Proceedings of CONF-MSS 2026 Symposium: Mechanical Control and Automation
DOI: 10.54254/2755-2721/2026.BJ32141

Endowing Continuum Surgical Robots with Tactile Perception Capability

Yixuan Chen

College of Mechanical Engineering, North China University of Science and Technology, Tangshan, China
15511898389@163.com

Abstract. With the increasing application of continuum robots in minimally invasive surgery and operations within complex environments, their lack of tactile perception has become a critical limitation affecting both safety and precision. This paper employs a literature review methodology to systematically examine and analyze relevant research advancements, with a particular focus on the theoretical framework proposed in the study "Magnetically Guided Continuum Robot with Programmable Shape and Functionality for Transluminal Procedures." By integrating Fiber Bragg Grating (FBG) technology, this work explores a viable pathway to endow continuum robots with tactile sensing capabilities. Research indicates that an FBG-based tactile perception system can achieve real-time sensing and feedback of force, deformation, and contact states, thereby significantly enhancing the robot's environmental interaction capability and operational accuracy. This study aims to provide essential theoretical support and future research directions for the development of intelligent and high-precision medical robotic systems.

Keywords: continuum robot, tactile perception, Fiber Bragg Grating (FBG), surgical robot

1. Introduction

Bio-inspired continuum robots are a novel class of robotic systems modeled after flexible biological structures such as elephant trunks or octopus tentacles. Their defining characteristic lies in achieving motion through continuous deformation rather than discrete joints, granting them superior environmental adaptability and operational safety compared to conventional rigid robots. Millimeter-scale continuum robots can realize tip extension, and at the same time, maintain the stability [1]. By leveraging phase-transition components, these robots can execute tip-based elongation cycles and be precisely steered via magnetic fields which are programmable.

This paper adopts a combined approach of literature review and case analysis to further investigate how, beyond the use of phase-change materials, the integration of Fiber Bragg Grating (FBG) sensors, embedded in arrays at the robot's end-effector and aligned with its continuum structure, can confer tactile sensitivity. Exploiting the principle of wavelength-selective reflection, FBG sensors effectively endow the robot with a "sense of touch" akin to that of biological organisms like snakes or vines, thereby enhancing its functional dexterity.

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.BJ32141

2. Literature review

Luminal structures in the digestive, respiratory, and urogenital systems, along with blood vessels, are responsible for transporting air, blood, fluids, food, and other substances between internal and external environments, providing potential access routes for invasive interventions targeting specific tissues. The concept of Lumina-enabled transmural surgery has been proposed to revolutionize medical treatment through ultra-minimally invasive approaches [2,3]. Miniaturized medical devices [4,5] can traverse endoluminal or intravascular pathways to reach surgical sites for diagnosing and treating pathological conditions, thereby reducing postoperative pain and incision-related complications.

In particular, millimeter-scale soft continuum robots demonstrate remarkable adaptability owing to their passive compliance, making them a promising solution for less invasive and more maneuverable transluminal procedures. This advancement has been propelled by developments in microfabrication techniques [6,7], innovative propulsion mechanisms [8,9], distal actuation approaches [10-12], and mechanics-based kinematic modeling [13,14].

Researchers from the School of Mechatronics at Harbin Institute of Technology have designed a millimeter-scale continuum robot capable of "superluminal" motion, in which the tip extends while the overall structure remains stable, enabling precise magnetic navigation through narrow and complex pathways. This vine-like movement helps reduce both tissue damage and friction. The system consists of multiple phase-transition components (PTCs), referred to as "leaders" and "followers." The leader is positioned coaxially within a silicone tube that contains the follower, and a miniature permanent magnet is embedded at the leader's tip to allow external magnetic control. Low-melting-point alloy (LMPA) and resistive heating elements are integrated inside the silicone tube, while hydrogel layers are applied to the surfaces of both components to substantially decrease friction. The geometries of the leader and follower are mutually dependent: throughout each locomotion cycle, the two PTCs alternately switch between solid and liquid states, corresponding to support and propulsion phases, thereby fully exploiting the characteristics of phase-change materials.

While these features offer substantial clinical advantages, the current system provides only visual guidance and lacks tactile sensitivity, a critical gap that must be addressed to advance surgical robotics.

