CHE 266 Final Report: Custom Test Fixture for Experimental Characterization of Laser Engraved Optical Fibers

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1 Abstract

Optic fiber bending sensors constitute a promising method for 3D shape sensing with potential applications in localization and control of continuum robots [1]. However, the existing instruments for fiber bending sensing are relatively expensive. This report presents laser cutting as a low-cost method for fabrication of sensitized optical fibers. We present a custom test setup for characterization of sensitized fibers and use this setup to empirically validate effective laser cutting parameters for creating bending sensors.

2 Introduction

Continuum 3D shape sensing is a challenging task due to the richness of the spatial information that it requires. However, effective 3D shape sensing is essential for taking full advantage of the capabilities of soft continuum robots as it enables both environmental mapping via movement and feedback control of the robot's shape.

One approach to shape sensing is to establish a correlation between the transmission of light through an optical fiber and the curvature of the fiber. This concept has been leveraged to create sensors that rely on the principle of total-internal reflection to selectively change the intensity of their transmission via a sensitized, or grated, zone [2]. By sensitizing one side of the optical fiber, these sensors leverage the fact that rays converge on the convex side of a bent fiber. Thus, bending the fiber in one direction causes the rays to align with the grated zone and refract out of the fiber, reducing the intensity of transmitted light. In contrast, bending the fiber in the opposite direction causes the rays to converge on the un-grated zone and reflect back into the fiber, increasing the intensity of transmitted light. A linear model for this phenomenon, validated in [3], is

$$-C_{convex} \cdot \theta + h \text{ if } \theta \leq 0 \tag{1}$$

$$C_{concave} \cdot \theta + h \text{ if } \theta > 0 \tag{2}$$

where $Theta$ is the bending angle, C_{convex} and $C_{concave}$ are linear parameters and we hypothesize that $|C_{convex}| > |C_{concave}$ due to the directional sensitivity of the gratings.

The objective of this report is to empirically validate laser cutting as a low-cost, repeatable method for fabrication of sensitized optic fibers. The following sections present the procedure that was used to guide the choice of laser cutting properties that yield the greatest optic sensitivity with respect to the curvature of an optical fiber.

3 Methodology

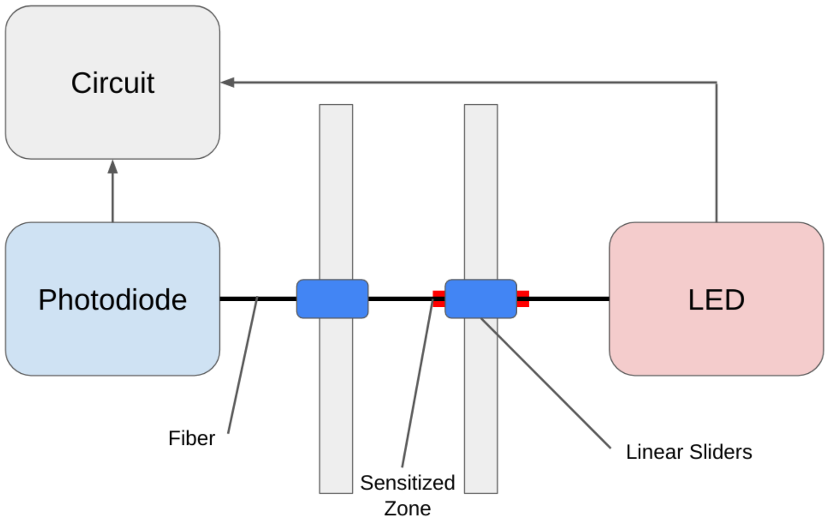
A custom test rig, detailed in Figure 1, was fabricated to study the sensitivity of engraved optical fibers. The setup secures the fiber between two cage plates. Two linear sliders are coupled to the fiber in between the cage plates - moving the sliders allows for creating repeatable bending configurations.

