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A Soft Continuum Robot with Multi-Modal Shape and Contact Force Sensing for Minimally Invasive Surgery

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INTRODUCTION

Minimally invasive surgery (MIS), e.g., interventional endoscopy and single-incision laparoscopy, has paved the way toward increased patient safety, fewer postoperative complications, and shorter recovery times [1]. The inherent compliant nature of soft robots makes them suitable for addressing current limitations in MIS, such as the lack of dexterity of rigid robotic devices; however, soft robots often lack adequate shape and contact sensing which makes them difficult to control [2], [3]. The future of laparoscopic surgical tools is moving toward flexible and soft robotic solutions for safer interaction with human tissue [4]. However, newly developed technologies lack effective embedded sensing [5]. Soft optical sensing technology has proven effective in advancing closed-loop control of soft robots [6]. This work presents a fully soft robot combining *i)* a soft optical sensorized multi-modal gripper for tip tracking and contact force sensing with *ii)* a multi-directional bending module with integrated 3D shape sensing (Fig. 1, a-b). The gripper embeds two soft pneumatic actuators to deploy the jaws, two soft pneumatic actuators to control grasping, and two fully soft optical waveguide sensors (WG) (one in each jaw) with tuned roughness to monitor both actuator tip positions and subsequent contact force on an object.

MATERIALS AND METHODS

A. Design and Fabrication: The 125 mm long, 36 mm diameter (d) robot module and 50 mm long, d = 25 mm gripper are fabricated using 3D printed and aluminum (Al) molds. Fig. 1, b shows a cross section of the embedded WG paths and highlights the roughened WG tip. We tune the response of the WGs by altering the roughness (R) of the Al molds via laser micromachining. These anisotropic WGs are used to develop 3D shape sensing with a distinctly bidirectional sensor response (i.e., optical gain or loss in opposite directions). The WGs consist of a cladding made with Mold Star™ 30, with refractive index n_2 = 1.40, and a core of Norland Optical Adhesive 73, with n_1 = 1.56. Light is coupled through a d = 1 mm plastic optical fiber to emit (LED) and collect (phototransistor) the signals through the "U" shaped soft WG paths. The output power change through a sensor (P) is determined from the WG output in its base (undeformed) state (I_0) and the current measured signal (I) as: $P = 10log_{10}(I_o/I)$, where $P > 0$ corresponds to optical loss and $P < 0$ corresponds to an increase in light intensity or optical gain. Upon bending, light reflecting off of the smoother side (Direction 2) creates optical gain and the rougher side (Direction 1) creates optical loss (Fig. 1, c). Three soft pneumatic actuators are integrated to steer the robot module in all directions, and constant curvature modeling is used for mapping the WG responses to the tracked positions in the workspace (Fig. 1, a). Light intensity increases due to an applied contact force on the end of a roughened WG tip, which causes bending in the opposite direction (Fig. 1, d, bottom).

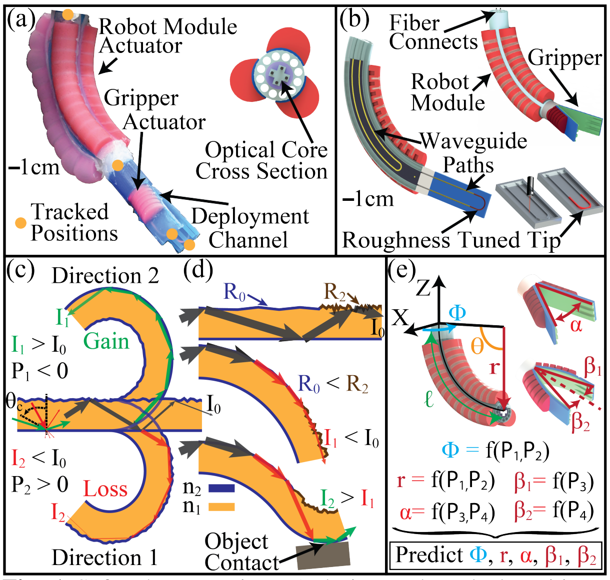

Fig. 1 Soft robot overview: a) design and tracked positions, b) fabrication, c-d) sensor physics, and e) control strategy diagrams showing mapping function parameter definitions.

B. Experiments: Fig. 1, e, shows the shape sensing module and gripper defining the constant curvature variables (r and ϕ) and deployment (α) and bending (β_1 and β_2) gripper angles. To develop functions to track the predicted positions, the continuum robot was calibrated using an Aurora electromagnetic (EM) tracker, an Instron machine, and a DAQ to collect the WG output power changes of the robot module (P_1 and P_2) and gripper (P_3 and P_4) as well as the gripper actuator pressure at known positions. To validate our robot functionality in a surgical scenario, we built a laparoscopic simulator. A graphical user interface (GUI) was developed in MATLAB to output the real-time shape sensing and contact force prediction of the system.

