A Modular, Multi-Arm Concentric Tube Robot System with Application to Transnasal Surgery for Orbital Tumors

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Abstract
In the development of telemanipulated surgical robots, a class of continuum robots known as concentric tube robots has drawn particular interest for clinical applications in which space is a major limitation. One such application is transnasal surgery, which is used to access surgical sites in the sinuses and at the skull base. Current techniques for performing these procedures require surgeons to maneuver multiple rigid tools through the narrow confines of the nasal passages, leaving them with limited dexterity at the surgical site. In this paper, we present a complete robotic system for transnasal surgery featuring concentric tube manipulators. It illustrates a bagging concept for sterility, and intraoperatively interchangeable instruments that work in conjunction with it, which were developed with OR workflow compatibility in mind. The system also includes a new modular, portable surgeon console, a variable view-angle endoscope to facilitate surgical field visualization, and custom motor control electronics. Furthermore, we demonstrate elastic instability avoidance for the first time on a physical prototype in a geometrically accurate surgical scenario, which facilitates use of higher curvature tubes than could otherwise be used safely in this application. From a surgical application perspective, this paper presents the first robotic approach to removing tumors growing behind the eyes in the orbital apex region, which has not previously been attempted with a surgical robot.

Keywords
medical robotics, robotic surgery, system design, continuum robots, concentric tube robots

1 Introduction
The transnasal approach enables minimally invasive access to a wide variety of surgical sites in the head, but is not more widely used because of the challenges of operating in small, highly constrained workspaces. Manipulating multiple hand-held tools (including an endoscope) with rigid shafts simultaneously through the nasal passages is challenging for the physician. Anatomical constraints and tool collisions both impose formidable obstacles to working dexterously at the surgical site, and some targets are simply out of reach with current manual tools.

These factors have motivated the development of robotic systems to assist in transnasal surgical approaches. Some systems have focused on accurate image-guided drilling of bone to access the surgical site [Wurm et al., 2005; Xia et al., 2008], and others have robotically manipulated the endoscope to assist the surgeon [Nimsky et al., 2004; Eichhorn and Bootz, 2011]. While these systems address access to the surgical site and visualization, robots with distal dexterity are useful for performing complex maneuvers at the surgical site.

Continuum robots [Burgner-Kahrs et al., 2015], which possess flexible bodies, are an ideal solution to the anatomical constraints imposed in transnasal

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Figure 1. Three-tube concentric tube robot. Each tube can be translated and rotated relative to the others to produce elastically-balanced motion of the overall structure.

Among continuum robots, the concentric tube robot (shown in Figure 1) can perhaps be scaled to the smallest overall diameters ([Burgner-Kahrs et al., 2015] [Gilbert et al., 2016]). These robots consist of several nested, flexible tubes (often composed of superelastic Nitinol), each of which can be shape-set into a desired curved shape at its distal end. Once the tubes are assembled concentrically, they are translated and rotated relative to one another by an actuation unit which grasps each tube at its proximal end. This results in elastic interactions between the tubes, causing the overall structure to bend and twist. Concentric tube robots have been applied to a variety of other surgical applications, including intracerebral hemorrhage evacuation ([Burgner et al., 2013]), transoral peripheral lung biopsy ([Swaney et al., 2017]), transurethral prostate surgery ([Hendrick et al., 2015]), neuroendoscopy ([Butler et al., 2012]), and cardiac interventions ([Bergeles et al., 2015]).

The unique advantages of concentric tube robots have led researchers to propose them for transnasal surgeries ([Burgner et al., 2014], [Swaney et al., 2012], [Yu et al., 2016], [Wu et al., 2017]). Much of this work has focused on pituitary tumor removal and biopsy. These systems provided the foundational work for the system we describe in this paper. This prior work has focused on proof of concept, and left to future work many developments needed to create a complete surgical system for delivery of concentric tube robots in the context of endonasal surgery.

In this paper we present a complete transnasal surgical system featuring concentric tube manipulators. Important advancements include (1) an OR workflow-compatible method for draping non-sterile components, (2) the first intraoperatively interchangeable concentric tube instruments which can be readily exchanged as single units, complete with end effectors, and motor control electronics developed specifically for this high-degree of freedom (DOF) surgical robot (the system in this paper has 21 DOF), (3) the first modular, portable surgeon console designed for use with a concentric tube robot system, (4) a new visualization approach for surgical robots involving integration of a variable view-angle endoscope, (5) the use of elastic instability avoidance for the first time on a physical prototype in a geometrically accurate surgical scenario, which facilitates use of higher curvature tubes than could otherwise be used safely, and (6) the first robotic approach to removing tumors growing behind the eyes in the orbital apex region, which has not previously been approached with a surgical robot.

