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Semi-Autonomous Electrosurgery for Tumor Resection Using a Multi-Degree of Freedom Electrosurgical Tool and Visual Servoing*

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Abstract

This paper specifies a surgical robot performing semi-autonomous electrosurgery for tumor resection and evaluates its accuracy using a visual servoing paradigm. We describe the design and integration of a novel, multi-degree of freedom electrosurgical tool for the smart tissue autonomous robot (STAR). Standardized line tests are executed to determine ideal cut parameters in three different types of porcine tissue. STAR is then programmed with the ideal cut setting for porcine tissue and compared against expert surgeons using open and laparoscopic techniques in a line cutting task. We conclude with a proof of concept demonstration using STAR to semi-autonomously resect pseudo-tumors in porcine tissue using visual servoing. When tasked to excise

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tumors with a consistent 4mm margin, STAR can semi-autonomously dissect tissue with an average margin of 3.67 mm and a standard deviation of 0.89mm.

I. Introduction

Robotic surgical systems have had a drastic impact on minimally invasive surgeries. Platforms such as the da Vinci™ robot (Intuitive Surgical, Sunnyvale, California) provide stereoscopic vision, dexterous tools, motion scaling, and improved ergonomics that enable minimally invasive surgery (MIS) in tight anatomic spaces such as the head and neck [1]. Patients diagnosed with head and neck squamous cell carcinomas (SCC) [2] require accurate tool placement and motion to resect tumors with exact margins. Tumor margins are particularly important as patients are at increased risk for recurrences, repeat surgeries, and reconstructive procedures [3] if the tumor is not sufficiently cleared. Alternatively, if the tumor margin is too large, the patient may suffer severe functional impairment of the upper aerodigestive tract, and a lower quality of life.

Today, tissue resection is performed by either open or endoscopic techniques. Robotic surgical assistants incorporate highly dexterous tools, hand tremor filtering, and motion scaling for MIS SCC resection in trans oral robotic surgery (TORS) [1]. There are two major limitations with a standard robotic assistive surgery (RAS) approach for TORS. First, tissue motion and irregular margins require high precision cutting over a long duration [4], placing burden on surgeons and contributing to variable tissue margins. Literature recommends a minimal margin of 4mm to adequately resect diseased tissue [1], [5]. Secondly, SCC is hard to visualize intraoperatively due to occlusion and textural similarity to surrounding tissues. The surgeon must rely on experience and preoperative imaging to determine how much tissue to resect, leading to inconsistent tumor margins with aforementioned negative consequences.

Semi-autonomous tumor resection is one solution to create consistent tumor margins independent of tumor location, size, shape, and surgeon experience. The first contribution of this paper is to determine the ideal cutting parameters of the Smart Tissue Autonomous Robot (STAR) [6]. This paper expands prior work by discussing the design and integration of a multi-degree of freedom (DOF) electrosurgical tool to adapt STAR for semi-autonomous electrosurgery. Using this tool, STAR performs cutting tasks in three tissue types to determine the ideal cutting settings for semi-autonomous operation. These parameters are validated by comparing STAR's cut quality to expert surgeons in cadaver tissue. Second, a surgical workflow is demonstrated to resect SCC pseudo-tumors under semi-autonomous control in ex vivo tissue using visual servoing. The integration of a visual servoing routine replaces the open-loop control presented in [6].

II. Prior Work

The advantages of autonomous robots have been demonstrated in applications from manufacturing to medical tasks [7], [8]. Limited autonomous RAS with pre-planned functionality was introduced in bony orthopedic procedures (e.g. ROBODOC, Caspar, and CRIGOS), radiotherapy, and cochlear implantation [9]–[17]. Another robot, Probot, uses

image guidance to perform repetitive motions of a cutter [18]. Completely automated soft tissue surgery is not yet possible, but the surgical subtasks of knot tying, needle insertion, and executing predefined motions have been achieved [19]–[23]. Challenges from living tissue such as occlusion, respiratory motions, or tissue char limit prior results to phantom tests.

