An Interchangeable Surgical Instrument System with Application to Supervised Automation of Multilateral Tumor Resection.

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***Abstract*— Many surgical procedures require a sequence of different end-effectors but switching tools for robot-assisted minimally-invasive surgery (RMIS) requires time-consuming removal and replacement through the trocar port. We present an interchangeable instrument system that can be contained within the body cavity. It is based on a novel mounting mechanism compatible with a standard RMIS gripper and a tool-guide and sleeve to facilitate automated instrument switching. Experiments suggest that an Intuitive Surgical system using these interchangeable instruments can perform a multi-step tumor resection procedure that uses a novel haptic probe to localize the tumor, standard scalpel to expose the tumor, standard grippers to extract the subcutaneous tumor, and a novel fluid injection tool to seal the wound. Design details and video are available at: http://berkeleyautomation.github.io/surgical-tools.**

I. Introduction

Robotic Surgical Assistants (RSAs) are frequently used with high success rates for Robotic Minimally Invasive Surgical (RMIS) procedures such as prostatectomy, ureterectomy, tumorectomy, and nephrectomy within the abdominal and thoracic cavities [7, 27]. Intuitive Surgical's *da Vinci* Robotic Surgical Assistant (RSA) facilitated over 570,000 procedures in 2014 with 3000 RSA systems worldwide [13]. RSAs are currently controlled by surgeons via pure tele-operation, requiring constant surgeon attention and control. Supervised autonomy of surgical sub-tasks has the potential to reduce surgeon tedium, fatigue, and operation time.

Interchangeable surgical end-effectors allow for smaller incision wounds [29] and decreased surgical time [23], but currently available modular tools do not have a wristed degree of freedom thus decreasing surgeon efficacy. To address the problem of modularity and interchangeability, we have developed several novel devices, including interchangeable low-cost instrument mounts for retractors with wristed articulation as illustrated in Figures 1 and 3, to be used to explore automated tumor resection.

We consider the multilateral surgical procedure of tumor resection which includes four sub-tasks: (a) *Palpation*, (b) *Incision*, (c) *Debridement*, and (d) *Adhesive Injection*. These sub-tasks represent a selection of those included in the *Fundamental Skills of Robotic Surgery* (FSRS) [32] used for training laparoscopic surgeons [8, 31]. We explore the automation of this procedure using the da Vinci Surgical Research Kit (dVRK), a commercial RMIS system from Intuitive Surgical [16] with silicone-based simulated tissue phantom. Tumor resection requires multiple instruments: a haptic device for palpation, a blade for incision, grippers for debridement, and a syringe pump for injection. Changing instruments during surgery is time consuming and currently requires a pause in the surgical procedure for human intervention. We consider a scenario where the standard surgical grippers can interface with multiple tool-tips to increase the automation during robotic laparoscopy.

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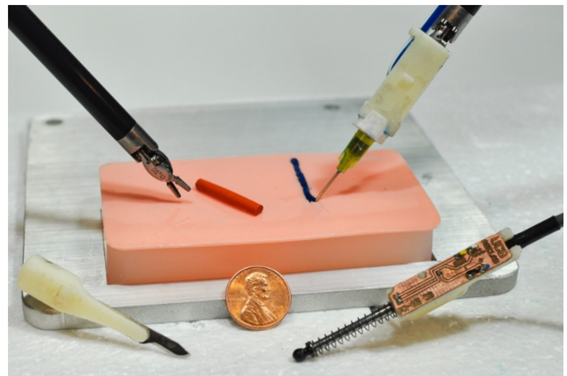


Fig. 1: Surgical tumor resection overview with interchangeable mounts for da Vinci surgical retractor and three end-effector extensions.

Contributions

1. Designs of novel interchangeable instrument mount compatible with standard RMIS gripper.
2. Design of a novel tool-guide and sleeve to facilitate automated switching between instruments.
3. Application of the interchangeable instrument system to multi-step supervised autonomous surgical tumor resection involving changes between haptic probe, scalpel, fluid injector, and standard grippers.

