Force Sensing Steerable Needle with Articulated Tip and Sensorized Tendons

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Introduction

This study examines a unique tip-force sensing steerable needle, composed of a metal tube with laser-machined multi-DOF hinge joints near the distal end. Sensor instrumented optical fiber bonded to Kevlar tendons (sensorized tendons) actuate these joints.

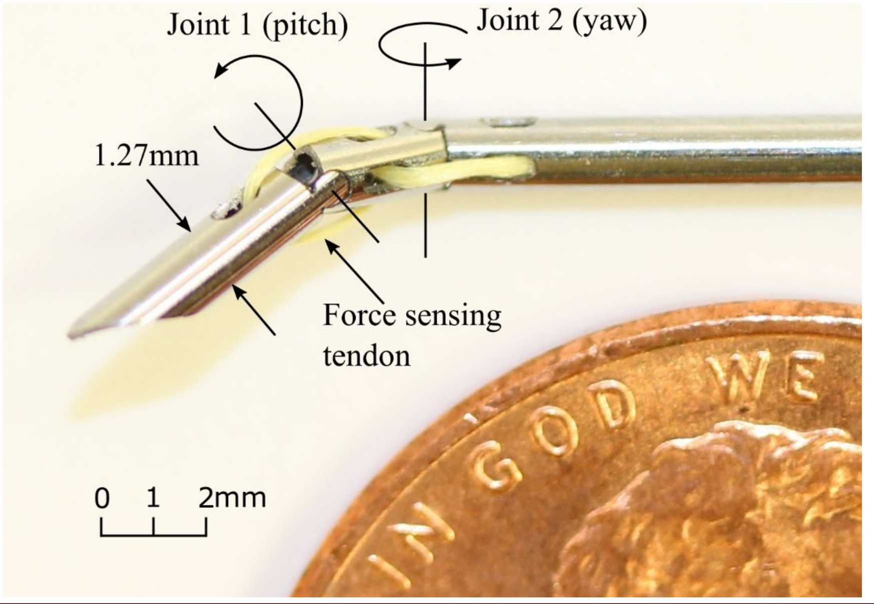


Fig. 1: Laser-machined steerable needle with orthogonal hinges for pitch and yaw. Polarization maintaining fiber Bragg gratings fiber (PM-FBG) enables force, temperature, and tissue stiffness estimation.

Objectives

Motivation:

- Introducing reliable sensing and means for actuation within micro-instruments for robotic surgery remains complex - *form factor, manufacturability, and sensor-response* limit design choices.

Proposition:

- To integrate multiple robotic functions within a single element – *Laser machined multi-DOF hinge segments on tubes with Sensorized actuating tendons.*