The fiber is coupled to a photoresistor at one of the cage plates, and to a red LED chosen to have a wavelength corresponding to the peak sensitivity of the photoresistor on the other plate. The photoresistor (R_1) is placed in a voltage-divider configuration off of a 5V voltage supply with a 680k resistor (R_2), chosen empirically to yield sensitive readings. The analog input pin of an Arduino Uno is used to monitor the voltage readout at the voltage divider junction. As the intensity of the light increases, the resistance of the photoresistor decreases. According to the voltage divider gain equation,

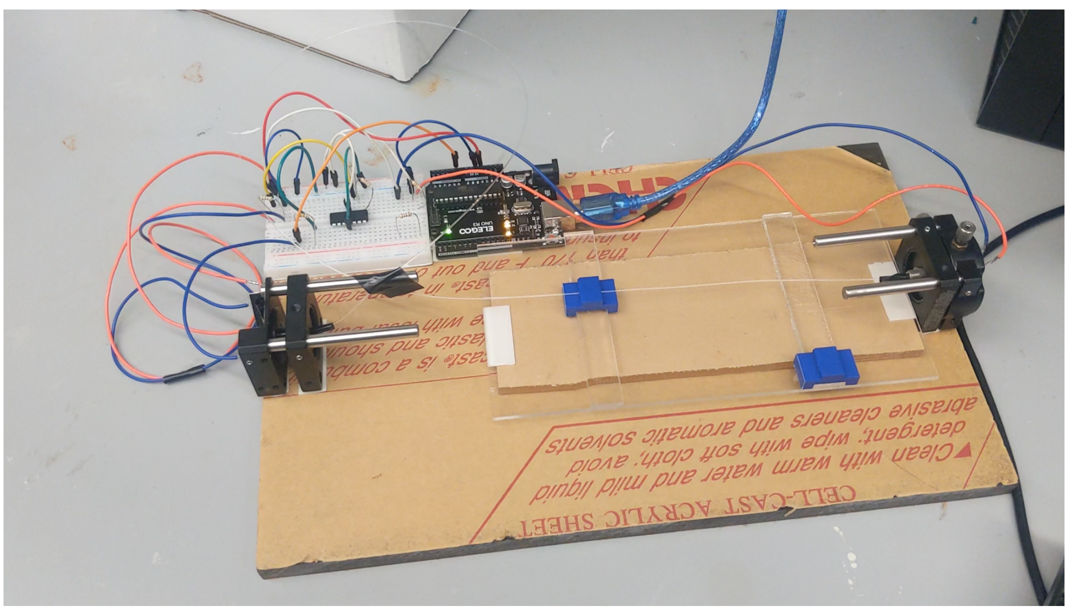
$$V_{out} = V_{in}(\frac{R_2}{R_1 + R_2}) \tag{3}$$

this corresponds to an increase in the output readout. Thus, we anticipate the voltage to trend proportionally to the transmitted intensity. Figure 2 provides a schematic of the circuit used in this setup.

With the testing setup defined, we turn our attention to the cutting parameters that we wish to investigate. The remainder of this report uses a Trotec Speedy 100 Laser Engraver (Trotech Laser, Marchtrenk, AU) which offers a maximum cutting power of 30W. The most straight-forward cutting parameter is the cut power, which corresponds directly to the size (depth and width) of the grating imparted on the fiber. We hypothesize that increasing the cutting power will increase the sensitivity of the fiber. A second parameter is the spacing



(a) Schematic of the testing setup.



(b) Image of the testing setup.

Figure 1: Custom test rig used for characterization of sensitized optical fibers.