2 Medical Motivation: Orbital Tumors

A variety of benign and malignant lesions can occur in the eye orbit that require surgical removal. The orbit is the socket in which the eye resides (see Figure 2), which contains a complex collection of structures. These include the optic nerve and the extraocular muscles that control eye motion, which are surrounded by fat and connective tissue. Traditionally, tumors in this area are removed via open surgical procedures ([Campbell et al., 2015]). Recently, toward reducing invasiveness and facilitating better access to and visualization of the tumor, otolaryngologists and ophthalmologists have teamed up to remove these tumors collaboratively, aided by a transnasal approach ([Stamm and Nogueira, 2009], [Muscatello et al., 2013], [Chhabra et al., 2014]). The ophthalmologist approaches the tumor through a small incision near the eye, while the otolaryngologist assists using a transnasal approach. On the transnasal side, the otolaryngologist uses a rigid endoscope and rigid tools to approach the target. After performing a septoplasty to increase range of motion within the nose, a small opening in the bone between the nasal passage and the orbit is created with
a surgical drill to enable transnasal access to targets behind the eye. Despite the promise of these emerging techniques, there remain many challenges associated with them. For example, the constraints of the nasal passages make dexterous tool motion at the surgical site challenging. In addition, the tumor can be hidden behind muscles and other tissues, requiring the surgeons to carefully retract them to access it. Coordinating motions between two surgeons with two different approaches and viewpoints adds another level of difficulty to this task. Surgeons performing the procedure have noted that it is so difficult that “it is paramount to have specialized [future] instruments” developed specifically for this procedure (Stamm and Nogueira, 2009). Providing such a specialized tool is the purpose of this paper. The above factors make the dexterity and small diameter afforded by concentric tube robots highly desirable for removing tumors in the orbit. Furthermore, an instrument that enhances maneuverability and range of motion could one day enable a purely transnasal approach, further reducing invasiveness.

A variety of tumors grow in the orbit. In the experiments in this paper we consider cavernous hemangioma (Tailor et al., 2013), the most common tumor occurring in the orbit in adults (Calandriello et al., 2017). These tumors are encapsulated, typically round or ellipsoidal masses that must be surgically removed to avoid compressive damage to the optic nerve and associated vision loss, as well as potential corneal damage (Hsu and Hsu, 2011). In Section 3 we construct a geometrically accurate phantom model of the orbit containing these tumors, and resect them using the robot described in this paper.

3 System Design

The complete system, including the patient-side robotic platform and surgeon control console, is shown in a mock operating room setting in Figure 3. A diagram of the major components of the system, and how they are connected is presented in Figure 4. The surgeon teleoperates the robot via two haptics-capable input devices and three foot pedal clutches (one for toggling each tool module). A high-definition display provides information to the surgeon in the form of endoscopic video and robot status information, within a graphical user interface (GUI). Custom motor controllers are responsible for the closed-loop control of the motors in the actuation units, which drive the concentric tube tool modules. These subsystems communicate over TCP/IP with a high-level controller using the Robot Operating System (ROS) (Quigley et al., 2009). The design of the individual components is described in the following subsections.

3.1 Actuation Unit and Tool Modules

One of the key features of this robotic system in comparison with prior transnasal concentric tube robot systems is its implementation of interchangeable tools. Similar surgical systems have approached this in a variety of ways, such as manually operated instruments passed through robotic overtubes (Shang et al., 2012), exchangeable end effectors mounted onto permanent robotic arms (Simaan et al., 2004), or concentric tube robots with removable tubes (Burgner et al., 2013; Yu et al., 2016). Our system is the first multi-arm concentric tube robot where the tubes, end effectors and their respective driving mechanisms are integrated into modular, interchangeable tool cartridges. It consists of a single base actuation unit and individual tool cartridges (see Figure 3) that attach to the base. The actuation unit has the capacity to drive up to three three-tube concentric tube manipulators simultaneously. The motivation for this modular design is twofold.

First, from a clinical workflow perspective, it is valuable to be able to quickly remove tools and install new ones, enabling tool changes during a procedure as needed. Incorporating the transmission elements
Figure 3. The complete system in an operating room setting, with the robot mounted over the patient and the operator seated at the surgeon console.

Figure 4. The surgical system is physically divided into two primary components. The surgeon sits at the control console and uses the surgeon input devices and foot pedals to teleoperate the robot, which is positioned over the patient.

Figure 5. The tool cartridge design. (a) The internal components of the tool cartridge which translate and rotate the tubes, (b) The end of the tool cartridge with coupling elements that mate to the robot actuation unit, and (c) The portion of the actuation unit which mates to the tool cartridges via spring-loaded couplings.
Figure 6. The lever-based locking feature allows for tools to be easily exchanged. (a) The user inserts the tool module, feeding it onto the alignment pins, and (b) The user brings the latch feature down, locking the tool module in place and coupling it into the motors.

(Linear rails, lead screws, gears, etc.) and tubes into a single instrument cartridge simplifies this process in comparison to our earlier systems, which required removing small screws on a retaining bar to release the tubes (Burgner et al. 2013). Figure 6 demonstrates how a quick lock mechanism and alignment pins on the base facilitate cartridge installation. This new design can be easily operated while wearing surgical gloves and requires no additional tools. A single user can complete the entire tool change process in less than a minute.

Second, the modular, cartridge-based design enables motors, encoders and other electronics, to remain non-sterile, and be isolated from the patient behind a sterile drape, as shown in Figure 7. Since the cartridges themselves consist primarily of passive transmission elements, they can be manufactured as either disposable or reusable instruments.