Background

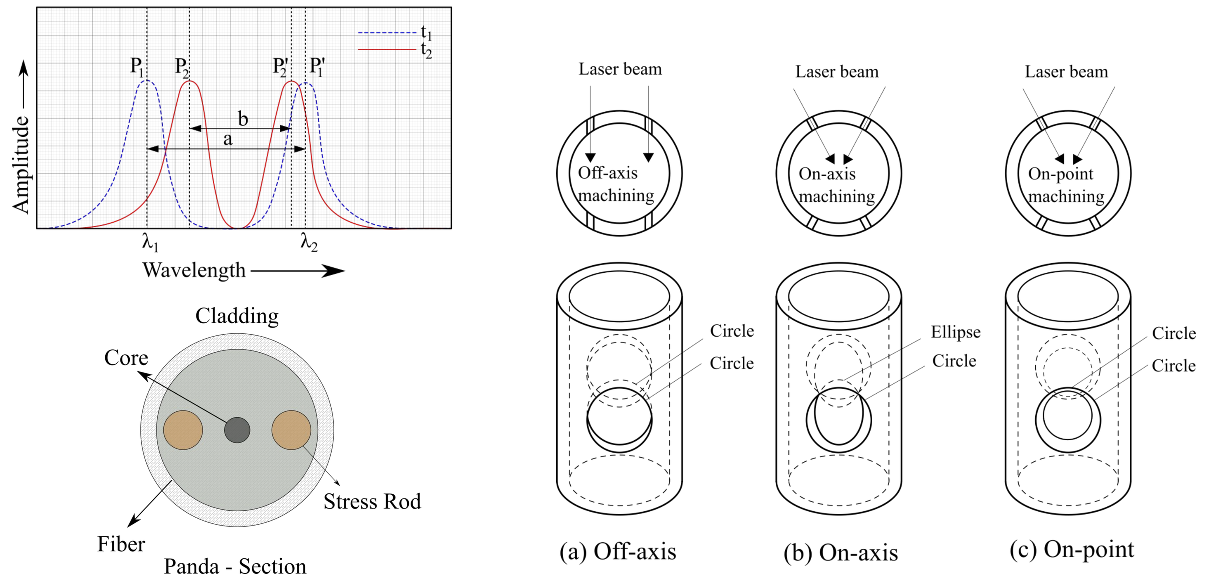


Fig. 2: Spectral response of a single PM-FBG fiber (Left-Top) and cross-section (Left-Bottom). Different modes of laser cutting leading to various geometrical outcomes (Right)

- **Optical sensing**: The instantaneous peak separation relates to temperature, while their temporal difference is proportional to strain. Hence the sensor data is decoupled.
- **On-Axis Machining**: In this mode of machining, elliptical sections are formed away from a circular surface cut. This helps prevent hinges from dislocating radially away from the tube axis.