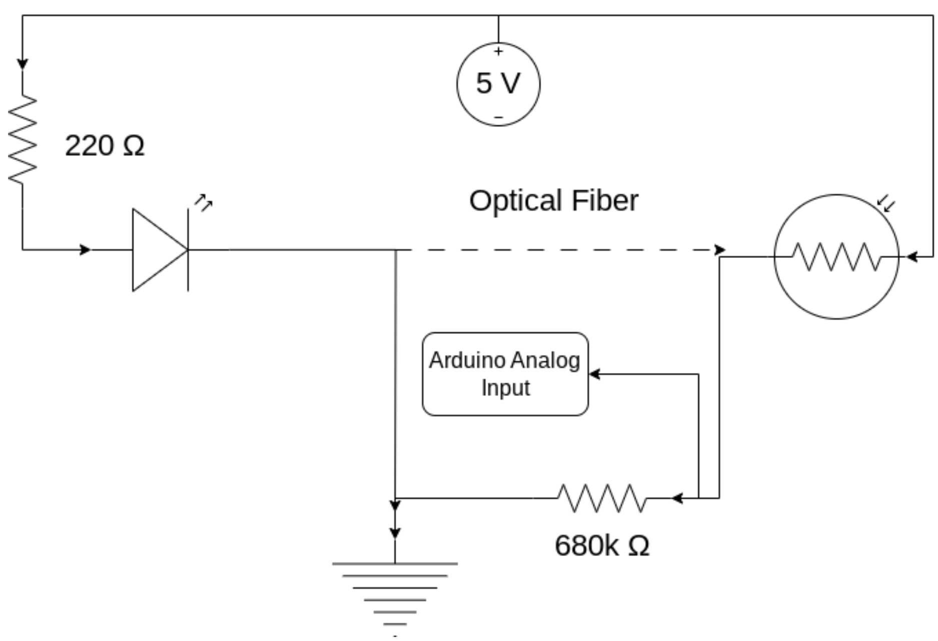


Figure 2: Circuit schematic of the testing rig.

between the gratings, or the grating period. Once again, we hypothesize that increasing the grating density, or decreasing the period, will result in greater sensitivity. Figure 3 shows a sensitized sample after laser engraving.

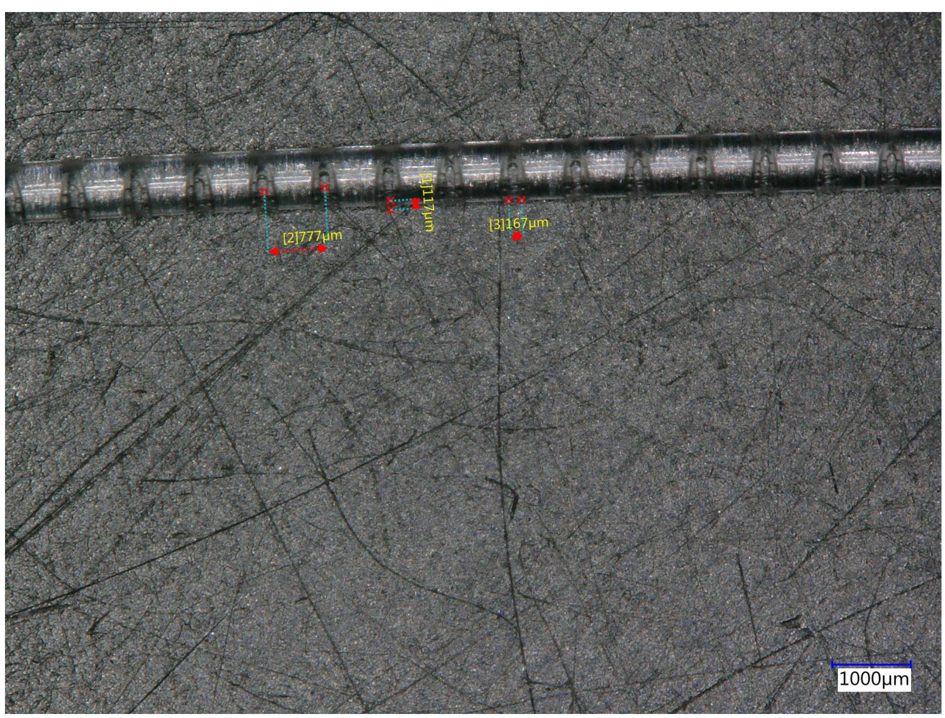


Figure 3: Laser-engraved sample under a microscope with the grating spacing, depth, and width dimensions highlighted.

4 Results and Discussion

8 sets of experiments were carried out with 8” fibers including a 2” sensitized zone, consisting of two parametric sweeps: 4 experiments varied the grating period, and 4 experiments varied the cutting power. Figure 4 is a visual illustration of the testing configuration; additionally, table 1 lists all of the measured dimensions of the samples that were used in the power-sweep experiments. As expected, the measured dimensions, acquired from a microscope, differ slightly from the specified dimensions. However, they follow the trends that are expected from the cutting parameters, indicating the repeatability of the fabrication process.

In each experiment, the slider that is located farther from the sensitized zone was moved along a distance of 100mm, with 5 data points collected with the fiber under convex bending and 5 data points under concave bending. To minimize the impact of ambient light on the measurements, the experiments were carried out in the same dark room and the setup was overshadowed by a cover. Finally, cutting power was fixed to 20% in the experiments that varied grating period while cut-spacing was set at 0.03” in experiments that varied cutting power. Cutting speed was set to 55 ips throughout all fabrication.

