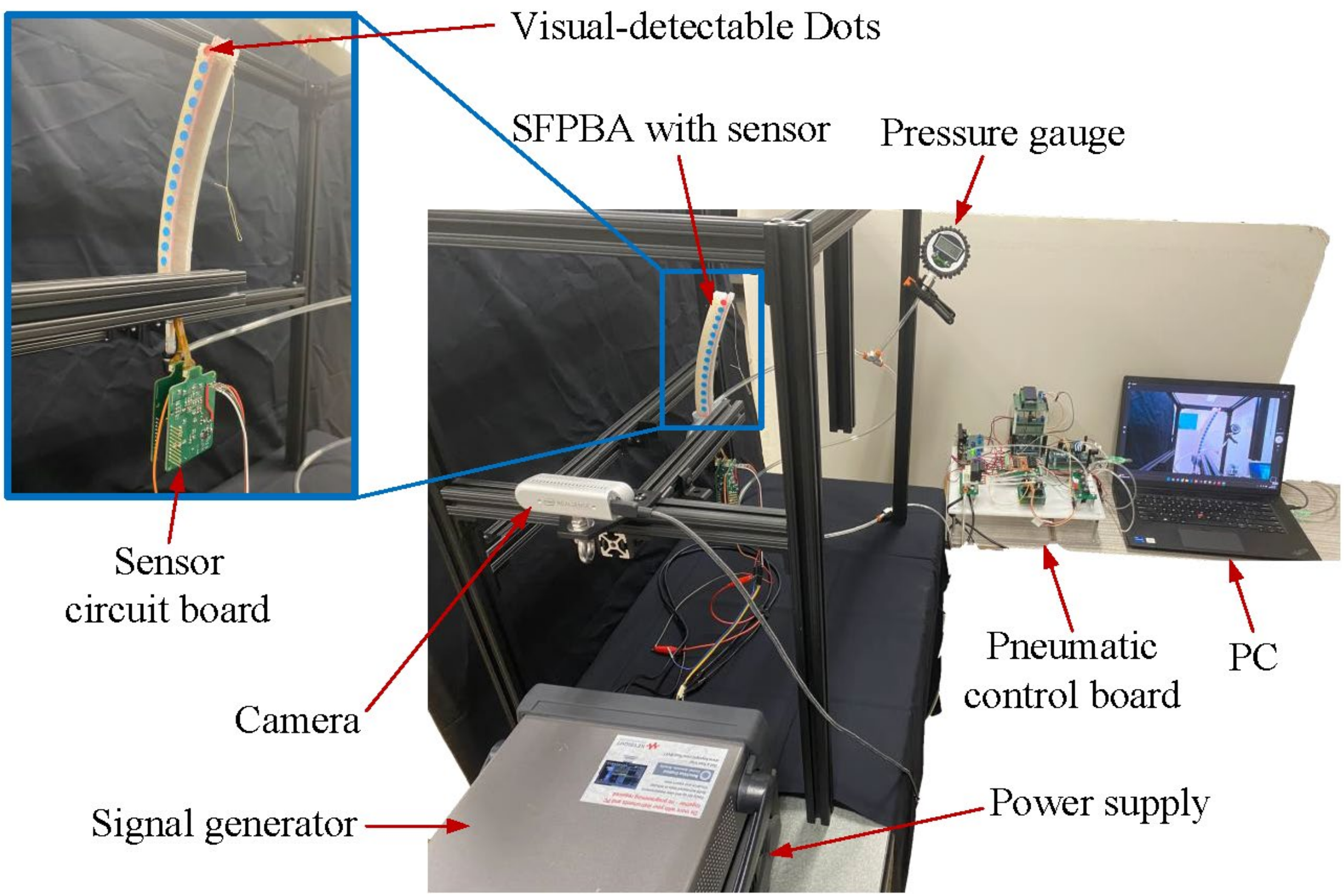


- Model-based optimization:

$$(\hat{F}_x, \hat{F}_y) = \arg\min_{F_x, F_y} \int_0^L \left(\left\| p^0(s) - p(s_t) \right\| \right)^2 \mathrm{d}s, \quad \text{s.t.} \quad f(F_x, F_y) = 0 \tag{6}$$

where $f(F_x, F_y) = 0$ captures constraints for practical application (Payload/Contact)

