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Ferromagnetic and IPMC-Based Cautery Tool for Robotic Surgery

I. ABSTRACT

Robotic surgery has become an extremely important innovation for the 21st century, as it has revolutionized modern surgery and allowed for an explosion of biomedical devices to begin development for use in aiding todays' operators. In particular, multiple papers have investigated the uses of ionic polymer-metal composite (IPMC) actuators as well as ferromagnetic polymer composites for use as an active catheter in biomedical applications. Ferromagnetic control is extremely precise and highly predictable, whereas IPMC control can achieve large bending angles, but can only be adequately controlled for a specific task with little chance for variation. Our proposed research would serve to marry the two control methods to create an electrocautery tool for use alongside robotic surgery platforms. This would reduce the wear on the cautery device, and give the surgeon far more precise control over what tissue is cauterized, thus reducing the likelihood of adverse conditions which currently cause hundreds of patients to die from cautery-induced electrical burns during robotic surgery. This paper provides data for as a proof-of-concept for such a device, demonstrating that it could (1) reach a bending angle of 90 degrees, (2) successfully navigate-to and cauterize a simulated artery within a cadaver, and (3) be controlled accurately without interference between the two main actuation methods for the tool. The results of our work would therefore serve as a foundation for which new cauterizer devices could be developed from, drastically improving patient outcomes and further extending the viability of robotic surgery for more complex procedures.

II. OBJECTIVES

The chief purpose of this research will be to determine if a cautery device with both ferromagnetic and IPMC actuator controls can feasibly be used as a more precise cautery tool alongside pre-existing robotic surgery platforms. Specifically, it will employ three tests alongside the da Vinci ® robotic surgery platform. The first will determine if the tip force of the IPMC actuator will be able to provide a large enough bending moment in order to freely rotate the cauterizer's tip greater than 90 degrees. Secondly, the tool will be employed in a bovine cadaver stomach to determine if the device can apply enough force to an average-sized artery to cauterize it effectively, without failing under the resulting stress. This will be done in the transoral route into the stomach of the cadaver, thus simultaneously simulating the device's potential application for repair of peptic ulcers as well as its use as a companion to the da Vinci system. Finally, we would analyze the accuracy of the device's magnetic control system via commanding the device to follow a circular path. The IPMC portion of the device will then be measured for electrical activity to determine if the magnetic controls interfere with the ionic-transport in the polymer and cause unwanted actuation.

III. BACKGROUND

Much work has been done in the past two decades on the prospect of minimally invasive surgery (MIS), which seeks to improve patient care by reducing recovery time, complications, reported pain, cost, and precision. As one of the most widely-employed and technically advanced of its time, the da Vinci robotic surgery platform serves as an excellent example of how robotic surgery in particular can accomplish MIS. Typically, a small incision is made in the abdomen of an anesthetized patient, creating a "port" for which the device's robotic manipulators can enter the body cavity and perform surgery without ever making any large external incisions. A surgeon will tele-operate the device in a separate room, while assisting surgeons may use additional ports to aid the robotic surgery with manually-operated laparoscopic instruments. The surgeon will make incisions internally using the robotic endowrist's scissors and grippers, and will then use a cauterizer to prevent blood loss from the patient.

Despite the glowing benefits of such a platform, a number of casualties have resulted from device failure, the majority of which from 2009-2010 "were related to the instrument wrist or tip (285), 174 [of which] were related to cautery problems" regarding the da Vinci platform in particular [1]. Investigations into the phenomenon have demonstrated that the high-traffic use of the endowrist cautery tool—a multi-DOF gripper and cauterizer for internal bleeds—leads to cracking and wear which causes electricity to arc into the patient, resulting in lethal electrical burns [2]. We therefore propose a solution to this problem via specializing cauterization into a single, extremely precise instrument which can be used alongside traditional robotic surgery grippers. It is intended to be used by a second surgeon during the procedure, such that the attention of the main surgical task is not taken away from the tele-operator, and cauterization can be done with much more intent than present systems allow.

The device would be a 1mm diameter cylinder formed from a ferromagnetic polymer composite with IPMC joints and an industry-standard bipolar electrocautery unit made from electrodes at the tip for safe heat generation. It can therefore utilize magnetic controls, as was previously established as an effective means to snake through the most tortuous portions of the human body, while remaining highly predictable at the same scale as the proposed tool [3]. In contrast, the IPMC joints utilize electrodes which provide a voltage to the polymer, causing ion transport to produce a controllable force or bending moment within the IPMC. Moreover, this device would attain a much higher level of precision than current cautery tools; in particular, the da Vinci robotic surgery platform utilizes induction heating through 5-7 mm grippers which heat large swathes of tissue which it grasps. Such grippers often cause bleeds to require upwards of 10 attempts to cauterize due to inaccurate assessment of the bleed origin site. In contrast, our instrument would be smaller than an artery itself, thus it could simply locate the origin of the bleed, snake directly into the entrance of the artery, and cauterize the entrance of the bleed in one attempt [4][5][6]. We hypothesize that this will drastically reduce the amount of wear on both devices, therefore reducing the likelihood of electrical burns for the patient.