II. Related Work

A. Interchangeable MIS Instrument Systems

There have been a number of studies on non-robotic laparoscopic instruments with interchangeable end-effectors [18, 30]. However, the end-effectors of these in-

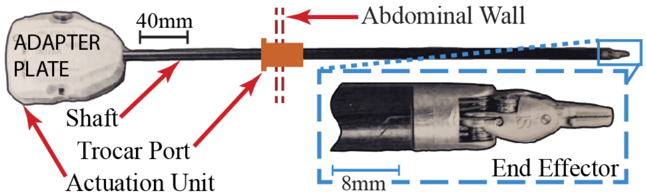


Fig. 2: A schematic view of a da Vinci Classic instrument inserted through a trocar port into the abdominal cavity.

TABLE I: Comparison of Wrist, Clevis, and Jaw Mounting.

	Wrist Mount	Clevis Mount	Jaw Mount
Wrist Rotation	(full) 360°	(full) 360°	(full) 360°
Clevis Rotation	(none) 0°	(full) 180°	(full) 180°
Jaw Rotation	(none) 0°	(none) 0°	(restricted) 60°

struments allow only a single degree-of-freedom (jaw opening/closing) and do not interface with existing surgical retractors. Most existing robotic systems such as the da Vinci and DLR MICA exchange the entire instrument instead of the end effector [1, 37].

Implementation of Interchangeable Systems: Currently, the instrument change procedure for the da Vinci RSA involves the complete removal of the instrument from within the abdominal cavity through the trocar port (see Figure 2). To make interchangeable instrument end-effectors beneficial to RMIS, end-effectors can be introduced through a separate utility trocar port as described in [33]. The utility trocar port can also be the point of entry for electronic cables and catheters as described in [18] allowing for sensorized and fluid delivery end-effectors to be introduced into the RMIS workspace.

Robotic Interchangeable Instrument Systems: In 2007, Friedman et al. proposed the early use of a robotic system to automate instrument change on the da Vinci RSA [10]. However, their method required additional automated infrastructure including an industrial arm used to change the entire da Vinci instrument after removing it from the abdominal cavity.

Commercially Available Devices: In 2015, Teleflex Medical was granted FDA clearance to market interchangeable instrument-tips for *non-robotic* MIS instruments with a single degree of freedom [36].

Existing non-robotic interchangeable instrument end-effectors are not compatible with existing retractor geometry, limiting the combination of possible instrument configurations. Additionally, all of these devices allow only a single controllable degree-of-freedom at the instrument tip with similar limitations as in our initial design for a wrist mount (described in Figure 3(b) and shown in Figure 3(c)).

B. Autonomous Multilateral Surgical Tumor Resection

This paper focuses on the demonstration of *tumor resection* as imagined in a silicone-phantom tumorectomy which includes four sub-tasks [9]: *Palpation*, *Incision*, *Debridement*, and *Injection*, using the finite element approach described in a previous work [25]. Several researchers have explored autonomous performance of RMIS sub-tasks [2, 6, 35, 39]. Moustris et al. [24] and Kranzfelder et al. [20] provide reviews of recent developments in semi-autonomous and autonomous execution of various experimental and clinical surgical procedures.

Palpation is necessary for surgeons to find inclusions within tissues. Konstantinova et al. [19] provide an extensive survey on recent advances for sensor design and deployment to enable successful haptic palpation. Algorithms for active exploration in tumor localization [26] and tumor ablation [12] offer new methods to consider for improved robotic palpation outcomes. Sterilization of instruments remains a challenging limitation for clinical use of tactile force sensing in RMIS [4]. In this work, we automate the palpation probe design presented by the authors in 2015 [22].

Scalpel instruments are available as stand-alone tools for the da Vinci. However, they do not allow for interchangeability of instrument-tips. We created a scalpel instrument-tip (shown in Figure 1(b)) compatible with the proposed instrument mount for use in the automated tumor resection pipeline as described in Section V. In surgical theaters, electrical cauterization is generally used for resection. However, these instruments won't function properly in a silicone-based phantom tissue.