One robot for autonomous surgical tasks is the RAVEN surgical system. Using stereo imaging and low level motion planning, the pose of surgical graspers could be detected during multilateral debridement of phantom tissue [27]. A da Vinci™ Surgical system outfitted with the da Vinci™ Research Kit (DVRK) [24] utilized learning by observation to perform surgical debridement of viscoelastic tissue phantoms including detection of circular targets, and completed circle cutting tasks [25]. The DVRK was also used in ultrasound guided dissection of cryogel phantoms [26]. These papers are limited in scope as they require the entire cut region to be marked, rely on a single pass, mechanical cutting technique, and are not used with animal tissues.

Custom surgical tools and automated tool changing have been integrated with the DVRK. This setup enabled the da Vinci™ Surgical System to autonomously detect, map, and remove pseudo-tumors in phantom tissues [27]. The RAVEN II surgical system, when equipped with stereo tracking and near-infrared (NIR) imaging, could detect pseudo neuroblastoma, generate a surgical plan, and execute semi-autonomous tumor ablation [28]. While each technology demonstrates proof of concept for autonomous cutting, they do not consider tissue motion, deformation, and textural similarity in clinical applications. Phantom experiments are also limited when assessing tissue char in electrosurgical and ablation tasks.

STAR, shown in Fig. 1, is the first robot to address the challenges of tissue motion, deformation, and similarity to complete tasks in soft tissue surgeries. STAR incorporates a 7-DOF lightweight robot (KUKA LWR 4+), plenoptic and NIR imaging system, motion planning software, and robotic tool sets. STAR tracks the deformable environment by detection of NIRF markers placed on target tissue. The NIRF markers are biocompatible and can be visualized through blood and tissue occlusions. The NIR and plenoptic cameras are registered together, so metric coordinates of each marker can be calculated. Using this setup, STAR can accurately track, account for, and respond to deformation.

Most recently, STAR performed semi-autonomous intestinal anastomosis in soft tissue with more consistency and quality than surgeons using open, laparoscopic, or RAS techniques in phantom and ex vivo tissue [29]. STAR was also used successfully in a pre-clinical study to perform intestinal anastomosis in four porcine models [30].

III. Methods

In this work, STAR is used to perform semi-autonomous cutting in porcine tissue, execute a comparison study to expert surgeons in line cutting tasks, and semi-autonomously resect pseudo-tumors with clinical margins (see supplemental video). The design and integration of a 2-DOF electrosurgery tool is first discussed. Performance of the electrosurgical cutting tool is dependent on the energy and current density applied to target tissue [31]. The

parameters *power* and *cutting speed* vary the applied energy, while *depth of cut* influences current density. To optimize parameters, STAR executes a cutting routine of 5cm long lines to a depth of 4mm. Parameters are varied between two power settings, two depths per pass, and three speeds. The routine is repeated in three tissue types to assess quality.

After quantifying cutting parameters, STAR is used to compare semi-autonomous operation against expert surgeons in line cutting tests. Surgeons are asked to make a 5cm long incision through porcine skin tissue. STAR, programmed with the cutting parameters found previously, is instructed to do the same task. The resulting incisions are compared on time, deviation from the ideal cut line, and tissue char. Finally, STAR demonstrates semi-autonomous tumor resection. Cadaver tumor models are created by implanting pseudo-tumors into porcine tissue plates. NIRF markers are manually placed along the tumor edge. STAR identifies the NIRF markers and generates a tumor resection plan consisting of a uniform 4mm margin. STAR uses visual servoing along the surgical plan to resect the pseudo-tumor.

A. Design of a Dexterous Robotic Cutting Tool

One advantage of RAS over manual MIS is the use of multi-DOF surgical tools. The extra DOF enable wristed motions of the robotic tools, and provide finer dexterity than standard laparoscopic tools, with improved ergonomics. When multi-DOF tools are combined with a robotic positioner such as the da Vinci™ Surgical System, the surgeon has 6-DOF control of the surgical tool for any tool orientation within the patient.