The ferromagnetic polymer composite previously mentioned was demonstrated to have difficulty making sharp angled turns, but was extremely precise for snaking through the body's more gradually changing pathways [3]. Thus, the ferromagnetic portion of the device will be utilized to travel to a general location in the body with ease, as the theoretical modeling of magnetic forces results in a more accurate control system than a solely IPMC-based device. Furthermore, the IPMC portion of the device will be utilized specifically for the purpose of shaping the end-effector such that it can cauterize the site effectively. Prior research has proven that a single Nafion™ IPMC film of 0.18 mm thickness and 30 mm length will create the largest bending angle—approximately 45 degrees—in response to 4.5 V. After being actuated 10 times in succession, this specific combination of IPMC, geometry, and voltage allows the maximum displacement to still maintain 80% of its initial value. By comparison, other combinations were found to result in as low as just 5% of the initial displacement, therefore making our proposed configuration optimized for age-resistance [7]. The large bending angles created by such an IPMC joint far exceed that of ferromagnetic controls alone, making IPMCs imperative for the cauterizer's functional purpose. Due to hysteresis effects however, the controls for IPMCs are more difficult to develop and maintain over time; thus, IPMC joints are only well-suited for very specific tasks such that the control system can be easily tuned—while more varied movements are handled by the highly-predictable magnetic controls.

The device will utilize optical tracking rather than electromagnetic tracking, as prior work has shown that ferromagnetic surgical implements can greatly interfere with the latter method [8]. This falls in-line with the main suggested application for such a device as an aid to preexisting robotic surgery platforms, as all of which are extremely conducive to optical tracking on account of their included endoscope attachment.

Two 30 mm length joints will be constructed with the IPMC, such that they can be actuated in succession and create a total bending angle to 90 degrees for the end effector. After forming an 'L' shape with the end effector, it could then be stamped into the bleed site to cauterize a length of tissue effectively—and since the actuator's initial position will be straight—the time response of the IPMC will gradually push the cautery device into the tissue as the IPMC attempts to straighten the 'L' shape and return to its equilibrium state. A second approach to cautery would be to snake the device into an exposed artery's entrance, then actuate the IPMC joints in combination to create anywhere from a 10-90 degree bend—depending on the size of the artery; the device could then use its ferromagnetic controls to rotate the tool inside the artery entrance in order to cauterize, continually spinning and working outwards in a conical shape to seal the artery while gradually straightening the joint as the end-effector moves towards the center (***Fig. 1***), thus eliminating any chance for excess thermal damage to surrounding tissue. Our paper will determine whether or not this proposed design will be able to withstand the forces involved with

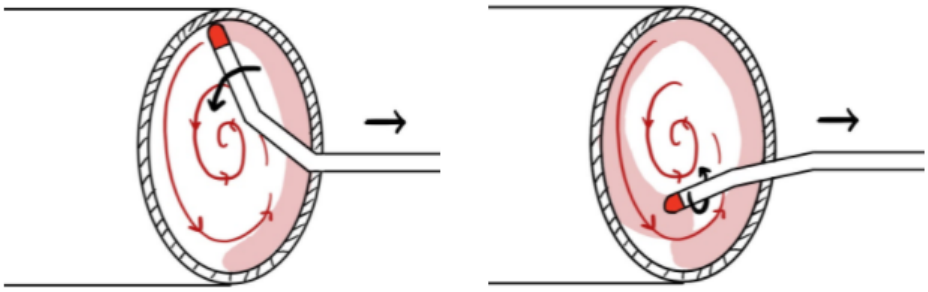

Figure 1: *artery cauterization method #2*

such a procedure, as previous work has demonstrated that the average blocking force of IPMC actuators are in the range of 11.96–37.04 mN, with an optimized maximum output of ~50 mN [9]. Despite multiple papers suggesting the use of these IPMC actuators as catheters, no paper to date has investigated the validity of IPMCs withstanding the fluid-mechanical forces involved with cauterizing an artery specifically, thus our paper will additionally serve to expand the field of biomimetic materials for potentially broader applications.

The IPMC actuator portion of the device will be formed as a hollow cylinder to follow with the shape of the ferromagnetic portion, as multiple papers have already established that hollow cylindrical geometry can perform similarly to traditional rectangular geometries [10]. Additionally, the IPMC will be made using the laser-cut electrode method established by Lu et al. in order to allow the IPMC to have multiple DOF, therefore making the device easier to control when attempting to cauterize a bleed origin site [11]. The IPMC will then be controlled using the closed loop PI control system established by Ruiz et al. for a similar cylindrical, multi-DOF, ~1mm average diameter, hollow IPMC. It is based off of theoretical modeling of ionic transport and solid mechanics, collapsed into finite element equations, and was proven to

be very accurate so long as a separate control input method is utilized; thus, we propose to use the da Vinci tele-operating station as the control input for our circular pathing test [12]. Our test would therefore mimic how the device could be implemented in industry and work synergistically with preexisting robotic surgery platforms. Finally, the Nafion IPMC joints will be covered with a silicone film such that they remain dry, as the tensile strength of Nafion joints are nearly doubled when compared to their wet state, due to liquid interfering with the ionic-transport that produces force for IPMCs [13].