Surgical debridement is a tedious surgical sub-task in which foreign inclusions or damaged tissues are removed from the body [5, 11]. Automated brain tumor ablation and resection with the RAVEN II has been explored in simulation [12]. Kehoe et al. [17] used motion planning to perform multilateral surgical debridement using the Raven II surgical robot. We have explored tissue debridement and multilateral cutting on deformable materials with the dVRK [25].

Targeted fluid injection allows for controlled and precise delivery of materials such as chemotherapy drugs, surgical glues, and stem cells. However, delivery to organs in inaccessible locations such as in the thorax, abdomen and pelvis is challenging because of the relatively high degree of trauma required [15]. Non-MIS robot injection tools have been developed and evaluated in the past [34]. Robotic catheter injection tools have also been studied [3]. However, there is a need for low-cost RMIS compatible delivery devices which enable access to internal organs and deliver controlled quantities of localized fluids [14].

There are a number of clinically used methods for **wound closure** including suturing, staples [38] and surgical adhesives. Padoy et al. [28] demonstrated execution of a human-robot collaborative suturing task on the daVinci platform with a research interface. Surgical glue has shown promise in closing small scale inter-cavity hernias [21], but little work exists on the use of RSAs for precision application of fluids.

III. System Design and Interfacing

Our design motivation is to develop modular tooling for the dVRK to allow for the demonstrable automation of a multi-step surgical procedure. The interchangeable mounting system has:

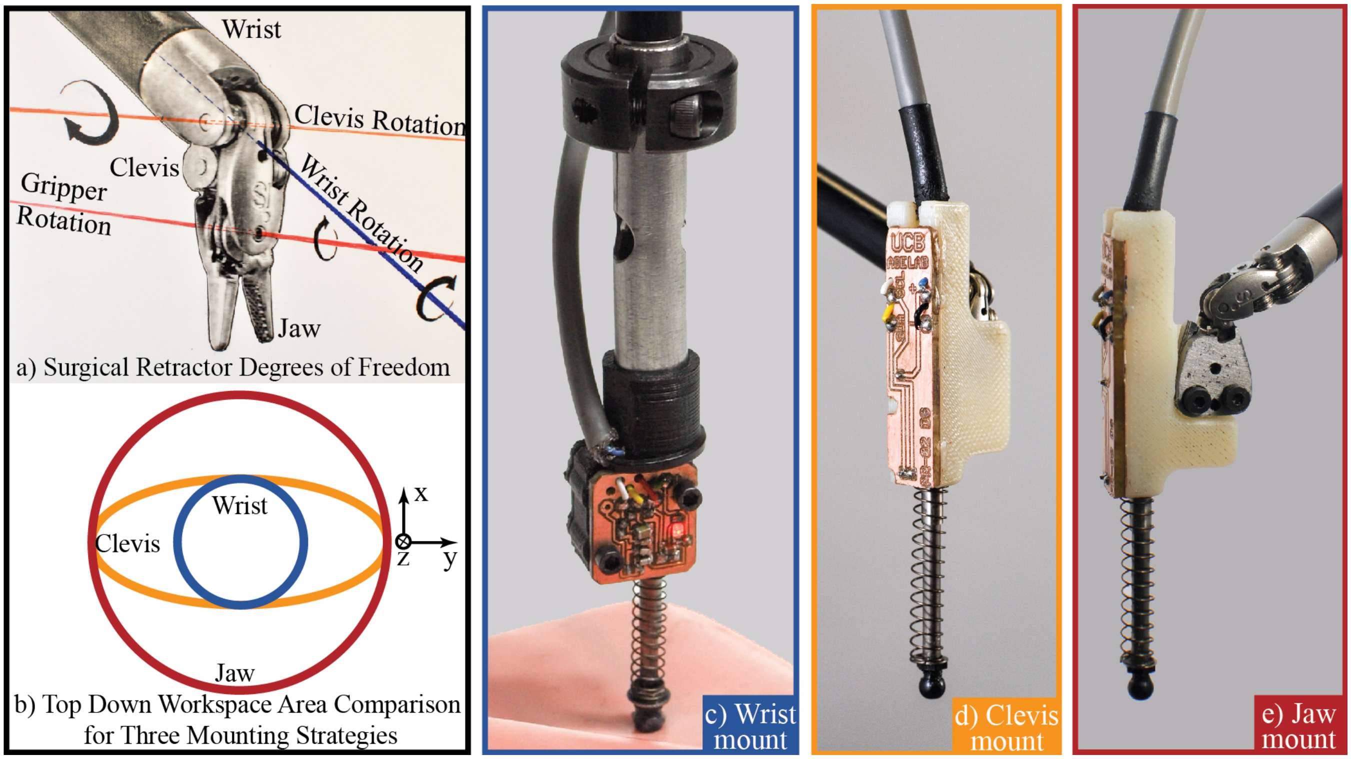


Fig. 3: Three designs for end-effector instrument mounts differentiated by attachment strategies to the surgical retractor. We found that the usable workspace of the Palpation Probe decreases as degrees of freedom (a) are restricted. The surgical retractor in (c) extends axially within the mount. The retractor in (d) is inserted at level with the clevis pulley seen in (a).

1. Kinematically constrained mounting on a standard surgical retractor end-effector using existing geometric features
2. Self-actuating retractor fixation requiring minimal grip force
3. Preservation of existing retractor articulation
4. Form factor to fit through a 15 mm cannula during minimally invasive procedures
5. Low-cost for single-use disposability.

A. *Clevis Mount Design*

We introduced a low-cost wrist-mounting design in our recent work for use as a minimally invasive palpation sensor [22] shown in Figure 3(c). However, due to the sleeve enclosure, the motion of the end-effector is restricted to only wrist rotation as shown in Table I. This limits the range of motion of the surgical retractor as illustrated in Figure 3(b).

We designed an interchangeable instrument-tip mount to address these limitations by mounting on the ‘clevis’ link of the surgical retractors (see Figure 3(a)) providing stabilization (as shown in Figure 3(d)). The cavity on the clevis mount (illustrated in Figure 5) was designed to help funnel the dVRK needle driver into its proper orientation, allowing a higher tolerance for misalignment in settings without visual feedback and easing the demands on software. The furthest proximal extent of the mount extends up to the clevis joint linkage; any further extension along this axis would limit clevis rotation as shown in Figure 3(b). The cavity of the mount mates with the side contour of the surgical retractor to limit rotation away from the ‘z’ axis (defined in Figure 5) yet maintains a sliding fit to allow the retractor to detach easily.

The internal cavity of the clevis mount is designed with locking pins extending from the walls of the interchangeable mount. The pins securely engage shoulders located on the retractor jaw when open (’Contact Points’ marked on Figure 5). The angle of these pins (angle ‘γ’ shown in Figure 5) matches the angle of the shoulders on the opened jaws to maximize contact area. A self-actuating lock is achieved as the points of contact on the jaw are angles such that a disturbance forces the jaws further open in contact with the internal cavity of the mount as a force in the positive ‘z’ direction is applied (shown in Figure 5). Movement in the negative ‘z’ direction is limited by contact between the clevis linkage and the internal cavity of the interchangeable mount.

The clevis mount allows greater range of motion along the ‘x-y’ plane as shown in Figure 3(b); however, because jaw rotational motion was restricted, the workspace is limited to a narrow ellipse along the ‘x’ axis as shown in Figure 3(b). Despite these limitations, we were able to demonstrate the utility of a self-engaging interchangeable instrument-tip mount by performing tumor resection surgeries in silicon flesh phantoms as described in Sections VI and V.