Fabrication and Design of the Prototype

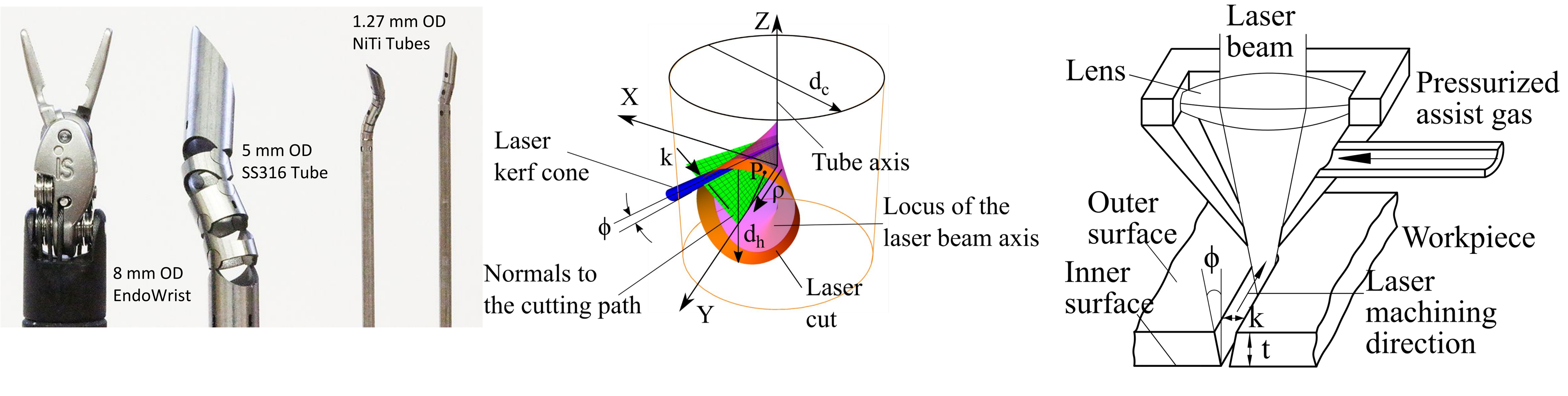
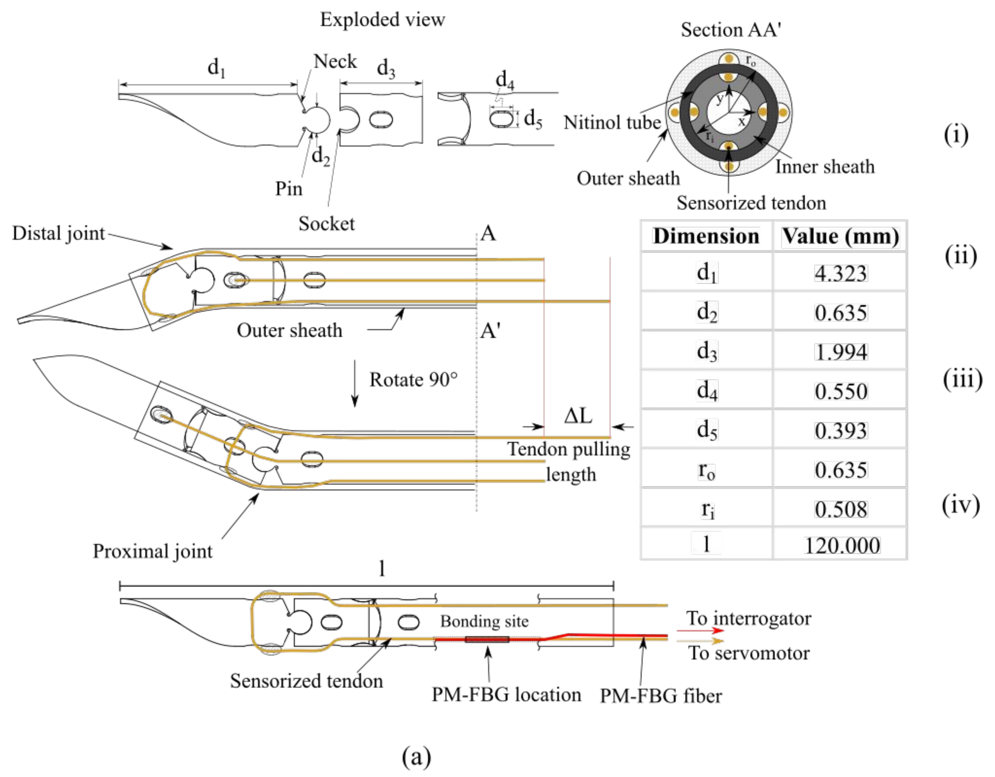
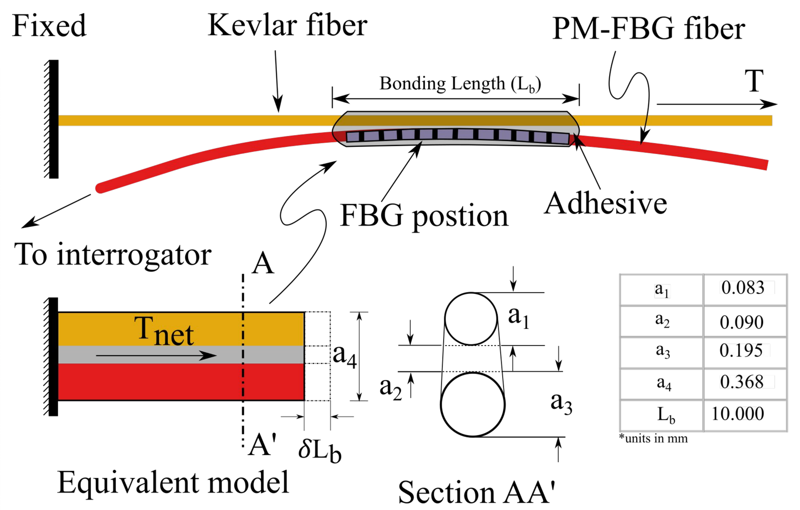


Fig. 3: Laser machined prototypes contrasted against the da-Vinci EndoWrist (Left), geometric model for the laser machined hinge segment to describe the region of interference, and the laser machining process whose effects can be approximated using a kerf width and a kerf angle.