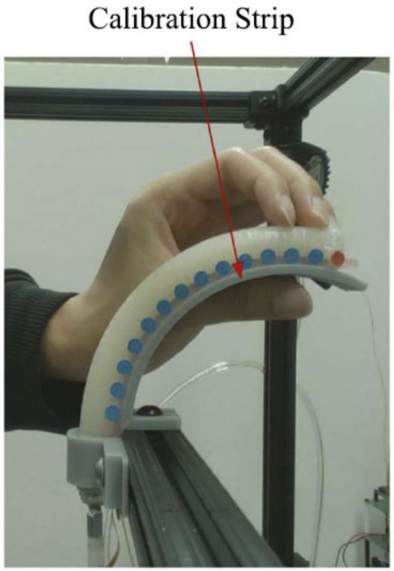
Experimental Setup

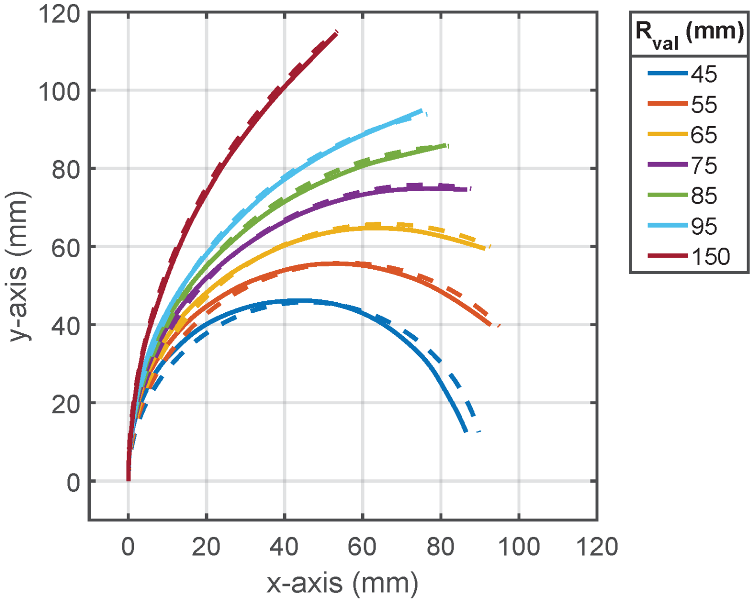


Results on Shape Reconstruction