B. *Jaw Mount Design*

The jaw mount design was created to extend the utility of the clevis mount design by allowing greater range of motion in jaw rotation axes. Mount movement in the negative ‘z’ direction is constrained by an internal spur that mates with the ‘palm’ of the surgical retractor clevis between the two retractor jaws. The mating cavity was created by laminating

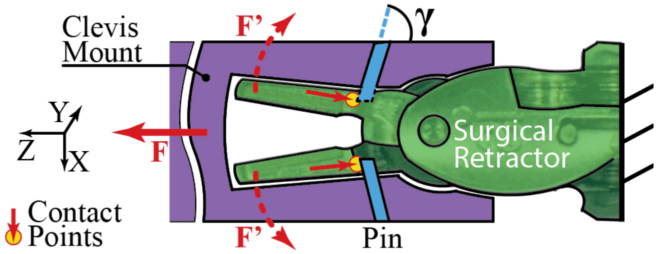


Fig. 4: A self-actuating mount: Force disturbance F in the negative z direction is countered by the contact points between the mount pins and the retractor shoulder. This results in an outwards clamping force F' to the clevis mount. The interchangeable mount can be designed with any external shape.

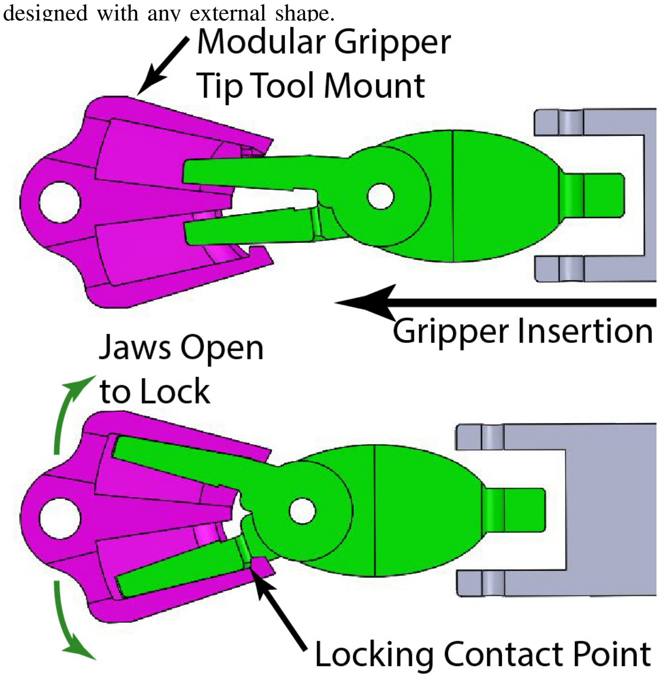


Fig. 5: The Jaw-Tip mount allows a smaller form factor and can be 3D printed as a single piece shown in purple (requiring no additional manufacturing steps). This component can be added to surgical peripherals to interface the Robotic Surgical Assistant to a wide variety of user-defined devices.

water-jetted 1095 spring steel sheets of 0.025 *in* thickness using two M2 machine screws. Points to engage the retractor shoulders were designed integrally to the laminate layers. This interchangeable mount is affixed to modular instrument tips and end-effectors as shown in Figures 3(e) and 5.

IV. Design for Autonomous Tool-Changing

Above we describe methods for interfacing tools and devices temporarily to the tips of surgical retractors. An extension of this concept would be to develop an interchangeable tool attachment for the 3-D printed jaw-tip mount that enables changing tools autonomously. We developed a novel Tool-Changing Adapter (TCA) that mounts on an 8mm Needle Driver as shown in Figure 6. The tool changer can be used with a two- or three-arm surgical robot. Tools can be loaded onto the tool-changer and inserted into the body cavity through the cannula to be affixed to the surgical arm(s) already within he body. The tool changing attachment consists of an indexing channel and a finger-tip mount that interfaces to the 8 mm Needle Driver as discussed in section III-B.

Aspects of the TCA design that were motivated by autonomous robotic interaction are highlighted in Figure 6; in this figure, the orange arm is removing the palpation probe for use elsewhere in surgery and is the *retrieving* tool. The modular jaw-tip tool mount described in Section III-B can be used for the point of attachment for the TCA, and remains the starting point for additional modular tools. The *Retaining Catch* holds the jaw-tip mount in place during repeated tool exchanges; this is a passive fixation. The *Tool Return Guides* force the returning jaw-tip mount to mate with the base of the catch basin, indexing the jaw-tip mount for the next removal. The *Shaft Catch Basin* provides a large landing area for the retrieving surgical arm to mate with the TCA rather than attempting to visually servo the points of the gripper jaws into the jaw-tip mount. The *Gripper Ramp* passively forces the retrieving arm to rotate its shaft such that the tips of the gripper jaws insert properly within the retrieved tool. The *Indexing Slot* guides larger tools (such as the Palpation Probe shown in Figure 6) into place within the catch basin.