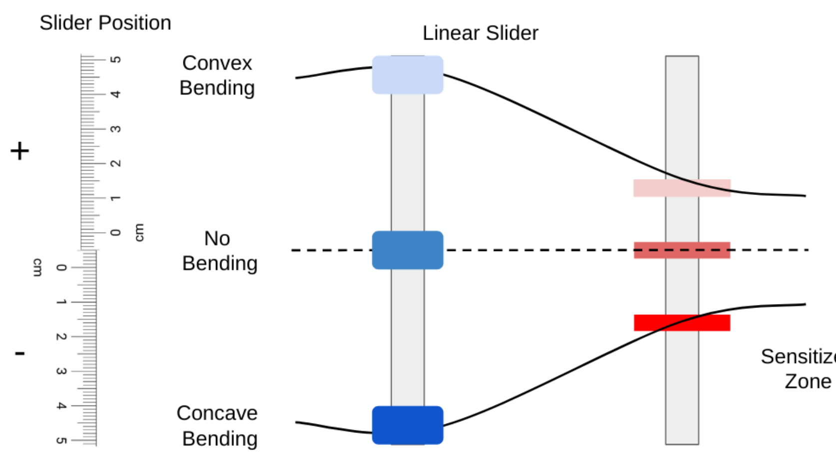


Figure 4: Visual illustration of the experimental setup, including the slider position referenced in the discussion of the results.

Cutting Power	Grating Spacing	Grating Width	Grating Depth
15%	784	91	40
20%	734	111	57
25%	759	125	77
30%	777	167	117

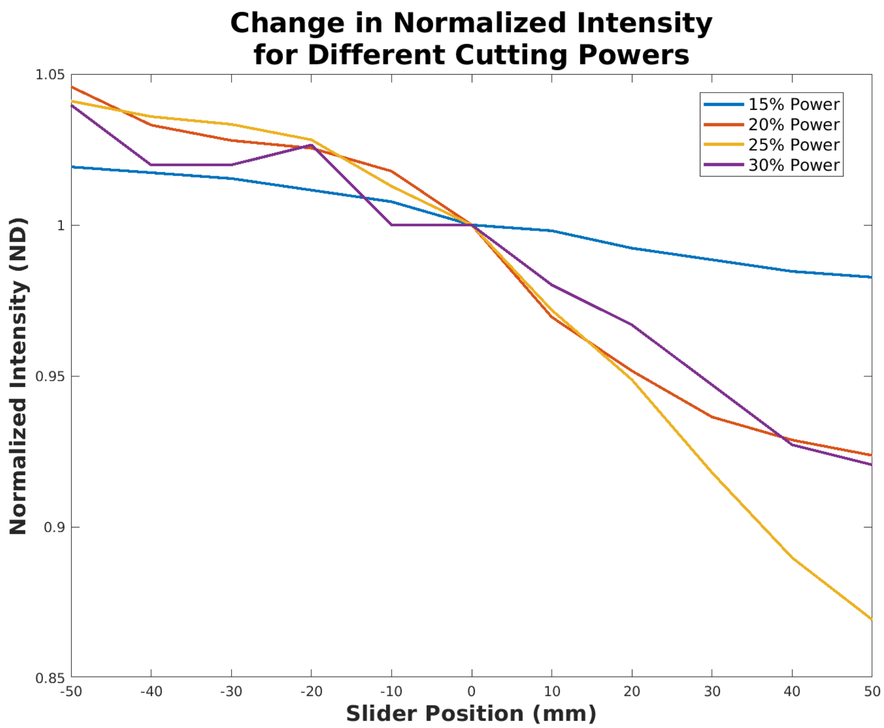
Table 1: Grating dimensions obtained from power-sweep samples using a microscope. All dimensions are in microns. The expected grating spacing is 0.03" or 762 microns. As expected, increasing cutting power increases engraving width and depth.