- Calibration for Voltage-Shift-Curvature Mapping

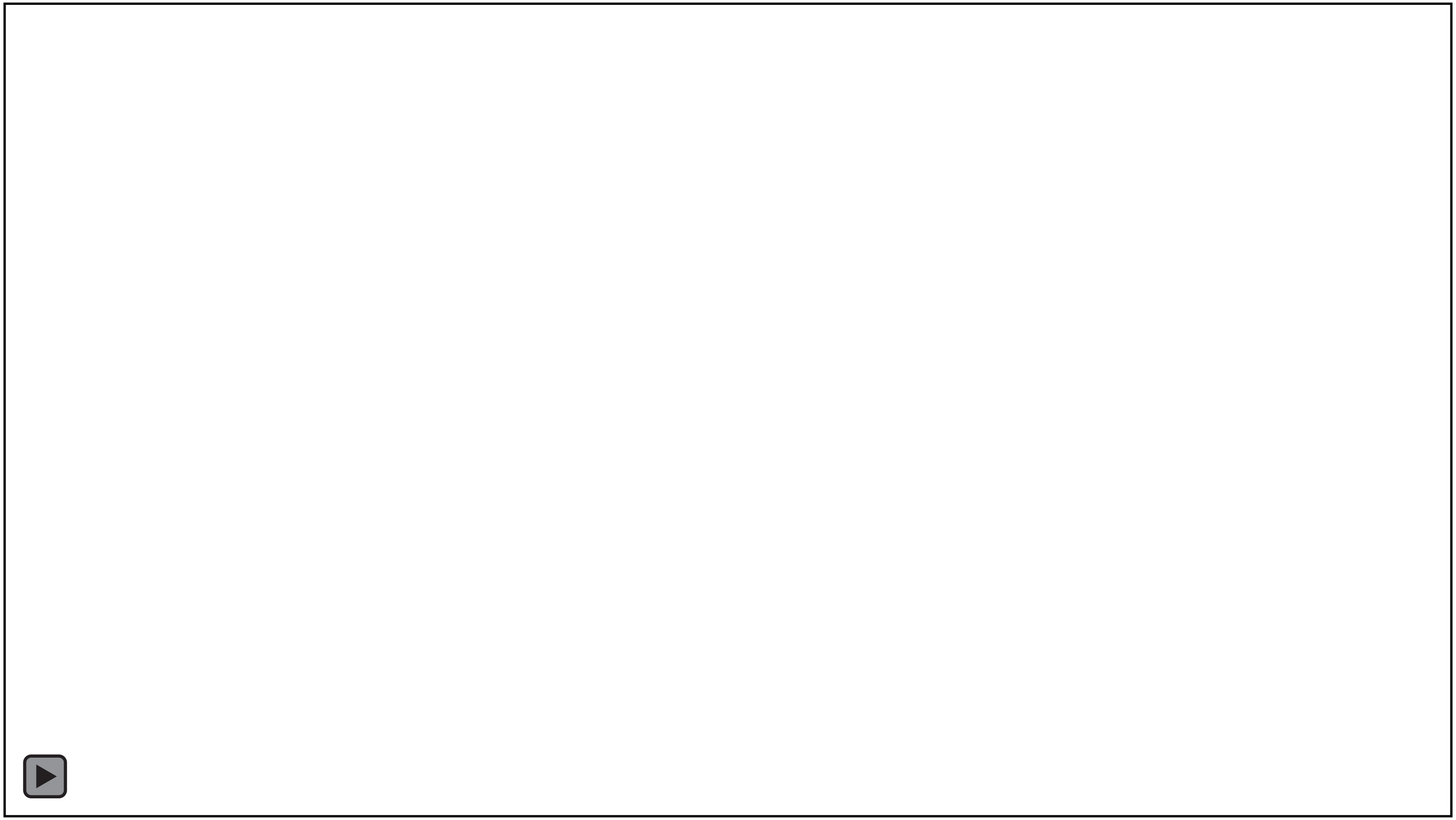
$$\delta\kappa = 0.65\% \pm 0.58\% \qquad (\delta p)_{max} = 1.59\% \pm 0.72\%$$