A robot designed for semi-autonomous cutting tasks would also need 6-DOF control of the cutting tool. STAR utilizes a 7-DOF robotic positioner (KUKA LWR 4+) for complete control in an open surgical setting. In a laparoscopic surgery, STAR's tools pass through a remote center of motion (RCM) reducing the system to 4-DOF. A two 2-DOF cutting tool is necessary to restore 6-DOF control for laparoscopic use.

The prototype robotic cutting tool was built by modifying a commercially available 2-DOF laparoscopic grasper Radius T (Tuebingen Scientific, GMBH, Tübingen, Germany). The tool was mechanized by a custom adapter to couple the 2-DOF tool to a 6-axis motor pack. The tool's tip was replaced by a quick release connector to accommodate electrosurgical electrodes with a shaft diameter of 3/16". The tool tip was electrically insulated from the Radius T, and electrical conductors were routed within the tool shaft. Each conductor was terminated with a standard electrosurgical connector. The pitch and roll motion of the cutting tool is inherently different than the wristed pitch and yaw of da Vinci™ tools. While both tools provide 2-DOF, the pitch and roll motion of the cutting tool is accomplished by beveled gearing within the commercial Radius T tool. The gearing systems allows the cutting tool to be disassembled, cleaned, sterilized, and withstand repeated clinical use, whereas da Vinci's™ cable and pulley setup cannot be disassembled and is only approved for a limited number of uses [32].

Fig. 2 shows a computer aided design (CAD) of the cutting tool. A standard quick release interface at the distal tip interfaces with standard electrodes. The needle electrode used in this paper has insulation which is tracked during visual servoing. The cutting tool is actuated

by a 6-axis motor pack with DC brush motors (Maxon Motors, Sachseln, Switzerland). One motor actuates pitch through two bevel gears and spur gear, while a second motor actuates tip roll through bevel and crown gearing. Each motor includes an encoder for precise positioning using EPOS2 controllers (Maxon Motors, Sachseln, Switzerland). Communication between the robot and tool is through a controller area network. The tool is homed by energizing the pitch motor with current control until it reaches a hard stop.

B. Electrosurgical Unit

The cutting tool is powered by a commercial electrosurgical unit (ESU) ASG300 (DRE INC, Louisville, Kentucky, USA). The cutting tool utilizes a monopolar setup, where high energy pulses are applied by the tip electrode and returned to the generator through a grounding plate. Controlled, localized heat using this monopolar setup vaporizes target tissue. In addition to cutting tissue, the ESU can output a modulated waveform to coagulate target tissue.

C. Imaging System

The dual camera NIR and color imaging system shown in Fig. 3 [6], [30], [33] is used. The system consists of a 760 nm high power light-emitting diode (North Coast Technical Inc., Chesterland, OH), NIR camera (Basler Inc., Exton, PA) with an $845\text{nm}\pm 55\text{nm}$ filter to capture the emitted NIR light (Chroma Technology Corp., Bellows Falls, VT), and a color camera for visible light (Point Grey Research, Richmond, BC). Both cameras are calibrated, where the NIR camera visualizes and tracks NIRF markers in the surgical field, while the RGB camera tracks position of the cautery tool. NIRF markers are advantageous because their spectral signal is easily segmented from tissue in the surgical field, while their emission wavelength penetrates thin tissues, making them robust to occlusion and char during electrosurgery. The NIRF markers are made from indocyanine green (ICG), biocompatible glue, and are applied with a syringe.

D. Straight Line Tests and Control

STAR's software can be represented by a series of related nodes communicating on the Robot Operating System (ROS) framework. Nodes deal with input from sensors such as cameras, communication between ROS and the KUKA LWR4+ robot, and with higher-level control and planning. For real time communication with the robot, an Open Robot Control Software (OROCOS) component acts as a bridge between ROS and the Fast Research Interface (FRI) on the KUKA control cabinet. Straight line cutting tests to identify cutting parameters were conducted. Three tissue types were prepared for cutting tasks. The operator inputs the total depth of cut, depth per pass, cut speed, and cut length. The software computes a trajectory consisting of the: approach, cut, retract, and reset motions. Between each motion the operator can inspect the tool prior to continuing the operation. This control scheme was repeated for comparison tests between STAR and expert surgeons.