Dimension	Value (mm)
d_1	4.323
d_2	0.635
d_3	1.994
d_4	0.550
d_5	0.393
r_o	0.635
r_i	0.508
l	120.000

Fig. 4: Design and prototype of steerable needle. (a) exploded view depicting each segment (top), actuation configurations of the orthogonal hinges (Angle >25 deg per hinge) and dimensions (middle) and PM-FBG location. (b) various tendon routing methods. (iii) is selected in this paper for prototyping.



a_1	0.083
a_2	0.090
a_3	0.195
a_4	0.368
L_b	10.000

*units in mm

Fig. 5: Schematic depicts the PM-FBG fiber reinforced with pre-tensioned Kevlar. Equivalently modeled as a composite bar under axial tension with Kevlar and optical fiber regions separated by an exaggerated adhesive layer.

Proof of Concept Experiments

Description:

- A test setup (See *Fig. 6*) was assembled with the instrumented prototype - all four tendons were driven by servo motors mounted atop the carriage of a linear slide.
- This system was used to interface the instrument with phantom tissue of varying stiffness. The performance of the hinge was contrasted with that of a flexure.

Observation:

Fig. 8 indicates that the proposed hinge-joint needle experiences about one-half the tissue reaction force compared to the flexure-joint needle for equivalent deflections.

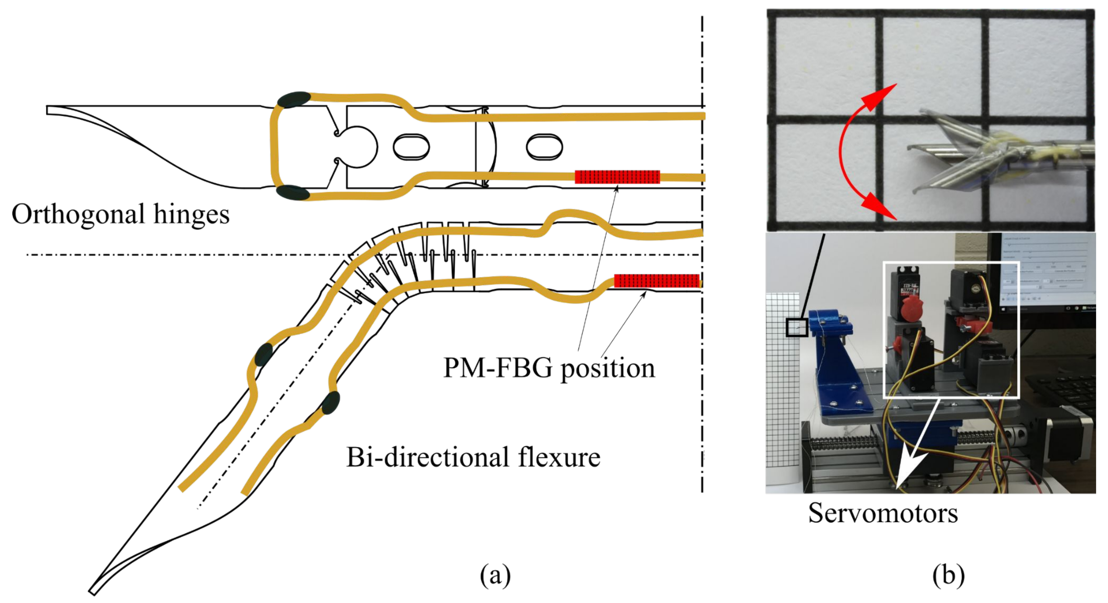


Fig. 6: Experiment setup (a) two different joint types (hinge and flexure) of needles tested. (b) bent joint in air (top) and experimental setup (bottom)