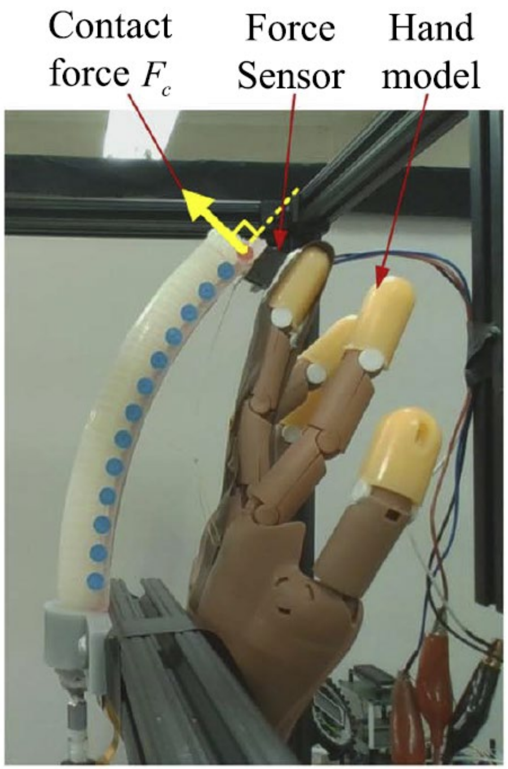


- Real-time at a minimum frequency of 35 Hz

Demonstration on Shape Reconstruction



Results on Contact Force Estimation



- Constraints: $f(F_x, F_y) = F_x \sin(\theta_0) + F_y \cos(\theta_0) = 0$

Demonstration on Contact Force

Results on Contact Force Estimation

- Contact force estimation error

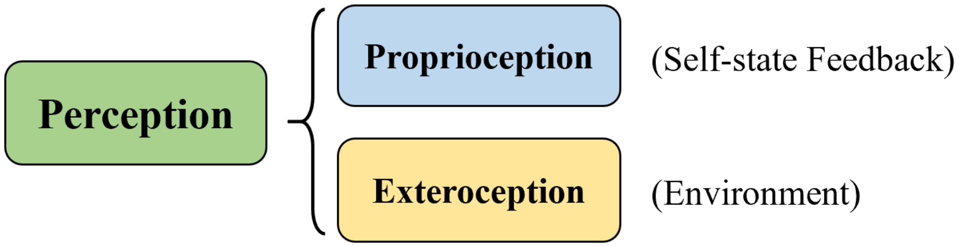
TABLE II
COMPARISON OF MEAN ERRORS (%) IN CONTACT FORCE ESTIMATION WITH AND WITHOUT GEOMETRIC CONSTRAINT

	Without Constraint			With Constraint		
Force Range (N)	$\hat{F}_x$	$\hat{F}_y$	$\hat{F}_c$	$\hat{F}_x$	$\hat{F}_y$	$\hat{F}_c$
0–0.1	4.13	2.93	4.27	1.57	3.91	2.61
0.1–0.2	8.13	2.51	4.40	3.02	3.43	1.35
0.2–0.3	17.70	13.18	9.04	7.42	4.29	7.52
0.3–0.4	6.29	42.95	12.19	9.15	21.01	8.17
Mean of Full Range	14.90	12.91	7.21	5.15	6.77	4.86

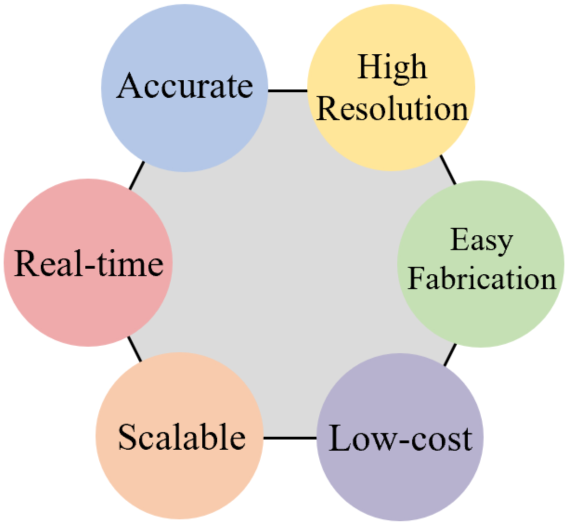
- Package into integrated App using Matlab *App Designer*

Conclusion

A high-fidelity perception system for soft robots



- ❑ A novel distributed inductive curvature sensor

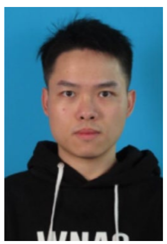


- ❑ Efficient model-based force estimation

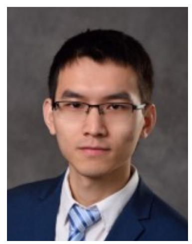
Future Work

1. Develop control algorithms based on continuous shape feedback
2. 3D shape extension

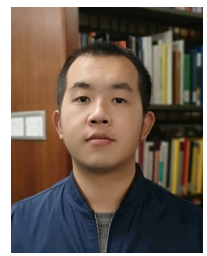
Acknowledgements:



Lei Peng



Dr. Hongyang Shi



Xinda Qi

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Dr. Vaibhav Srivastava

Dr. Xiaobo Tan

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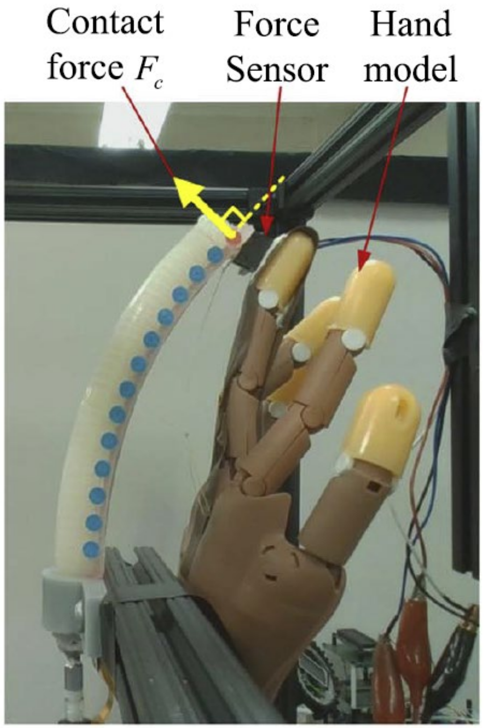
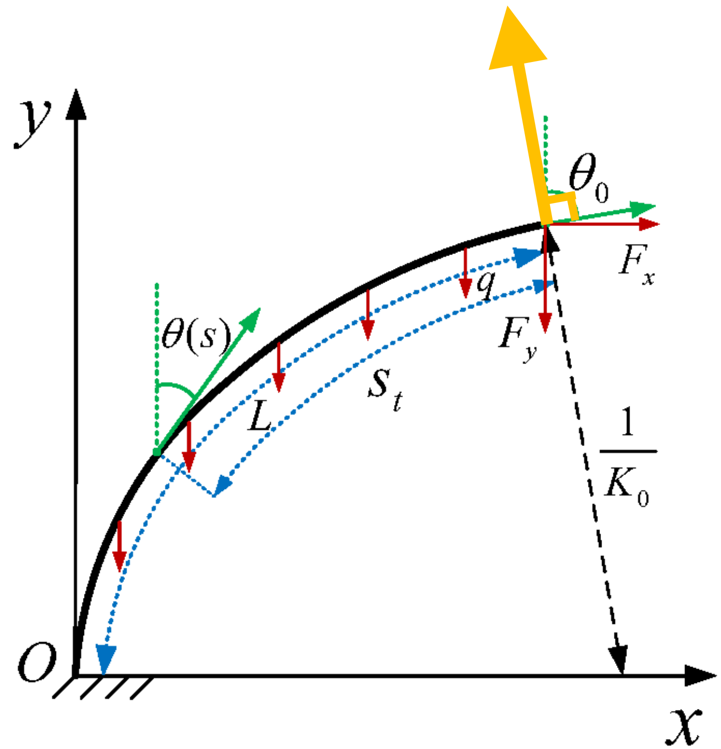
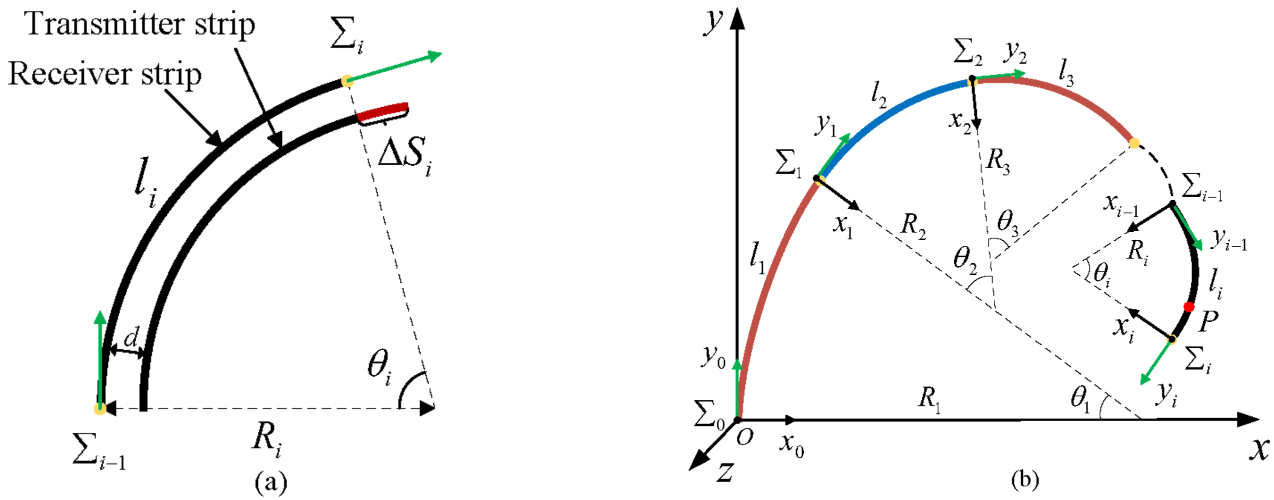
Results on Contact Force Estimation