While this paper intends to only test the proposed device for use alongside a typical intra-abdominal da Vinci procedure, its applications can be extended for use in Transoral Robotic Surgery (TORS); this is a hot topic in the current literature, and has been proven to be safe enough for TORS procedures to be developed in the future, particularly for the aforementioned application to peptic ulcer repair [14][15], thus posing an exciting, but untouched prong for further research to be directed towards.

IV. TECHNICAL PLAN

First, the device will be constructed using the combined methodology of Lu et al. [11] for the Nafion joints and Kim et al. for the ferromagnetic portions [3]. The joints and electrodes will then be coated with a 0.5 mm layer of biocompatible silicone elastomer, such that the IPMCs are protected from bio-fluids. The polymer gel coating used in the construction of the ferromagnetic guidewire from Kim et al. will then be planted across the entire device except for the electrocautery tip, such that friction is reduced by over 10x for the device, allowing it to move unimpeded during surgery [3]. The control system devised by Ruiz et al. will then be implemented to control the IPMC joints, while a simple magnet will be used to steer the ferromagnetic portion of the device, as promising research is still currently underway to refine a multivariable control system for ferromagnetic catheters.

The first experiment will be prepared via cantilevering the device in a lab vice, with the IPMC joints positioned such that their electrodes will actuate the device to bend directly upwards, thus requiring the maximum expected force under gravity. The device will be angularly constrained by machined PVC blocks to ensure that the device remains perfectly vertical. A voltage of 4.5V will then be applied to both IPMC joints simultaneously and the max bending angle will be measured using optical sensors, as using more traditional strain gauges might interfere with the electromechanical surface properties of the device. The trial will be performed 50 times and a statistical analysis will then be performed to determine the mean bending angle produced by the device. After each actuation, the device will be allowed to rest for 5 minutes to prevent the time response of the IPMC material from affecting the results. This experiment will then be repeated with no elapsed time between actuation tests, thus simulating the device's capabilities in a fast-paced environment which may be affected by its stress response time.

The second experiment will use a bovine cadaver and have the device inserted into the esophagus, down into the stomach alongside the da Vinci X commercial endoscope attachment for optical tracking. The success of the device's ferromagnetic navigation will be determined based on how many times the device makes unwanted contact with the walls of the stomach, and the total time spent performing the task when compared to the da Vinci endowrist cauterizer as a control group. A plastic tube of 5 mm diameter carrying blood will be stapled to the inside of the stomach as well, therefore simulating an artery for the device. The tube will be cut using the da Vinci's endowrist scissors, then the device will be inserted into the plastic tube entrance and tasked with cauterizing the blood to the degree that subsequent flow into the stomach is ceased. This will be performed once using the 'L'-shaped technique that was first discussed, and once more using the conical technique which was discussed second (***Fig. 1***). The task will then be timed and compared to the da Vinci endowrist cautery device performing the same task. This will be performed 10 times for both the proposed device techniques as well as the da Vinci cauterizer control group, and the surrounding tissue damage to the stomach will be assessed by a surgeon afterwards. All mechanical failures of the device will be recorded and analyzed to determine the failure mode for the tool.

The third experiment would also utilize a bovine cadaver's stomach and the device would be tasked with following a circular path, as controlled manually by a strong magnet for 1 minute. No voltage will be input into the IPMC joints. The electric signal within the IPMCs will then be measured from the electrodes already implanted in the IPMC multi-DOF design to determine if the magnetic controls had caused any unwanted actuation of the IPMC joints.

V. TIMELINE

The construction of the device is expected to take approximately three months, leaving room for the research team to perfect the procedures laid out by the papers previously mentioned. Additionally, during this time period, the research team will develop the precise set up for the bovine cadaver stomach to properly constrain it, as well as properly mimic human blood pressure within the simulated artery. Three months will then be spent performing the first and third experiments, as well as searching for a surgeon to evaluate the future results of the second experiment. Approximately 3 months will then be spent performing the third experiment, as it contains the most time-consuming and complex procedure of the proposed project. Finally, three months will be allotted for statistical analysis and the finalization of the research's findings into a publishable paper.

After this initial proof-of-concept paper, future research could be done for two potential projects. The first would be a statistical analysis testing how much, if at all, the likelihood of wear-induced electrical burns has decreased for the cautery tool. The second would be an investigation into the feasibility for application to TORS procedures, because as was previously mentioned, there is a high demand for such procedures to be developed

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