E. Visual Servoing

Delicate interactions between the electrocautery tip and tissues are difficult to model and simulate, while thickness and composition can affect cutting effectiveness. These variations

can result in tissue deformations and the accumulation of potential energy that can cause erratic motions when released. These complex interactions, compounded with low stiffness, mechanical compliances, sensor calibration, and kinematics errors can decrease the accuracy of the interaction [9], [29]. To mitigate these sources of modeling errors, image-based visual servoing is used (IBVS) [34] to control the motion of the robot from errors measured directly in image data. This approach is robust to small calibration errors and other deformations that can be observed [35]. Using IBVS, the system ensures the cautery tool will follow a trajectory defined by image coordinates. The advantage of using IBVS is that position of the cautery tool is controlled by $\mathbf{e} = \mathbf{p}^* - \mathbf{p}$, which defines the error between the measured image coordinate of the tool tip, $\mathbf{p} = [\mathbf{u} \ \mathbf{v}]^T$, and the desired tip coordinates $\mathbf{p}^*$. For an eye-to-hand configuration, the velocity of the camera $\mathbf{v}$ decreases the error $\mathbf{e}$ to zero by solving the IBVS control law for point features [36].

The implementation handles a vector of N target points $P = [\mathbf{p}_1^* \dots \mathbf{p}_N^*]$; once the measured tip position is within a certain threshold number of pixels of the current target $\mathbf{p}_i^*$, it advances to the next target, $\mathbf{p}_j^*$. Once it has reached $\mathbf{p}_N^*$ it starts from $\mathbf{p}_1^*$ again, enabling it to make several passes to complete a cut.

NIRF marker Tracking—Experimentally, the Visual Servoing Platform (ViSP) [37] library is used to track the tumor position using NIRF markers with the NIR camera and the tip of the cautery tool in the RGB camera. The image coordinates of the NIRF markers determine the pose of the tumor in the coordinate frame of the camera by using a 2D–3D registration algorithm based on the minimization of reprojection errors [38]. The image-based excision trajectory is generated using the tumor pose to calculate and project a 3D tumor model with 4 mm margins in the camera frame.

RGB Tool Tip Tracking—While ViSP works well for blob tracking the main body of the tool, it places coordinates of this blob at the centroid instead of the tip of the tool. To obtain position of the tool tip, a covariance matrix was constructed for the tool tip blob by computing the centroid $\bar{\mathbf{x}}$ of all of the points within that blob, finding the difference vector $\mathbf{d}_i = \bar{\mathbf{x}} - \mathbf{x}_i$ between any point $\mathbf{x}_i$ inside the blob and the centroid, and finding the covariance matrix for that point as $C_i = \mathbf{d}_i \mathbf{d}_i^T$. then, the total covariance matrix for the tracked blob of the tool can be found as $\Sigma_i C_i$.

The eigenvalue decomposition of matrix C provides the eigenvectors that indicate major and minor axes of the tool. Knowing the tool is longest along the length, the largest eigenvector in magnitude can be followed from the centroid of the tool towards the tip. To find the tip of the tool $\mathbf{p}$, the edge of the blob is intersected with the major eigenvector extended from the centroid of the blob.

Image-Based Trajectory—The excision trajectory P and the tool tip $\mathbf{p}$ must be expressed in the same coordinate frame. Since P is defined in the coordinate frame of the NIR camera and $\mathbf{p}$ is measured in the coordinate frame of the RGB camera, the planar trajectory is transformed into the latter frame by a homography and the position of the cautery tip is

moved along the image-based trajectory in the RGB images. The trajectory is repeated several times, increasing the cutting depth by 2mm for each iteration.