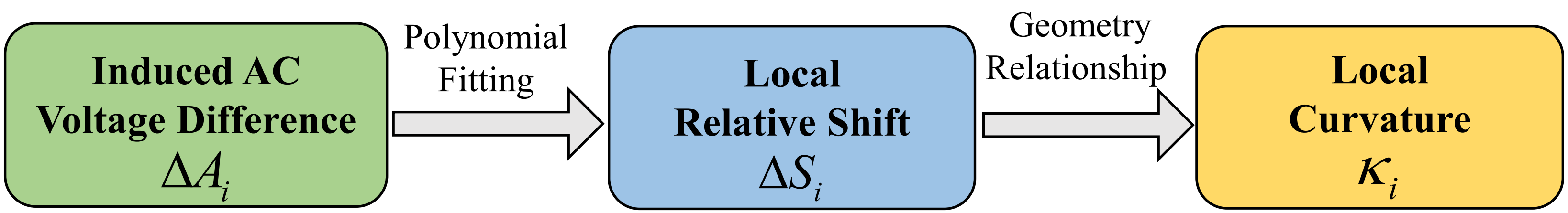




- Constraints: $f(F_x, F_y) = F_x \sin(\theta_0) + F_y \cos(\theta_0) = 0$

Shape Reconstruction Algorithm

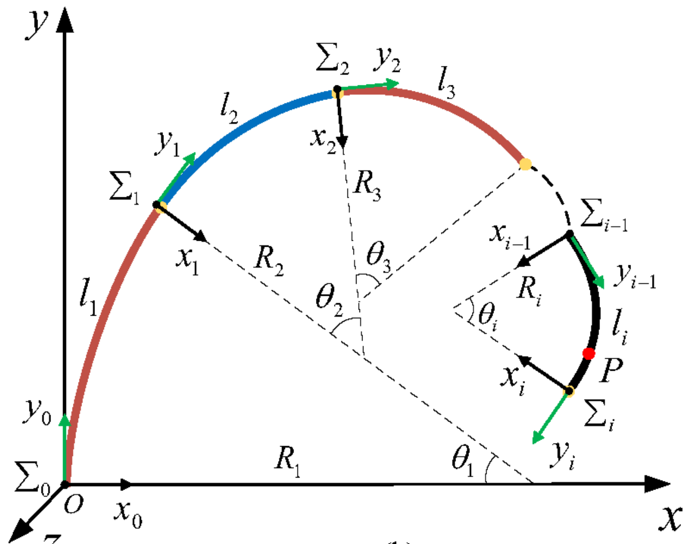




- Voltage-Shift-Curvature Mapping:

$$S_i = \begin{cases} f_{\text{odd}}(\Delta A_i) = \sum_{k=0}^{n} a_k (\Delta A_i)^k, & i \text{ is odd}, \\ f_{\text{even}}(\Delta A_i) = \sum_{k=0}^{n} b_k (\Delta A_i)^k, & i \text{ is even}, \end{cases} \quad \& \quad \kappa_i = \frac{\Delta S_i}{dl_i} \tag{1}$$