Results

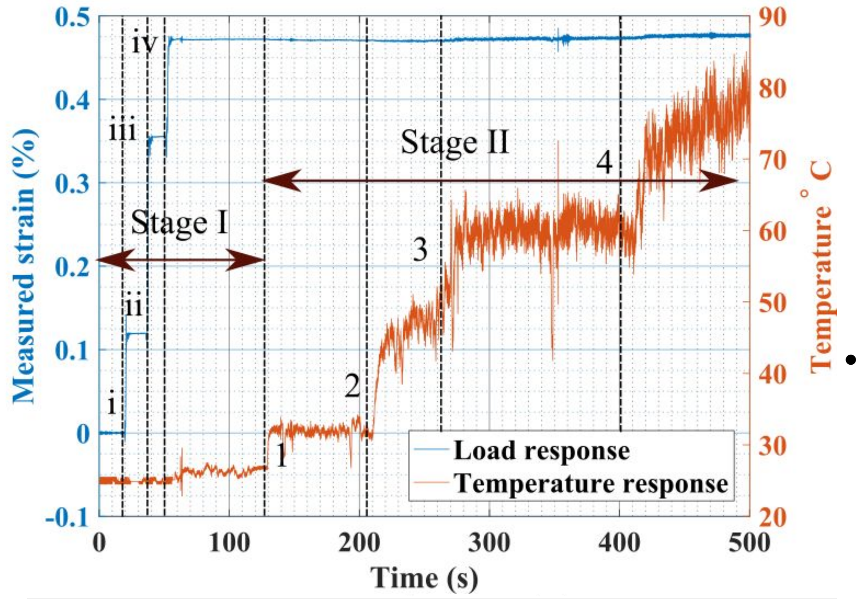


Fig. 7: Temperature independence of the PM-FBG fiber. Stage I – Constant temperature and incremental load. Stage II – Constant load and increasing temperature

- Validates the temperature independent force-sensing in sensorized tendons.

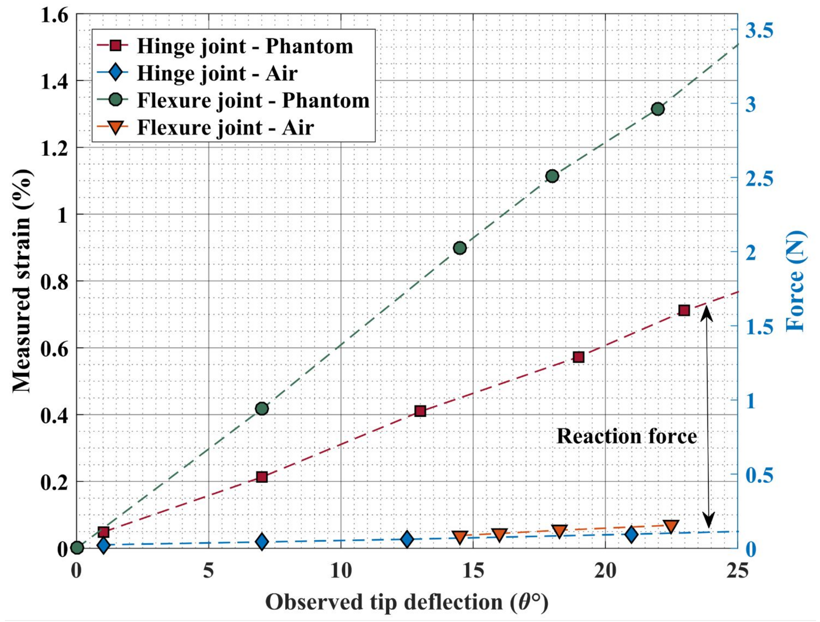


Fig. 8: Strain and measured force for the actuated hinge and flexure within air and phantoms.

- Shorter tip length, improved tendon routing, and joint stiffness aid the performance of the laser-machined hinge. Tensile load > 40 N.

Conclusions

- We demonstrated the feasibility of an articulate robotic needle, where, laser-machined orthogonal hinge joints permit multi-DOF tip-motion and inherent working channel, while Kevlar reinforced PM-FBG fibers enable local temperature and force-estimation.
- The difference between the strain measured when in air and when within phantom, provides an estimate of the reaction force component generated by tissue
- The approach of embedding laser machined hinge joints can spatially accommodate an inner channel for drug delivery, enabling customization, and eliminating the need for micro-assembly.
- Concurrently, the Kevlar reinforced PM-FBG fibers can provide means for friction-free haptic feedback through localized force, temperature and stiffness estimation.

Future Work and Acknowledgement

- We will perform combined insertion and tip actuation tests to reach specified targets. An outer multi-lumen tube will guide these tendons, keep the pin in place and strengthen the joint against buckling.
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