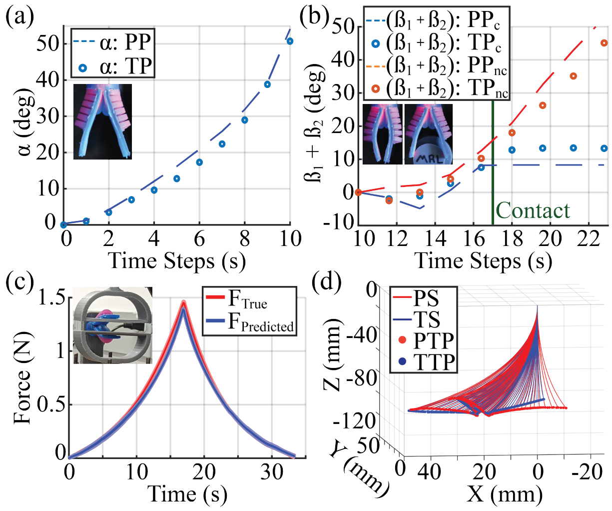

Fig. 2 Validation experiments. a-b) Comparison of predicted (PP) and true positions (TP) of the multi-modal gripper deployment and bending shape sensing with contact ($_c$) and without contact ($_{nc}$). c) Force prediction accuracy test at 21 mm thickness (average difference 8.9%). d) Comparison of the predicted tip position (PTP) and shape (PS) of the robot module compared to the true tip position (TTP) and shape (TS).

RESULTS

A. Shape Sensing and Contact Force Accuracy Validation: The accuracy of the calibration of the gripper deployment, bending, and contact recognition was tested and the gripper predicted and true positions are compared at subsequent steps of deployment (Fig. 2, a) and bending (Fig. 2, b) both with and without subsequent contact. The contact recognition capabilities of a single multi-modal tuned WG is validated by showing the predicted bending angle remaining constant after contact. Then, the accuracy of the force prediction (maximum 1.5 N) of the soft gripper was tested between thicknesses of 10-21 mm to demonstrate the capability of picking up different sized objects (Fig. 2, c). Further, the shape sensing module is oriented throughout its workspace and the predicted position and shape of the module are compared to the true position of the EM tracker. The entire 3D projection of the tip position of the robot module compared to the true tip position had an average error of 3.4 mm (Fig. 2, d).

B. Peg Transfer Task: Our in-vitro test shows the ability of the robot to move autonomously in a mock laparoscopic environment and complete a peg transfer test with full shape sensing and contact force prediction relayed via the GUI. The results of the test are shown in Fig. 3 wherein the shape of the robot is tracked accurately from its base state configuration (Fig. 3, a) through moving to an object (Fig. 3, b), grasping it with force monitoring (Fig. 3, c), and releasing it in another position (Fig. 3, d-e).

DISCUSSION

Our roughness tuning fabrication approach for multi-modal soft optical sensors allows for embedding more intelligence into soft robots without requiring many sensors and can improve closed loop control of soft robots. Our soft robot can predict force interactions with objects of varying sizes and monitor shape with minimal embedded sensors. Ultimately, this technology moves toward making MIS procedures easier for the surgeon and safer for the patient. The robot demonstrated its ability to perform a peg transfer task in a mock laparoscopic environment while providing real-time shape sensing and contact force prediction to the surgeon via a GUI. Future works will focus on miniaturizing the system to fit within ports common to single-site laparoscopic procedures (i.e., 25 mm) while maintaining adequate force output and performing *ex-vivo* and *in-vivo* validation experiments.

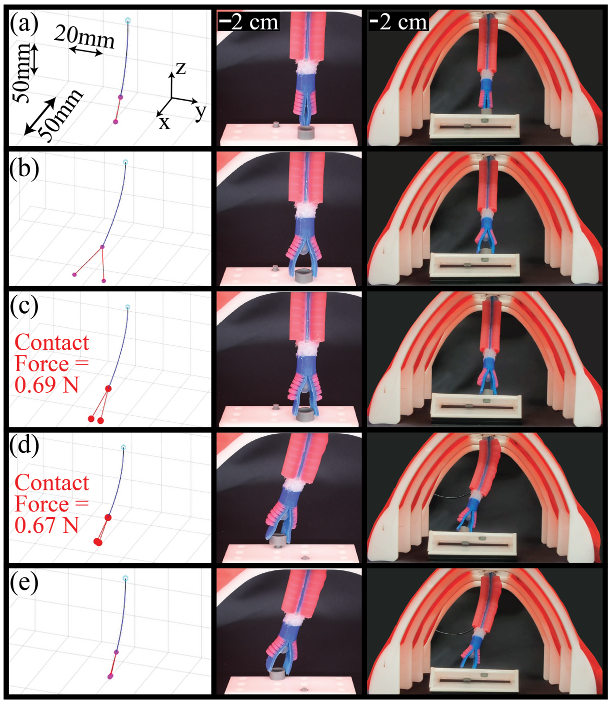

Fig. 3 Shape sensing and contact force prediction during laparoscopic peg transfer test moving from the a) base configuration to b) object position and deploying the gripper, c) grasping an object with force prediction, d) moving an object to the next peg, and e) releasing the object and returning to deployment state.

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