Shape Reconstruction Algorithm



(b)

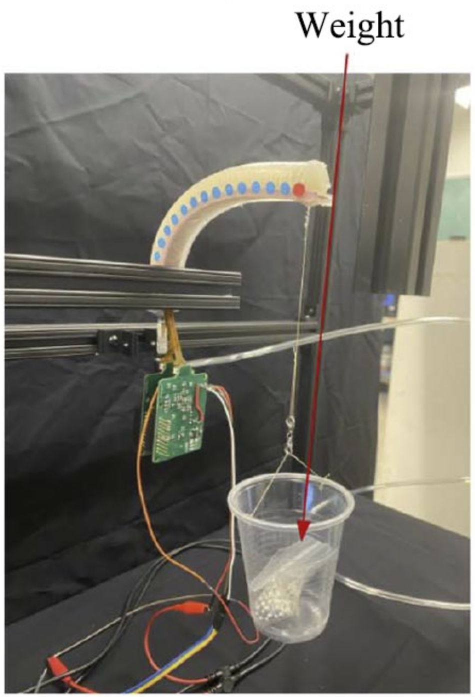
- The homogeneous transformation matrix mapping from Σ_{i-1} to Σ_i :

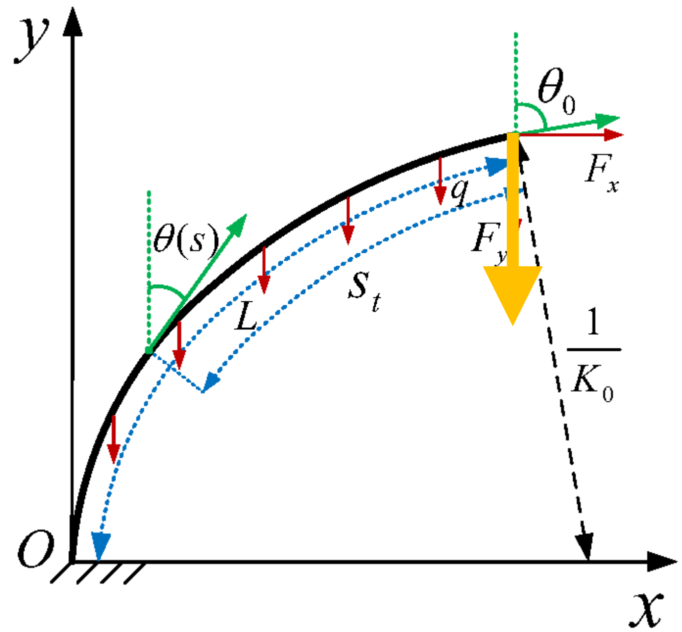
$$T_i^{i-1}(\theta_i) = \begin{bmatrix} R_z(-\theta_i) & p_i^{i-1}(\theta_i) \\ 0 & 1 \end{bmatrix} \quad (2)$$

- P in the inertial frame Σ_0 :

$$\begin{bmatrix} p^0(s) \\ 1 \end{bmatrix} = T_1^0(\theta_1) \cdot T_2^1(\theta_2) \cdots T_{i-1}^{i-2}(\theta_{i-1}) \cdot \begin{bmatrix} p^{i-1}(s) \\ 1 \end{bmatrix} \quad (3)$$

Results on Tip Load Estimation





- Constraints: $$f(F_x, F_y) = F_x = 0$$

Demonstration on Tip Loads

- Tip loads estimation error: 0~0.3N 11.9%

  0~0.2N 5.49%