IV. Experiments

A. Determining Tissue Cutting Parameters

The ESU has two coagulation settings, two cut settings, and ten blend settings that affect the waveform used for semi-autonomous electrosurgery. Additionally, the ESU power can be adjusted from 1W-300W for each of these waveforms, resulting in 4200 unique electrical settings from the ESU alone. The shape and power of each waveform directly impacts physiological response in tissue. For instance, a cutting waveform delivers continuous high frequency energy best for vaporizing tissue. To create a coagulum on target tissue, one would use a pulsed waveform that simultaneously vaporizes and coagulates tissue.

In addition to electrical waveforms, cutting speed and depth have the potential to impact the quality of cut in target tissue. As cutting speed and depth increase, less energy will be delivered to target tissue, resulting in a reduction of collateral tissue damage but less vaporization of target tissue. Alternatively, as cutting speed and depth decrease, more energy will be delivered to target tissue resulting in a cleaner cut with more collateral tissue damage. In the following experiment, the parameters power, speed, and depth of cut that produce the best quality of cut are determined. The continuous cutting waveform was assumed to be ideal for a cutting task and used for all experiments.

Porcine fat, muscle, and skin were purchased from a butcher (Smithfield Foods, Smithfield, VA) and sliced into square tissue plates approximately 100mm on each side. Each tissue plate was placed on top of the ESU grounding electrode and clamped using four wing nuts and an insulated cover as shown in Fig. 4. A 75cm $\times$ 75cm window was cut into the insulated cover to allow the electrosurgical tool to access the tissue plate. STAR was programmed to cut a 5cm length in each tissue along the +X axis as described in section IIID above. The speed of cut was selected to be 1, 5, or 10 mm/s for the muscle and skin plates, and 10, 15 or 20 mm/s for the fat plates. The depth of cut was set to 0.5 or 1mm/pass and cuts were performed to a total depth of 4mm. A power setting of 20W and 30W for muscle and skin or 10W and 20W for fat was used for each combination of cutting depth and speed. All 12 cutting parameters were tested using the needle electrode shown in Fig. 2, in each of the 3 tissue types (n=1) for a total of 36 trials.

To determine the quality of cut, metrics for each tissue are evaluated against tissues of the same type. The quality of cut based on the amount of tissue char, overall length of cut, average distance of cut length from the ideal cut, and maximum distance of cut length from the ideal cut was evaluated. The amount of residual char is one of the most important metrics to consider as char corresponds with tissue damage. Additionally, a sample with too much char is assumed to correlate with collateral tissue damage and impact proper healing after surgery. When two settings have similar char, they are ranked according to the length of cut. A cut that is not the full 5cm indicates that cutting parameters are not sufficient to complete the task and cannot be relied upon for consistent outcomes. Finally, average deviation and

maximum deviation from the cut lines indicate the straightness of the cut. A perfect incision would have zero deviation from the cut line.

Length of cut—Images of each tissue sample next to a surgical ruler (Medline, Mundelein, Illinois, USA) were taken for each setting. The imaging software ImageJ (National Institutes of Health, Bethesda, MD) was used to calculate the straight line distance between the beginning and ending of each cut in mm.

Deviation from Ideal Cut Line—After segmentation of the cut, ImageJ was used to create a mask of the cut edge. The image mask was exported to Matlab (Mathworks, Natick, Massachusetts, USA) where the start and end of each cut were selected. Matlab generated the ideal trajectory between the end points, which was overlaid on the segmented edge. The minimum distance between each point on the segmented mask and the straight line trajectory was calculated. The average and maximum of these distances are reported as the average and maximum cut deviation. When choosing cutting parameters, it is most important to reduce the maximum deviation of the cut line. This strategy minimizes the risk of not adequately clearing the entire tumor margin.

Average Tissue Char—After cutting, tissue samples were folded along the cut line to expose the cut edge as shown in Fig. 5. RGB images were taken and imported into ImageJ. The exposed cut area of each sample was manually segmented and the image converted to gray scale. Gray scale pixel values were used to calculate average pixel intensity. To account for variations in lighting conditions between images, the average pixel intensity immediately adjacent to the cut was used to normalize the data. Normalized pixel intensity values are inverted to get a measure for char. An average inverted pixel value of 255 indicates complete char of the tissue. It should be noted that because the automated char analysis is dependent on the contrast between the cut edge and healthy tissue, the strategy only works for light colored tissues.