The results from the experiments are highlighted in Figure 5. We note that the plotted quantities are obtained by subtracting the voltage readout from the "dark" voltage, or the voltage that was measured when the LED was turned off. The results were then normalized with respect to the transmission intensity in absence of bending:

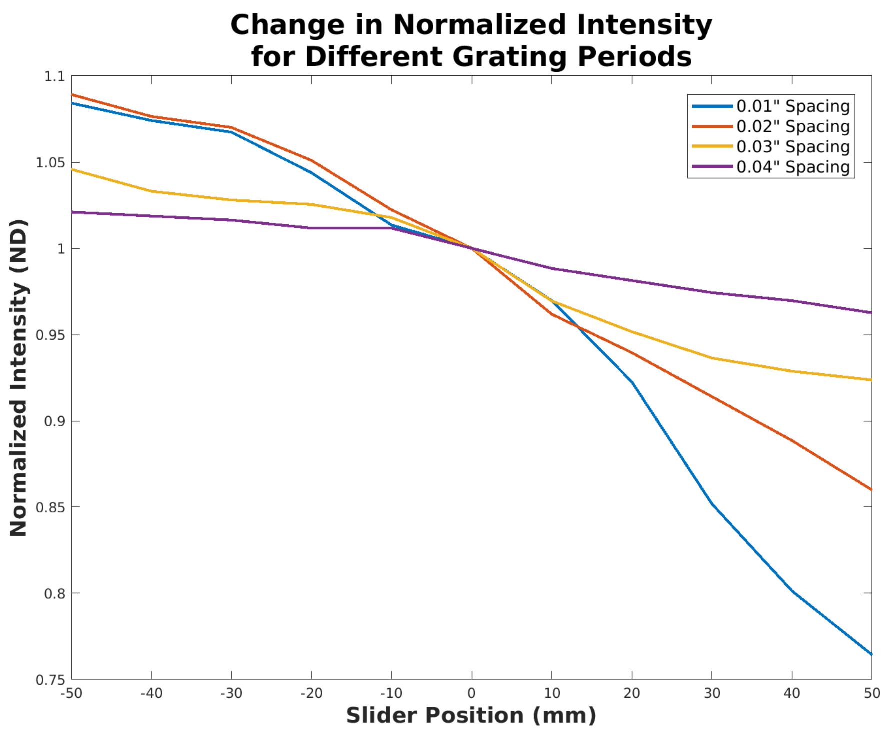
$$I = \frac{V_{bent} - V_{dark}}{V_{straight} - V_{dark}} \tag{4}$$

The experimental results largely confirm the initial hypothesis: it appears that increasing grating period and cutting power makes the fibers more sensitive. However, we note an interesting exception for increasing power above a threshold; at some point, the gratings begin to overlap more than half of the circumference of the fiber, which results in additional, undesirable sensitivity to concave bending. This causes the results from the corresponding experiment to appear as an outlier. Furthermore, we note that the results agree with the predicted relationship $|C_{convex}| > |C_{concave}|$.

Finally, we note that a major challenge in data collection was ensuring that the orientation of the grating pattern was unchanged throughout testing. This was accomplished by fixing the two ends of the fiber in a position that oriented the grating in the desired sense. However, the grating itself was left free from constraints during testing to monitor it's curvature, resulting in some testing variability that was not compensated for.



(a) Results obtained by parametric variation of cutting power.



(b) Results obtained by parametric variation of grating period.

Figure 5: Results obtained from experimental characterization of sensitized optical fibers indicate an improvement in sensitivity as cutting power and grating density are increased.

5 Conclusion

The above discussion presented laser-cutting as a fabrication process for creating sensitized optical fibers for 3D shape sensing. Additionally, we reviewed the impact of two critical laser cutting parameters (cutting power and grating period) on the sensitivity of the transmitted intensity of the fibers to bending. We note that the presented results are characteristic of the laser-cutting tool used in fabrication, and that custom fabrication with different machines would require additional fine-tuning. Furthermore, future test can improve the quality of the characterization data by improving the fixture method of the fiber to ensure minimal variation in the grating orientation. The outcomes of this paper will be used to fabricate bundles of multiple sensitized fibers that can sense 3D shapes rather than planar bending.

