Twining Plant Inspired Pneumatic Soft Robotic Spiral Gripper with High-Birefringence Fiber Optic Sensor

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Abstract: Twining plant-inspired pneumatic soft-robotic spiral gripper embedded with a high-birefringence fiber-optic sensor is designed and demonstrated. The fiber-optic sensor enables the spiral-gripper to sense the twining angle and target cylinder radius as small as 1mm.
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1. Introduction

Pneumatic soft robotics that are made from soft and elastic materials has been an emerging technology in robotics to offer unique opportunities where conventional rigid robots are not a viable solution. Its soft, elastic, and deformation nature, allowing it to mimic complex motions of human, animals, and plants. Pneumatic soft robotics is powered by air or gas, making it of particular interest because it is lightweight, inexpensive, and is safer around human and harsh environments. Intensive research has been on the design of soft robotic gripper due to its critical role to healthcare treatment and sophisticated automation industry including advanced assembly and food handling. There are two major types of pneumatic soft robotic gripper – robotic hands [1] and robotic tentacles [2]. Both designs require a large operation space to allow the soft robotic gripper to gain access to the target object.

In this paper, we turn to nature for an effective solution – the twining plant, which is designed to securely grip onto a small target in a confined operation space. We designed and experimentally demonstrated a high-birefringence fiber optic sensor embedded pneumatic soft robotic spiral gripper that is inspired by the wrapping motion of a twining plant, as illustrated in Figure 1(a). The uniqueness in twining plant is that during its spiral movement around the target, the plant establishes discrete points of contacts which create anchorage points to securely holding onto the target. In twining plant, a directional growth movement - Thigmotropism, governs how the plant twining onto the target, such that the growth rate on the side of the stem which is being toughed is slower than the opposite side that is not being touched, making the stem grow spiral on the target. In our design, a single spiral air channel for pneumatic powering is used to mimic the directional growth movement in twining plant, such that the soft robotic gripper can wrap around the target spirally, eliminate the need of multiple pneumatic controls. The embedded high-birefringence fiber optic sensor enables the sensing of the twining angle, target cylinder radius as small as 1mm, as well as identifying the target property and external perturbation. High-birefringence fiber based twisting sensor is used in the spiral soft robot due to its low cost and simplicity configuration, compare with other existing fiber optic based twist sensors [3-5].

2. Principle and Experimental Setup

Figure 1(b) shows the design of the proposed high-birefringence fiber sensor embedded twining plant-inspired pneumatic soft robotic spiral gripper. The spiral gripper is 85 mm in length, 13.5 mm in diameter, and is made of silicone material with various elasticity and hardness. There is an elastic spine with 3 mm diameter at the center of the spiral gripper and a spiral air channel with 2 mm in diameter around the elastic spine for pneumatic control.

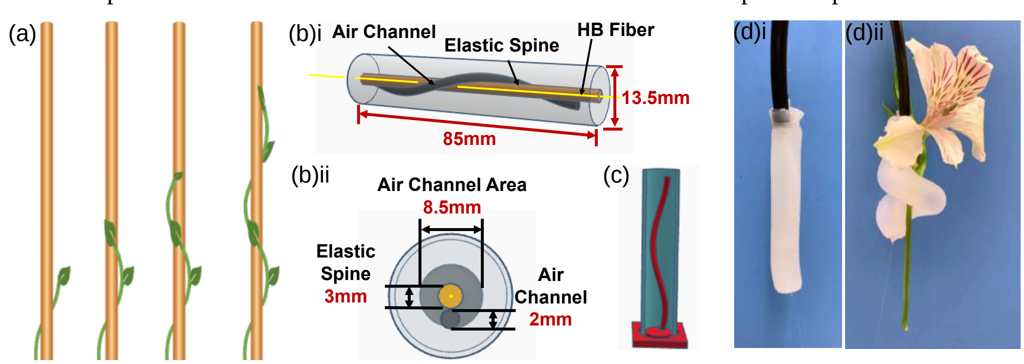

Figure 1: (a) Illustration of the wrapping motion in a twining plant; (b)i. 3D view of the twining plant inspired soft robotic spiral gripper with embedded high-birefringence (HB) fiber optic sensor; ii. Cross-section view of the spiral gripper; (c) 3D printed molds for fabricating the spiral gripper; (d)i. Photo of the robotic spiral gripper before actuation; ii. Photo of the robotic spiral gripper after actuation and twining around a flower stem.