Analysis of the data revealed average and maximum deviation from the cut line were consistent among each tissue type, irrespective of the cut setting used. The positional accuracy of STAR accounts for these results. Axial deviation of the cutting electrode from the tool base was measured to be 0.127mm using a concentricity gauge, and the line cutting trajectory was normal to the pitch joint minimizing the effects of backlash on the resulting cut. The most notable differences in cutting metrics were from the average amount of char. Fig. 6 illustrates the average inverted pixel intensity for each cut in both skin and muscle tissue. After identifying the top three trials that produced the highest average pixel intensity for each tissue type, the settings were cross referenced against the total length of cut. The ideal cutting parameters listed in Table I are the settings that produced the least amount of char for the full 5cm incision length. The amount of char was not quantified for fat, as the tissue melts during electrosurgery. To determine the ideal cutting parameter in fat, parameters that produced the least deviation at the fastest cutting speed were chosen.

B. Line Cutting Comparison Tests

In this task, the experiments are expanded to compare a semi-autonomous paradigm against expert surgeons performing a line cutting task. Porcine skin tissue was prepared as described in section IVA above. Skin was chosen for this experiment due to the uniformity in preparing the samples, ability to segment the cut edge from surrounding tissue, variation in char between cutting parameters, and the tissue type cut during SCC.

In practice, surgeons are trained to cut tissue between known landmarks instead of absolute distances. To conduct a fair comparison for the line cutting test, 5cm long lines were drawn on each tissue sample using a surgical marker. Surgeons were asked to use these surgical markings for reference to cut a 5cm long straight line, using both open and laparoscopic techniques. Surgeons were given the option to choose the waveform and power settings on the ESU to match what they would use clinically. Surgeons were instructed that their samples would be evaluated on length of cut, cut deviation, amount of char, and time. For the open surgical group, tissue plates with 5cm long tissue markings were fixated and the surgeon was provided a surgical pick-up and electrosurgical pencil (Bovie, Purchase, NY, USA). For the laparoscopic group, tissue samples were placed within a laparoscopic surgical trainer (Storz, Tuttlingen, Germany) as shown in Fig. 7 and surgeons were provided with a laparoscopic grasper, and electrosurgical pencil. A 5mm laryngoscope was used for visualization. Surgeons could adjust white balance, zoom, and picture orientation before beginning the trial, and were allowed to practice with the electrosurgical pencil and trainer prior to the experiment. A new insulated needle electrode was used for each tissue sample.

For the robotic samples, STAR was instructed to cut a 5cm long line in porcine tissue plates. The robot was operated under open surgical constraint, with tissue prepared the same as for surgeons in both control groups. STAR was programmed to cut at a speed of 10mm/s, and depth of 1mm/pass using the 30W cutting waveform. These settings matched the ideal parameters for skin found in the first experiment. Similar to the control groups, a new insulated needle electrode was used for each sample.

After completion of tests, samples from open (n=4), laparoscopic (n=4), and STAR (n=4) were evaluated for length of cut, average cut deviation from the ideal cut line, maximal deviation from the ideal cut line, char, and time. An independent two-sample T-test was performed between STAR and open, and STAR and laparoscopic modalities.

Examining Table II STAR performed linear cuts that were closer in length to 5cm ($P<0.01$, $P<0.05$), demonstrated smaller average deviation from the cut line ($P<0.05$, $P<0.05$), and reduced amount of char ($P<0.05$, $P<0.01$) than open or laparoscopic techniques respectively. Additionally, STAR performed better than laparoscopic ($P<0.05$) and similar to open ($P>0.05$) when considering the maximal deviation. Additionally, STAR performed similarly to both open and laparoscopic ($P>0.05$, $P>0.05$) modalities in time.