Autonomous Tool-Changing Evaluation: A static third arm was added to the DVRK as shown in blue in Figure 6 and is know as the *presenting arm*. The position of the presenting arm was calibrated to the global coordinate frame of the DVRK by tele-operating the individual arms to the location of the indexing channel on the tool-changing interface. Once the location of the static presenting arm is known the tool change process is repeatable. In experiments, we were able to demonstrate robustness by exceeding 30 repeated tool change operations with the same hardware being re-used. However, this trial was performed 'open-loop': once the position of the presenting arm deviates from the initial setup, all repeatability is lost. Further development of the TCA will include features that are designed to facilitate visual servoing of the retrieving arm into the Shaft Catch Basin.

V. Experiments

Tumor resection includes four sub tasks: *Palpation*, *Incision*, *Debridement*, and *Injection*. Palpation of tissues is a means by which surgeons verify the location of tumors to make precise incisions using their sense of touch. Retraction and debridement require the interaction of the dVRK with flexible tissues. Surgical adhesive applications require the placement of discrete amounts of fluid to precise locations.

Experimental Setup: The palpation probe was affixed to the 8mm Needle Driver by manually placing the clevis-mounted probe below the surgical retractor, then prompting the jaws to open. The location of the flesh phantom was registered to the dVRK robot by manually tele-operating to the corners of the phantom and recording the global robot pose when palpation probe end effector distance was non-zero. These recorded points were used to fit a plane to the surface of the tissue.

For wound closure, we designed an automated injection instrument with three components: end-effector mounted

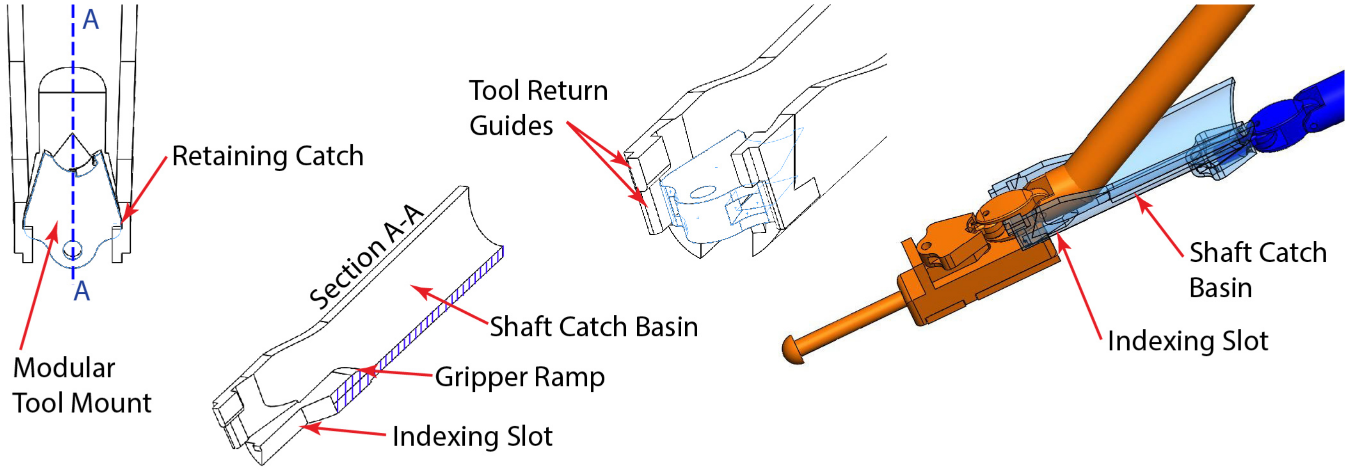


Fig. 6: Changing tools within the body cavity could reduce surgical time. In this configuration the blue arm carries a new tool into the surgical workspace, the orange arm interfaces with the tool and carries it to the point of use.