The high-birefringence fiber optic sensor has a birefringence of 6.33×10^{-4} and length of 90 mm, that is embedded at the center of the elastic spine. The soft robotic spiral gripper is fabricated with the use of 3D printed molds, as shown in Figure 1(c). A spiral shape rod (red mold) with inner and outer spiral diameter of 4.5mm and 8.5mm is used to create the air channel in the spiral gripper (blue mold). 1.5 spiral cycles in the air channel will result in a 540° twining motion in the spiral gripper. The 90 mm high-birefringence fiber sensor is first embedded in the 3-mm elastic spine made from harder silicone (Dragon Skin 10). The elastic spine not only minimize elongation at the gripper center to prevent delamination at the fiber optic sensor, it also strengthens the spiral gripper center to ensure that the spiral gripper will go spiral vertically. The elastic spine is then insert in the middle of the red air channel mold, where the blue gripper mold is then filled with a softer silicone mixture – 00-10 and 00-30 with a 1:2 ratio. The twining plant inspired spiral gripper is ready once the silicone mixture is cured and the 3D printed molds are removed.
A standard Sagnac loop [6] is used to identify the birefringence change in the high-birefringence fiber sensor resulted from twining through interference and wavelength shift measurement. The amount of wavelength shift also tells us the twining angle, target cylinder radius, as well as identifies the target property and external perturbation. A broadband light source at C-band and an optical spectrum analyzer with resolution of 0.08 pm is used to monitor the interference optical spectrum, while a laser source at 1545.363 nm (aligned at the transmission peak of the interference spectrum) and an optical power meter controlled by LabView is used for real-time monitoring of the spiral gripper. The soft robotic spiral gripper is power by air, which is steadily actuated and deactuated through the control of pump, vacuum, and valve. When the pneumatic system is at pumping state, air goes into the gripper from the top and the inflation begins at the top and gradually finish at the bottom, resulting in a spiral movement in the gripper that mimic the growth movement in twining plants. As the soft spiral gripper is twining spirally, the high birefringence fiber is being twisted and resulting in a decrease in birefringence. Therefore, the free spectral range $\Delta\lambda$ of the interference spectrum formed at the Sagnac loop changes according to, where *B* and *L* are the birefringence and length of the high birefringence fiber. When looking at a small wavelength range, i.e. within 30 nm of the spectrum, a wavelength shift of the destructive interference notch is observed as a result of a birefringence change.

3. Results and Discussion

Figure 2(a) shows the measured optical spectra for various twining angle in the spiral gripper. A 16.66 nm shift to the longer wavelength in the transmission notch is observed as the spiral gripper is actuated and gone through twining angle from 0 to 540°. The optical spectrum returns to its initial position when the spiral gripper is completely deflated, proofing that there is no delamination between the high-birefringence fiber sensor and the elastic spine in the spiral gripper. The prevention of delamination enables accurate and repeatable monitoring of the soft spiral gripper status.

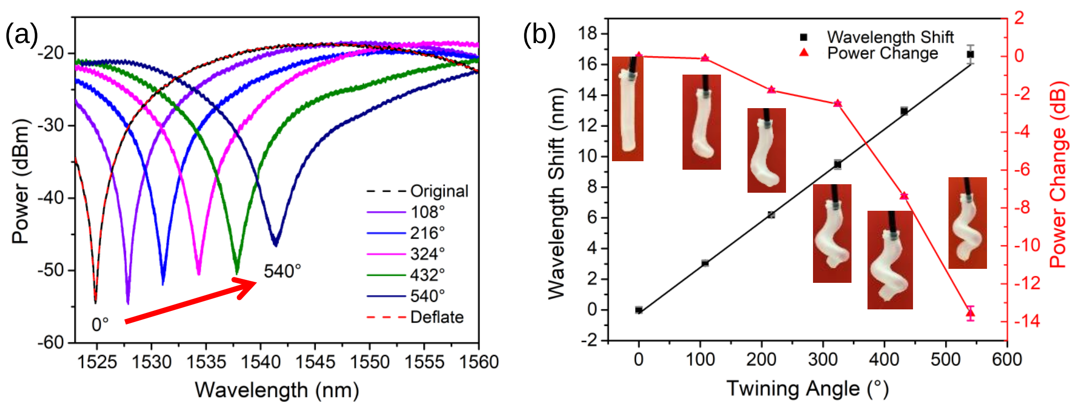

Figure 2: (a) Interference optical spectra of the embedded high-birefringence fiber sensor in the spiral gripper; (b) Relationship between twining angle and wavelength shift (black) and power change (red).

A plot of the relationship between the twining angle and the wavelength shift is shown by the black curve in Figure 2(b). A linear relationship is observed with a sensitivity of 0.03nm/°. Small error bar (shown in grey) is observed that proves that the high-birefringence fiber optic sensor embedded spiral gripper has very high repeatability. To enable real-time monitoring of the spiral gripper, optical power measurement is used instead. An 8-dBm laser source at 1545.363 nm that is spectrally align with the transmission peak of the original state (0° twining angle) spectrum is used with a LabView controlled optical power meter. By monitoring the power change as the spiral gripper is twining from 0 to 540°, a plot showing the relationship between power change and twining angle is resulted, as shown by the red curve in Figure 2(b). Again, small error bar (shown in pink) is observed that proves that no delamination occurs and a highly repeatable twining plant inspired spiral gripper is achieved.

Next, we studied the ability of the soft robotic spiral gripper to hold a target object with various diameters, and the ability for the high-birefringence fiber optic sensor to detect the twining process and identify the size of the target object. The advantages of a spiral gripper are its ability to hold small objects and to operate in a confined area by approaching the target from the top – parallel with the target object. Figure 3 shows the power change of the interference spectrum of the embedded high birefringence fiber at the spiral gripper as the gripper is performing various tasks and experiencing external perturbations.