When considering the clinical impact of these results, there is a significant adverse association between tissue margins less than 1.6mm and disease specific survival in SCC [39]. Assuming the recommended 4mm margin is followed, the maximum cutting deviation permissible to clear a tumor margin is 2.4mm. While differences in average deviation are

less than 0.5mm across all modalities, only STAR and open technique would consistently excise a tumor. Additionally, excess char should be minimized to help prevent poor wound healing and risk of infection [40]. STAR was able to significantly reduce the presence of tissue char by 15.3% and 20.7%, indicating a better clinical outcome compared to open and laparoscopic resection comparatively.

C. SCC Pseudo-tumor Resection with Visual Servoing

The final experiment used STAR for automated tumor resection in a simulated clinical workflow (Fig. 8). A SCC tumor mimic was prepared by generating a CAD model of a non-regular hexagonal pseudo-tumor (Fig. 9a). A stencil generated from the model was used to cut a 2mm thick pseudo-tumor from modeling clay (Fig. 9b). Using a scalpel, porcine fat was excised from a tissue plate, and replaced by the pseudo-tumor to mimic SCC. Thin tissue was placed on the pseudo-tumor to occlude STAR's vision. Finally, NIRF markers were placed at the corners of the tumor (Fig. 9c). A more general shape requires marks to be evenly placed around the tumor. This strategy is consistent with clinical practice where SCC borders are tattooed with India ink [41].

The pseudo-tumor and tissue was then presented to STAR. An operator initialized each fiducial by clicking on their locations in the NIR image, and initialized tracking of the cutting electrode by clicking on the electrode's insulation in the RGB image. STAR generated a surgical resection plan with 4mm tumor margin based on the NIR fiducials. STAR used the visual servoing schema discussed in section III E (Fig. 9e) with a cut depth extending the entire thickness of the fat sample. Successful resection was quantified by measuring the maximal, minimal, and average $\pm$ SD tissue of the tissue margin seen in Fig. 9f.

Calculating Tissue Margins—Using minimum thresholding, the cut and pseudo-tumor edges were segmented in ImageJ. Matlab calculated the minimal distance between each pixel on the cut edge to tumor profile. The average, minimum, and maximum values are reported as the average, minimum, and maximum tissue margin.

The resected tumor had an average margin of 3.67mm with standard deviation of 0.89mm, maximum margin of 5.62mm, and minimum margin of 2.30mm. All margins were above the clinical threshold for disease survival of 1.6mm [40]. Tumor resection time was about 10 minutes. These metrics compare to expert surgeons who average SCC margins between 2–4mm in 22.4% of cases [40].

V. Discussion

STAR is designed for semi-autonomous and autonomous soft tissue tasks. By incorporating NIR imaging, STAR overcomes the challenges of occlusion and tissue char when executing a cutting task. Although STAR performed slower than surgeons, these experiments demonstrate STAR achieves more consistent length and significantly less deviation than any human modality. Successful first approach to resection of pseudo-tumors was demonstrated.

One limitation of the experiments is a broad, flat, pseudo-tumor model that closely mimics SCC tumors. To handle more complex tumor geometry, a three dimensional plenoptic camera will be integrated with the system. Plenoptic imaging was previously shown to tracking NIRF markers with an accuracy of 1.61mm that degrades to 1.71mm when occluded by blood [42]. Multimodal imaging will be coupled with a bimanual cutting strategy to expose and dissect three dimensional geometries. After each cut, the system updates the surgical plan for exposed tissue.

Secondly, in this study STAR did not operate under RCM constraint, but relied on boundary conditions to restrict motion. This distinction is important when comparing results with STAR against the laparoscopic approach. However, because STAR outperformed surgeons using open technique, it's expected the RCM analogue would perform at least as good as the laparoscopic approach. An open cutting strategy is acceptable for superficial SCC on the skin or mouth. To accommodate SCC at the base of tongue or deep in the aerodigestive tract, the RCM constraints for laparoscopic motion developed previously [30] should be used.

Finally, tumor margin consistency can be improved with better registration of the vision system. While tumor margins are similar to 4mm requirements, results could be improved by biasing cutting error away from the tumor to ensure a minimum margin of 4mm is achieved with each pass.