needle (seen in Figure 1(c)), a flexible catheter assembly, and a drive motor assembly mounted to the upper portion of the dVRK arm behind the sterile barrier. The Fluid Injector precision constraint is guided a theoretical dose volume of surgical glue (6 uL dose for each 2 mm of wound closure) based on [21]. Injection force is provided by a Haydon-Kerk 21F4AC-2.5 linear actuator, powered by Allegro's A4988 micro-stepping bipolar stepper motor driver, and controlled by an Arduino Pro Mini 328 microcontroller. Syringes up to 10 mL in volume are carried by a 3D-printed enclosure along a linear stage which is mounted to the RSA arm.

Palpation: The dVRK retractor manipulates a palpation probe (as shown in Figure 3(d)) affixed to a modular instrument-tip mount to search for inclusions within a tissue phantom. The dVRK slides the lubricated end effector of the probe over the surface of the tissue in eight parallel passes while the end-effector deflection is recorded by the ROS node. Each parallel pass covers the entire 150 mm length of the tissue phantom (details in [22]). In each palpation pass the relatively stiff tumor causes a local maxima in end-effector displacement indicating the position of the tumor. Robot position data associated with the probe deflection data is used to filter out noisy data near the edges of the tissue where the probe loses contact with the surface of the tissue. In Figure 7(a), a haptic probe is shown palpating a flesh phantom; the position estimate of the underlying tumor is shown in the inset.

Incision: The surgical retractor is prompted to close and the palpation probe is detached and replaced with a clevis-mounted type-15 scalpel shown in Figure 1(b). A linear incision is made in the cutaneous phantom at a fixed offset from the estimated location of the tumor to create a retractable flap. The incision is performed in 1 cm linear slicing motions rather than incising continuously in one single pass because of friction at the blade-silicone interface. Once all the segments are complete, a finishing pass is made along the full length of the incision to ensure a single continuous incision.

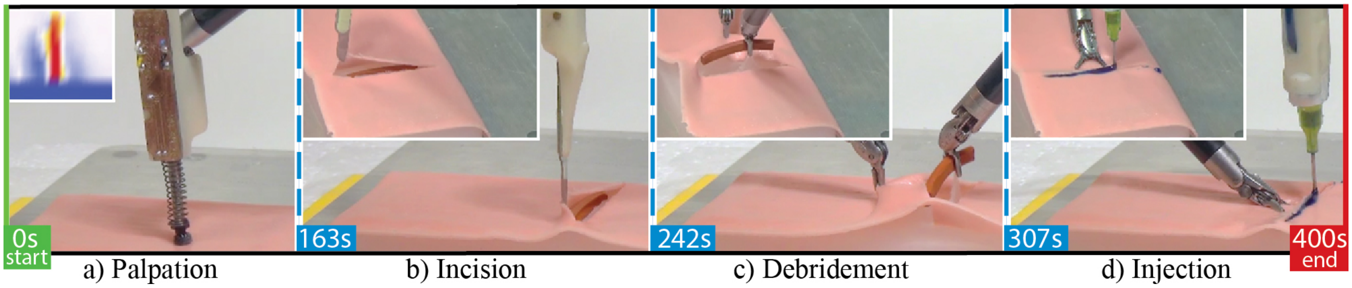
Without jaw articulation, this instrument is used to cut only in lines parallel to the 'y' axis. A third redesign allows for full articulation (similar to the mount shown in Figure 3(e)).

Debridement - Retraction and Resection: The next step in the pipeline is *Debridement*: after removing the clevis-mounted scalpel, the left retractor grasps the cutaneous flap created during incision by moving to a pose below the surface of the tissue and closing the jaws then *retracting* the skin to reveal the tumor. The right arm approaches the tumor and uses repeated grasping-and-retracting motions to incrementally *resect* the tumor from the subcutaneous tissue before removing it from the workspace. Depth of each arm is controlled as offsets from the surface plane created during indexing.