3. Robotic design principles and technical implementation

To overcome the deficiency in tactile sensitivity of existing millimeter-scale continuum robots, Fiber Bragg Grating (FBG) sensors have been introduced. FBG sensors offer high precision, high sensitivity, corrosion resistance, and immunity to electromagnetic interference, making them exceptionally well-suited for complex medical environments. By embedding FBG sensors into the robot's main body structure, the system effectively gains a network of "tactile nerves."

As the robot navigates tortuous luminal pathways within the human body, the FBG sensors continuously detect subtle environmental changes, such as wall pressure, local geometry, and friction, and convert these physical stimuli into optical signals relayed to the control system. Advanced algorithms process and interpret these signals to accurately determine the robot's contact state and interaction forces with surrounding tissues, enabling precise motion control. For instance, upon encountering a narrow passage or fragile tissue, the control system can dynamically adjust the robot's speed and applied force based on real-time tactile feedback, thereby preventing iatrogenic injury and significantly enhancing procedural safety.

DOI: 10.54254/2755-2721/2026.BJ32141

Material selection was also refined: in addition to the original LMPA phase-change material and silicone tubing, biocompatible and highly flexible materials were chosen to encapsulate and secure the FBG sensors. This ensures seamless integration with the robot's structure while avoiding immune responses. Using micro- and nano-fabrication techniques, FBG sensors were precisely integrated into targeted regions of the robot (as shown in Figure 1), guaranteeing stable sensor performance without compromising the robot's inherent mobility.

Through these design enhancements, the millimeter-scale continuum robot retains its original advantages, including superluminal locomotion, precise magnetic navigation, and low-friction movement, while gaining sophisticated tactile perception capabilities.

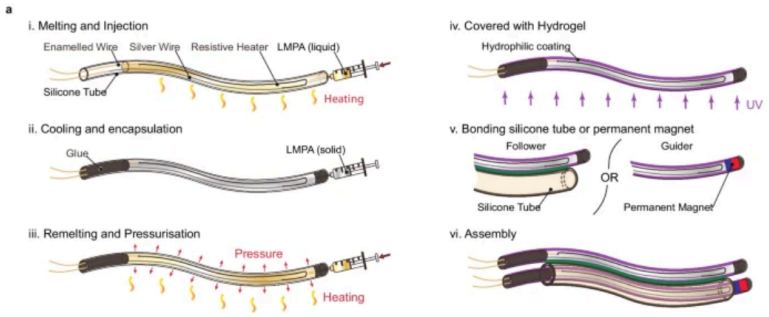


Figure 1. LMPA phase-change material configuration

4. Application scenario analysis: surgical procedures

In surgical contexts, the tactile-enabled millimeter-scale continuum robot demonstrates transformative potential. Its ability to sense contact forces and environmental contours in real time allows surgeons to operate with greater precision, safety, and confidence, especially in anatomically complex or delicate regions.

4.1. Gastrointestinal surgery

The gastrointestinal tract features numerous narrowings and sharp curvatures. Previously, non-tactile robots risked perforating the intestinal wall during navigation. With FBG-based tactile feedback, the robot can precisely sense luminal pressure and contour, automatically adjusting speed and trajectory to gently bypass obstacles and accurately reach target lesions—thereby reducing procedural risk. In addition, the robot's flexible body enables it to conform to the natural shape of the digestive tract, minimizing friction and tissue irritation. This not only improves navigation efficiency but also shortens procedure time and reduces postoperative complications, leading to faster patient recovery.

4.2. Respiratory surgery

Respiratory tissues are extremely delicate. Traditional instruments often cause collateral damage. Equipped with tactile sensitivity, the robot can enter tracheal and bronchial passages while dynamically modulating its posture and force based on real-time sensor data. This enables precise removal of foreign bodies or ablation of small pulmonary tumors with minimal trauma to the respiratory system. The robot's soft interaction with airway walls also helps maintain structural integrity and reduces the likelihood of inflammation or bleeding, making it particularly suitable for fragile or high-risk patients.

DOI: 10.54254/2755-2721/2026.BJ32141

4.3. Intravascular surgery

Vessel walls are highly vulnerable, and even minor mechanical stress can lead to rupture. The enhanced robot, combining tactile perception with phase-change actuation, can safely navigate vasculature by responding to real-time variations in wall pressure and geometry. It can precisely perform interventions such as angioplasty for stenosis or thrombectomy, markedly improving success rates and patient safety. Moreover, its miniature size allows it to access smaller or more tortuous vessels that are difficult to reach with conventional tools, expanding the range of treatable conditions.