Despite study limitations, this work has potential to be translated to the clinic. With redesign of the adapter in Fig. 2, the electrosurgical tool can be coupled to the motor stage of any clinical robot. The vision system can also be reduced within a 10mm boroscope [43], to capture surgical images with a laparoscopic incision. Furthermore, the IBVS control is closed loop which enables the same cutting tasks to be completed with a less repeatable robotic platform. Finally, the impact on clinic workflow is minimal. Surgeons frequently mark tumor boundaries with India ink [41] that could be replaced by a NIR dye. After initialization, a 4mm margin is automatically generated, and the cutting path followed without the need to remark tissue between cuts.

The current resection strategy is based on the assumption that tumor location and boundary are known. While spatial information is frequently available to the surgeon, manual delineation of the tumor is necessary. A fully autonomous robot would require spatial information and tumor segmentation before and during the surgery. Magnetic resonance imaging (MRI) or computed tomography (CT) performed preoperatively are two strategies to determine tumor size and location. Intraoperatively, tumor tracking could be performed using a systemic NIR dye that binds to the target tumor. Pre- and intraoperative imaging could be registered together to generate the surgical resection plan.

VI. Conclusion

This paper reported the design, development, tissue experiments, and evaluation of a semi-autonomous electrosurgery robot. Phantom work of other groups is expanded by performing experiments in cadaver tissues that have challenges associated with occlusion and char. A new 2-DOF electrosurgical tool and experiments to determine ideal cutting parameters in

porcine fat, muscle and skin are also reported. The robotic system, with this new cutting tool, outperformed expert surgeons performing line cutting tasks in charring and accuracy. Successful resection of pseudo-tumors using visual servoing demonstrates feasibility of the robotic system for semi-autonomous electrosurgical tasks.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1. STAR with attached electro-surgical tool (left), closer view of workspace showing NIR and color cameras (right).

Fig. 2. Computer aided drawing of the 2-DOF electro-surgical tool, compatible cutting electrodes including needle electrode used in experiments, quick connect for electrode insertion and novel components.

Fig. 3.
NIR and color camera imaging system.

Fig. 4.
Setup of tissue plates for cutting parameter tests.

Fig. 5.

Representative results for line cutting tasks: cuts in porcine skin (left) and the same cuts folded to expose and measure the amount of char (right). Each cut was made at a depth of 0.5mm/pass with speeds of 1mm/s, 5mm/s, and 10mm/s from top to bottom using a 20W power setting.

Fig. 6.

Average inverted pixel intensity for each cutting combination as a measure of local tissue char in porcine skin and muscle.

Fig. 7.
Laparoscopic setup for comparison line tests.

Fig. 8.
Clinical workflow using STAR to resect SCC pseudo-tumors with visual servoing.

Fig. 9. CAD drawing of the psuedo-tumor (a), clay model of the psuedo-tumor (b), SCC tissue sample with embedded psuedo-tumor (c), NIR image with tumor margin overlay (d), STAR executing semi-autonomous resection plan with visual servoing (e), excised pseudo-tumor with tissue margin (f). NIR fiducials are labeled with arrows.

TABLE I

Ideal Cutting parameters for STAR

Tissue	Cutting Parameter		
	<i>Power (W)</i>	<i>Depth of Cut (mm/pass)</i>	<i>Speed of Cut (mm/s)</i>
Fat	10	0.5	20
Muscle	20	0.5	10
Skin	30	1	10

TABLE II

Comparison Results for Linear Cutting Task

Metric	Surgical Modality		
	<i>STAR</i>	<i>Open</i>	<i>Laparoscopic</i>
Length (cm)	5.05	4.68	4.73
Avg. Cut Deviation (mm)	0.99 ± 0.26	1.16±0.30	1.48 ±0.54
Max Cut Deviation (mm)	1.77	1.94	3.08
Amount of Char (inverted pixel intensity)	153.89	181.77	194.10
Time (s)	44.24	34.05	38.15