Robust, low-cost, modular mm-scale distal force sensors for flexible robotic platforms

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INTRODUCTION

Innovation in surgical robotics has seen a shift away from traditional rigid systems (such as Intuitive Surgical's *daVinci*^{TM} platform) towards flexible systems that can access remote locations inside the body. However, the flexible nature of these delivery systems, coupled with a lack of haptic feedback, could result in the application of unregulated forces that could damage or perforate tissue in delicate intraluminal spaces.

Several groups have recognized the need for distal force sensing in flexible surgical tools and robotics [1, 2]. However, a general reliance on conventional fabrication techniques ultimately limits the complexity and sophistication of distal implementations of such sensor systems, and poses a barrier to further innovation and widespread adoption. Herein we present a mm-scale force sensor manufactured using a composite lamination fabrication process, wherein linkages pre-machined in the laminate provide the required degrees-of-freedom and fold patterns to facilitate self-assembly. Using purely 2-dimensional batch fabrication techniques, energy contained within a planar elastic biasing element directly integrated into the laminate is released post-fabrication, allowing the sensor to `self-assemble' into its final 3-dimensional shape. The geometry of the sensor was selected based on size constraints inherent in minimally-invasive surgery, as well as with specific focus on optimizing the sensor's linearity. The sensor is unique from fiber-based force sensors in that the emitter and the detector are encapsulated within the sensor itself, allowing it to be retrofitted onto existing tools.

MATERIALS AND METHODS

The sensor operates by the principle of *light intensity modulation (LIM)*, a transduction method which has already been FDA-approved (St. Jude Medical's *TactiCath* force-sensing ablation catheter). The principle works as such: a light-emitting source (infrared LED) is separated from a detector (infrared phototransistor) by some distance as determined by an elastic mechanism. As a force is applied, the elastic mechanism deforms, bringing the source closer to the detector. By measuring the output current of the detector, the input force can be determined.

Up until now, due to difficulties in manufacturing and assembly of the requisite components, this modality has been practically realized by transmitting the light from a proximal source through optical fibers to the distal end of the tool where the force is being applied [3, 4]. Other light-based approaches (Fabry-Perot interferometry, fiber-Bragg gratings) also require optical fiber transmission as well as expensive interrogation hardware [5, 6]. The drawback of fiber-based approaches is that the tool must be designed 'around' the optical fibers and, as such, is not a modular solution.

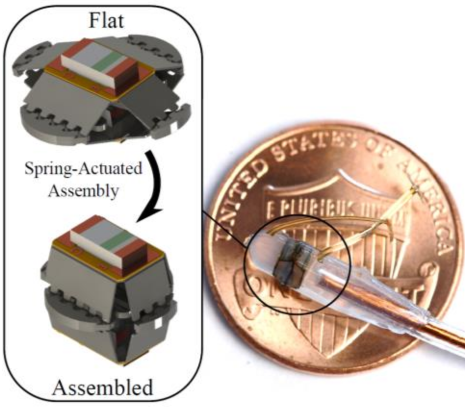

Fig. 1 Image of force sensor molded onto a 6F mock catheter, where the detail shows the sensor self-assembling as a result of a pre-stressed biasing spring contained within.

We have designed, fabricated and tested a modular LIM force sensor (see Fig. 1) that fully contains the emitter and detector and is compliant with the strict size requirements of endoscopic working ports (2.8mm OD). Using a manufacturing process based on printed circuit board fabrication, several layers of structural (304 Stainless Steel), flexible (Kapton polyimide), adhesive (DuPont FR1500 acrylic adhesive), and conductive (copper) material were laser-machined and laminated together. A pre-stretched spring (a) provides a restoring force that causes the sensor to 'self-assemble', much like a pop-up book, (b) serves as the elastic mechanism which deforms upon force application, and (c) serves as a grating which allows more light through as the spring is expanded to increase sensitivity. Fig. 2 shows an overview of the manufacturing process.