Injection: In the final step, the clevis-mounted injector tip (shown in Figure 1(c) connected to the Fluid Injection Device shown in is affixed to the surgical retractor on the right. The left surgical retractor then restores the skin flap to its original location before opening its jaws and depressing the cutaneous layer to stabilize the wound. The right arm uses the Fluid Injector to seal the incision with surgical adhesive. The needle tip passes over the incision at a constant rate as the externally mounted syringe pump injects the adhesive to facilitate uniform coverage of the incision site.

Design of Tissue Phantoms: Tissue phantoms as shown in Figure 7 were created for testing. A cylindrical tumor of Silicone Rubber (thickness 3 mm; Shore hardness 70A) was coated in Vaseline and placed in the bottom of a 100 mm long, 50 mm wide, 20 mm deep *Delrin* mold prior to casting. Silicone Rubber *Ecoflex 00-30* (*Smooth-On*) was cast into the mold to create subcutaneous tissue. After setting, the subcutaneous phantom was demolded and inverted. A cutaneous phantom was created using a stiffer (shore hardness 2A) *DragonSkin 10 Medium* Silicone Rubber (*Smooth-On*). Opaque pigmentation was achieved using a 0.5% by volume addition of Oil Pigment (Winton Oil Colour, Flesh Tint). The dermal layer was cast at a thickness of 1 mm into a *Delrin* mold (width 60 mm and length 100 mm). Upon solidification, the dermal phantom was overlaid on the subcutaneous phantom to create the final tissue phantom setup.

Timeline of an Autonomous Tumor Resection



a) Palpation b) Incision c) Debridement d) Injection

Fig. 7: An autonomous simulated-tumor resection was performed using our suite of interchangeable instrument-tips and the da Vinci 8 *mm* Needle Driver; the dVRK performed a) Palpation with a haptic probe, b) Incision using a scalpel, c) Debridement using the Needle Drivers, and d) Injection of a surgical adhesive. Full video of the task is available at: http://berkeleyautomation.github.io/surgical-tools

dVRK Hardware and Software: We use the Intuitive Surgical da Vinci Research Kit (dVRK) as described in [25] along with open-source electronics and software developed by WPI and Johns Hopkins University [16]. The software system is integrated with ROS, and controls robot pose in Cartesian space by interpolating between requested points. Our manually created finite state machine consists of four segments with a manual tool change occurring between each as described in Figure 7.

VI. Experimental Results

Tumor Resection End-to-End Performance: The end-to-end tumor resection was repeated ten times with no prior knowledge of tumor location. Each phantom had a skin-phantom layer of thickness (1 mm +/- 0.25 mm), tumor-phantom 25 mm in length and 3 mm in diameter. Success was determined based on a complete tumor removal and wound closure. During trial 1 and trial 6, the position of the tumor was incorrectly estimated by the palpation probe resulting in respective failures in *Debridement* and *Incision*. In trial 4 and 7, the left retractor failed to grasp the dermal phantom fully and the tumor was not uncovered during skin retraction. In trial 8, the tumor was not fully resected from the flesh phantom during *Debridement*. Five of the ten trials were successful.

VII. Discussion and Future Work

This paper describes an interchangeable instrument system that can be contained within the body cavity. It is based on a novel mounting mechanism compatible with a standard RMIS gripper and tool-guide and sleeve to facilitate automated instrument switching. We evaluated a prototype of the system on the dVRK with da Vinci Classic Large Needle Driver instruments. Experiments suggest that this interchangeable instrument system can perform a multi-step tumor resection procedure that uses a novel haptic probe to localize the tumor, standard scalpel to expose the tumor, standard grippers to extract the subcutaneous tumor, and a novel fluid injection tool to seal the wound. In future work we will perform additional experiments with tumor resection and other surgical procedures. Design files and fabrication instructions are available online at: http://berkeleyautomation.github.io/surgical-tools/.

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