6 Appendix

6.1 Arduino Script

```
//Arduino script for data collection
//CHE266, Vedad Bassari, Last Edit: 6/5

//Declare variables
const int pin = A0;
int readOut = 0;
int sample = 0; //Number of samples used in averaging
float val = 0; //Storage variable


void setup() {
  pinMode(A0,INPUT); //Declare pin mode
  Serial.begin(9600); //Begin serial com.
}

void loop() {
  for(int i=0;i<=sample;i++){ //Average readouts to smooth readings
    readOut = analogRead(pin);
    val = val + readOut;
  }
  val = val/sample;
  Serial.println(val); //Display the measured value
  val = 0;
}
```

6.2 MATLAB Script

```
    %% Process experimental characterization data
close all; clc; clear;

Slider = [-50,-40,-30,-20,-10,0,10,20,30,40,50]; %Slider position [mm]
%Measured intensities
blank1 = 318; %Readouts without LED
blank2 = 190;
P20_S003 = [729,724,722,721,718,711,699,692,686,683,681];
%Baseline measurement [V, 0-1023]
P20_S003 = (P20_S003 - blank1)./(P20_S003(6)-blank1); %Normalize intensity

%Parameteric study 1: grating spacing
P20_S001 = [512,509,507,500,491,487,478,464,443,428,417];
P20_S001 = (P20_S001 - blank2)./(P20_S001(6)-blank2); %Normalize intensity
P20_S002 = [532,528,526,520,511,504,492,485,477,469,460];
P20_S002 = (P20_S002 - blank2)./(P20_S002(6)-blank2); %Normalize intensity
P20_S004 = [627,626,625,623,623,618,613,610,607,605,602];
P20_S004 = (P20_S004 - blank2)./(P20_S004(6)-blank2); %Normalize intensity

%Parametric study 2: cutting power
P15_S003 = [720,719,718,716,714,710,709,706,704,702,701];
P15_S003 = (P15_S003 - blank2)./(P15_S003(6)-blank2); %Normalize intensity
P25_S003 = [596,594,593,591,585,580,569,560,548,537,529];
P25_S003 = (P25_S003 - blank2)./(P25_S003(6)-blank2); %Normalize intensity
P30_S003 = [347,344,344,345,341,341,338,336,333,330,329];
P30_S003 = (P30_S003 - blank2)./(P30_S003(6)-blank2); %Normalize intensity

%% Plotting results

%Plotting parameters
LW = 2; %Line width
AF = 14; %Axis font
LF = 16; %Label font
TF = 20; %Title font
LLF = 12; %Legend font
```

```
%For varying spacing
figure(1);
set(gca,'FontSize',AF);
plot(Slider,P20_S001,'LineWidth',LW);
hold on;
plot(Slider,P20_S002,'LineWidth',LW);
hold on;
plot(Slider,P20_S003,'LineWidth',LW);
hold on;
plot(Slider,P20_S004,'LineWidth',LW);
ylabel('Normalized Intensity (ND)','FontWeight','bold','FontSize',LF);
xlabel('Slider Position (mm)','FontWeight','bold','FontSize',LF);
title({'Change in Normalized Intensity', 'for Different Grating Periods'},...
'FontWeight','bold','FontSize',TF);
legend('0.01" Spacing','0.02" Spacing','0.03" Spacing','0.04" Spacing',...
'Location','best','FontSize',LLF);

%For varying cutting power
figure(2);
set(gca,'FontSize',AF);
plot(Slider,P15_S003,'LineWidth',LW);
hold on;
plot(Slider,P20_S003,'LineWidth',LW);
hold on;
plot(Slider,P25_S003,'LineWidth',LW);
hold on;
plot(Slider,P30_S003,'LineWidth',LW);
ylabel('Normalized Intensity (ND)','FontWeight','bold','FontSize',LF);
xlabel('Slider Position (mm)','FontWeight','bold','FontSize',LF);
title({'Change in Normalized Intensity', 'for Different Cutting Powers'}...
'FontWeight','bold','FontSize',TF);
legend('15% Power','20% Power','25% Power','30% Power',...
'Location','best','FontSize',LLF);
```

References

[1] S. C. Ryu and P. E. Dupont, “Fbg-based shape sensing tubes for continuum robots,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 3531–3537.

[2] J. Metz, “Closed loop control of continuum robot using an intensity-based optical fiber bend sensor,” in *UC Santa Barbara, ME225EH Soft Robotics*, 2022.

[3] A. Djordjevich and M. Boskovic, “Curvature gauge,” *Sensors and Actuators A: Physical*, vol. 51, no. 2, pp. 193–198, 1995. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0924424795012222