RESULTS

The sensor was calibrated using a reference load cell to generate the calibration curve shown in Fig. 3. The sensor exhibits linearity over 0-100mN range, after which, an exponential relationship more accurately describes sensor behavior. The calibrated behavior closely matches the predicted behavior based on a simple point-source emitter model. The sensor exhibits sub-mN resolution which was quantified by integrating the power spectral density of the sensor output given no

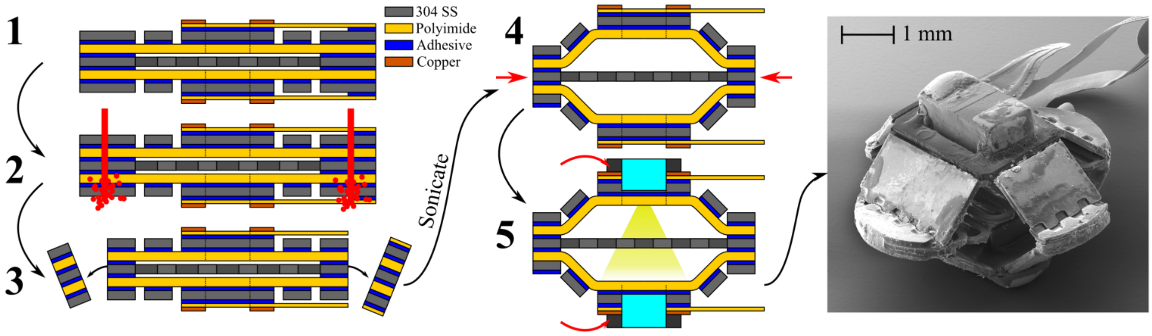

Fig. 2 Manufacturing process used to fabricate self assembling sensor: (1) multiple individually-machined layers of material are laminated to form a composite, (2) release cuts are made using a laser, (3) the alignment scaffold is discarded, (4) the sensor is submerged in an ultrasonic bath which causes assembly spring to retract and assemble the sensor, (5) pick-and-place components are reflow soldered to complete assembly. A scanning-electron microscopic (SEM) image shows sensor detail.

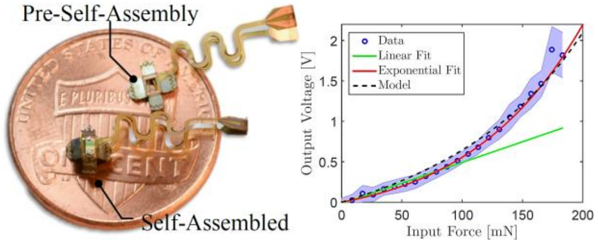

Fig. 3 *(left)* fabricated sensors, both pre- and post-assembly, *(right)* sensor calibration curve, compared with a linear and exponential fit, as well as a comparison with the deterministic model based on the optoelectronic properties of the system.

Table 1 Sensor Specifications

Parameter	**Value**	**Unit**	**% FS**
Sensitivity (0-100 mN)	5.0	V/N	N/A
Range	0-200	mN	N/A
Resolution	0.8	mN RMS	0.4
R^2 (Exponential)	0.99	N/A	N/A
R^2 (Linear, 0-100 mN)	0.97	N/A	N/A

input stimuli. The sensor's sensitivity can be controlled by selecting the appropriate thickness of the spring layer, and also by encapsulating the sensor in various polymers or rubbers which are IR-transparent. Sensor specifications are given in Table 1.

The sensor's efficacy was determined *in vitro* by encapsulating the sensor in silicone rubber, integrating the sensor onto the distal end of a 6F catheter and performing a palpation task on a block of silicone rubber (EcoFlex 00-50, Smooth-On) through a tortuous GI tract analog (rubber tubing bent at a 180-degree angle). A reference load cell measures the insertion force (a combination of the palpation force and frictional forces). The results are shown in Fig. 4. The distal sensor is necessary to discriminate distal forces at the proximal end due to friction in the system and other sources of contamination.

DISCUSSION

The results presented herein indicate a promising solution to developing robust, low-cost, modular, millimeter-sized force sensors with the resolution necessary for delicate MIS surgical interventions. Preliminary calibration tests have shown that the sensor can detect sub-mN forces over a range of 0-200 mN. An *in vitro* palpation simulation showed that the sensor has the sensitivity necessary to extract ~mN-level distal forces from an otherwise contaminated haptic profile, indicating the need for distal sensing modalities for obtaining accurate information from the tool-tissue interface. Future work will focus on optimizing the sensor design, improving methods of encapsulation and integration, and investigating multi-axis capabilities.

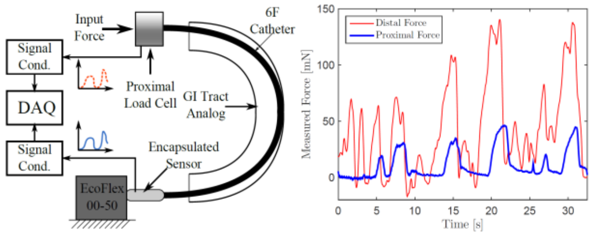

Fig. 4 In-vitro palpation test, showing a significant discrepancy between the haptic force surgeon-side and the distal force measured by the sensor.

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