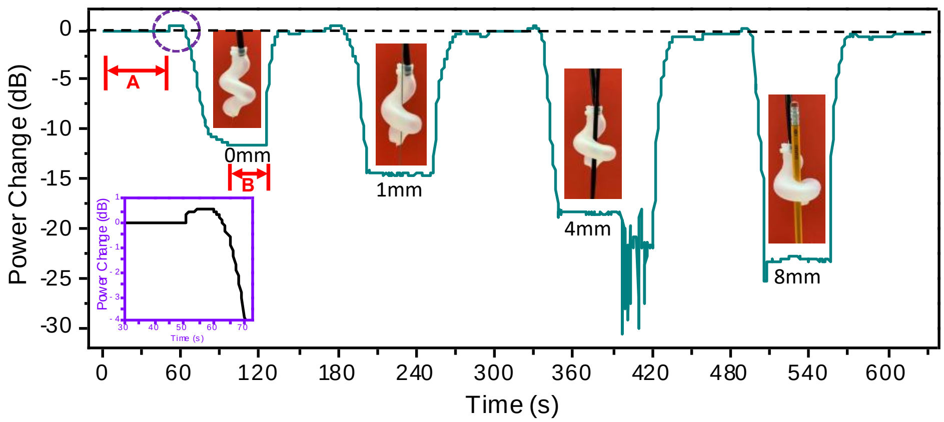

Figure 3: Real-time monitoring of the twining plant inspired spiral gripper using optical power measurement of the embedded high-birefringence fiber optic sensor.

First, the soft robotic spiral gripper is at the original deflated state (region A), then the pneumatic system is activated to actuate the gripper, indicated by the small peak in the purple dashed circle (zoom in view in the inset). The whole actuation process takes about 35s, and the gripper is completely twining without a target object (region B), a -11.48 dB of power change is observed. The spiral gripper is then deactuated through the enabling of vacuum in the pneumatic system and the power change returns to zero. Next, the spiral gripper is used to hold a small object – 1-mm paper clip wire. As the pneumatic spiral gripper is actuated, optical power drops and results in a -14.59-dB power change at its stable state. Although the paper clip is only 1-mm in diameter, the high-birefringence fiber optic sensor is sensitive enough to tell the presence of the 1-mm paper clip, a 3.11 dB additional power drop is observed with the presence of the 1-mm paper clip. Then, the spiral gripper is deactuated and actuated again to hold a 4-mm paint brush. A 7.02 dB additional power drop is observed with the presence of a 4-mm paint brush. External force is applied to attempt to pull away the paint brush, the fiber optic sensor picked up the event and is showing high frequency fluctuation in the optical power, proving that the sensor is capable to identify any external perturbation to the target object. The twining plant inspired spiral grip has strong anchorage points on the object and it is not possible to remove the object. Lastly, an 8-mm pencil is used as the target object, the spiral gripper can hold the pencil firmly and resulting in a 4.68 dB additional power drop with the presence of the 8-mm pencil. The soft robotic spiral gripper has excellence repeatability and the power can always return to the original state as shown by the dashed line in Figure 3.

4. Conclusion

We designed and demonstrated a twining plant-inspired pneumatic soft robotic spiral gripper embedded with a high-birefringence fiber sensor. The elastic spine and the single spiral air channel enable the spiral gripper to operate in a confined area and to firmly hold onto objects with diameter as small as 1 mm, as well as prevents delamination to occurs for high-repeatability performance. The embedded fiber sensor has a sensitivity of 0.03nm/° and facilitates the sensing of the twining angle, target cylinder radius, as well as identifying the target property and external perturbation.

References

[1] Y. She, C. Li, J. Cleary, and H. J. Su, "Design and Fabrication of a Soft Robotic Hand With Embedded Actuators and Sensors," J Mech Robot **7**, 021007 (2015).

[2] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario, "Soft Robot Arm Inspired by the Octopus," Adv. Robot. **26**, 709-727 (2012).

[3] B. Huang and X. Shu, "Ultra-compact strain- and temperature-insensitive torsion sensor based on a line-by-line inscribed phase-shifted FBG," Opt Express **24**, 17670-17679 (2016).

[4] H. M. Kim, T. H. Kim, B. Kim, and Y. Chung, "Temperature-Insensitive Torsion Sensor With Enhanced Sensitivity by Use of a Highly Birefringent Photonic Crystal Fiber," IEEE Photonics Technol. Lett. **22**, 1539-1541 (2010).

[5] B. Song, Y. Miao, W. Lin, H. Zhang, J. Wu, and B. Liu, "Multi-mode interferometer-based twist sensor with low temperature sensitivity employing square coreless fibers," Opt Express **21**, 26806-26811 (2013).

[6] O. Frazao, J. M. T. Baptista, and J. L. Santos, "Recent Advances in High-Birefringence Fiber Loop Mirror Sensors," Sensors **7**, 2970-2983 (2007).