5. Conclusion

This study demonstrates that integrating phase-change materials with Fiber Bragg Grating (FBG) sensors significantly enhances the tactile perception of millimeter-scale continuum robots. The FBG system enables real-time environmental awareness and precise motion control within complex anatomical environments, thereby improving both the safety and efficacy of surgical procedures. Across gastrointestinal, respiratory, and vascular applications, the robot exhibits substantial clinical promise—minimizing tissue trauma and lowering operative risks.

Nonetheless, considerable development opportunities remain. Future work should focus on optimizing FBG sensor performance—enhancing sensitivity and response speed to detect finer environmental cues. Additionally, integration with artificial intelligence and adaptive control systems could enable autonomous decision-making tailored to individual patient anatomy and surgical context. Beyond medicine, this platform holds potential in industrial inspection, search-and-rescue operations, and other domains requiring dexterous navigation in confined, unstructured spaces.

At the same time, this study also has certain limitations. The analysis presented in this paper remains primarily at the level of theoretical discussion and case-based scenarios, without incorporating empirical experimental validation. Future research will address these limitations by incorporating comprehensive experimental verification. By collecting and analyzing quantitative data across different operational conditions, subsequent studies aim to provide stronger empirical support for the proposed system. Through these efforts, the research seeks to contribute more robust evidence to the field and accelerate the practical adoption of tactile-enabled continuum robots in both medical and non-medical applications.

References

[1] Mao, L., Yang, P., Tian, C. et al. Magnetic steering continuum robot for transluminal procedures with programmable shape and functionalities. Nat Commun 15, 3759 (2024). https: //doi.org/10.1038/s41467-024-48058-x

[2] Wagh, M. S., & Thompson, C. C. (2007). Surgery insight: natural orifice transluminal endoscopic surgery--an analysis of work to date. Nature clinical practice. Gastroenterology & hepatology, 4(7), 386–392. https: //doi.org/10.1038/ncpgasthep0867

[3] Robert I. Levy, Jay Moskowitz , Cardiovascular Research: Decades of Progress, a Decade of Promise.Science217, 121-129(1982).DOI: 10.1126/science.7046047

[4] Alessandri, H., Acevedo, E., del Solar, A. & Katz, R. Percutaneous coronary intervention in the elderly. Nat. Rev. Cardiol. 8, 79–90 (2011). DOI: 10.1038/nrcardio.2010.184

[5] 5Hu, W., Lum, G., Mastrangeli, M. & Sitti, M. Small-scale soft-bodied robot with multimodal locomotion. Nature 554, 81–85 (2018).

[6] Cianchetti, M., Laschi, C., Menciassi, A. et al. Biomedical applications of soft robotics. Nat Rev Mater 3, 143–153 (2018). https: //doi.org/10.1038/s41578-018-0022-y

DOI: 10.54254/2755-2721/2026.BJ32141

[7] Madou, M. & Florkey, J. From batch to continuous manufacturing of microbiomedical devices. Chem. Rev. 100, 2679-2692 (2000).
[8] Azizi, A., Tremblay, C. C., Gagné, K. & Martel, S. Using the fringe field of a clinical MRI scanner enables robotic navigation of tethered instruments in deeper vascular regions. Sci. Robot. 4, eaax7342 (2019).
[9] Pancaldi, L. et al. Flow driven robotic navigation of microengineered endovascular probes. Nat. Commun. 11, 6356 (2020).
[10] Gopesh, T. et al. Soft robotic steerable microcatheter for the endovascular treatment of cerebral disorders. Sci. Robot. 6, eabf0601 (2021).
[11] Kim, Y., Parada, G. A., Liu, S. & Zhao, X. Ferromagnetic soft continuum robots. Sci. Robot. 4, eaax7329 (2019).
[12] Tiryaki, M. E., Elmacıoğlu, Y. G. & Sitti, M. Magnetic guidewire steering at ultrahigh magnetic fields. Sci. Adv. 9, eadg6438 (2023).
[13] Wang, L. et al. Evolutionary design of magnetic soft continuum robots. Proc. Natl Acad. Sci. USA 118, e2021922118 (2021).
[14] Edelmann J, Petruska AJ, Nelson BJ. Magnetic control of continuum devices. The International Journal of Robotics Research. 2017; 36(1): 68-85. doi: 10.1177/0278364916683443