The sterility concept is inspired by the da Vinci system from Intuitive Surgical, Inc. (Bhandari et al. 2005), the most widely used telemanipulated surgical robot, and was first applied to concentric tube robots by Burgner et al. (2013). This system builds upon that earlier design with a focus on improving usage in the OR. In particular, requirements for tools and precise alignment during setup have been eliminated. The tool modules couple into the actuation unit through a set of spring-loaded shaft couplers (shown in Figure 5), which mate the transmission elements in each cartridge to the motor shafts on the actuation unit. In a commercial version of this system, the drapes would be manufactured with plastic adaptors fused into them to create a sterile seal around the transmission coupling. The six brushless DC motors that mate through the drape (Maxon Motors, EC-13) control the rotations of all three tubes, the translation of the two innermost tubes within the cartridge (via leadscrews), and the motion of an end effector. A seventh brushless DC motor (Maxon Motors, EC-16) translates the entire...
cartridge along a track on the actuation unit via a leadscrew.

Another important aspect of this actuation unit design is its ability to deploy all of the manipulators into the patient in close proximity to one another; the narrowest portion of the workspace is the nostril opening, which is approximately 16 mm by 35 mm (Swaney et al., 2012). The track for each cartridge is angled inward toward a tube collimator, shown in Figure 8. This enables the tubes to be actuated off-axis, enabling easy loading of the cartridges onto the robot.

To reduce the build-up of torsional strain energy in the nitinol tubes as they are actuated, stiffer, stainless steel tubes are used to span much of the length between the cartridges and the tube collimator, transmitting translations and rotations to each nitinol tube. This design feature, previously proposed in Lin et al. (2015), reduces the tendency for the tubes to undergo elastic instabilities in the robot’s workspace (Gilbert et al., 2016; Ha et al., 2016) (we also address this from a control perspective in Section 4). Each nitinol tube is attached to its own stainless steel tube via a machined aluminum adapter and cyanoacrylate adhesive (Loctite). Each stainless steel tube is then affixed to its corresponding stage via a set screw in the rotational gear, and a shaft collar, which clamps it to its translational stage.

### 3.2 Robotic End Effectors and Endoscope

A variety of end effectors can be used with concentric tube robots: accessory actuation mechanisms within the cartridge have been designed for translation (Figure 9a) and rotation (Figure 9b) of tools passing through the lumen of the innermost tube. The translation mechanism works by rotating a lead screw on a square shaft, and similarly the rotation mechanism turns a gear on a square shaft. For the set of experiments described in this paper, one cartridge is equipped with a tendon-actuated gripper, one is equipped with a rotatable curette, and the other provides an auxiliary tool option, if needed.

For visualization of the surgical field, an adjustable view-angle rigid endoscope is mounted to the robot on a lockable positioning arm (Figure 3b). The endoscope, the EndoCAMeleon (Karl Storz SE & Co. KG), is a 4 mm diameter endoscope with a view angle that is adjustable between 15 degrees and 90 degrees. This angular range, combined with the freedom to arbitrarily pose the endoscope, enables visualization of a large volume of the sinuses, skull base and orbit. The presence of three concentric tube arms also leaves open the option of equipping one of the arms with a chip-on-tip endoscope camera for future experiments (as in Yu et al., 2016, e.g.); this could prove especially useful as we seek to approach even more difficult-to-reach targets in the future.

![Figure 8. Front end of the robot, with tube collimator collecting the three concentric tube manipulators. The adjustable endoscope is mounted on a lockable positioning arm. Concentric tube arms are shown in a state of maximum extension from the collimator.](image1)

![Figure 9. Example end effectors and corresponding actuation mechanisms, each of which is mounted to the back of the inner tube’s translational stage. (a) Translational actuation mechanism used to open and close the gripper via a small lead screw. The tendon is attached on the inner ring of a bearing, enabling the tendon to rotate freely to prevent the accumulation of torsion. (b) Rotational actuation mechanism used to turn the curette via a set of gears. (c) Curette and gripper end effectors.](image2)
Figure 10. The custom designed motor control PCBs assembled into their modular enclosure. (a) Ethernet and power are the only incoming connections necessary for operation. (b) A microcontroller on each motherboard provides closed-loop control of up to six motors while communicating with the high-level controller via an Ethernet connection. Each daughterboard contains its own servo controller, as well as standardized connectors that support a wide variety of motor types.

3.3 Electrical Hardware

We created custom printed circuit boards (PCBs) for motor control for this system. Our modular solution distributes the computational load among multiple units, each responsible for the real-time, synchronous, closed-loop position control of six motors (see Su et al., 2015 for a similarly modular motor driver design for surgical robots). This enables the use of microcontrollers rather than a traditional computer, reducing both cost and size. More importantly, this approach is safer in the event of a disconnection from the high-level control computer. The microcontrollers will ensure the motors simply remain fixed at their last commanded position.

A single motor control module, as shown in Figure 10, consists of a motherboard PCB with six sockets for daughterboard PCBs. On the motherboard is an ARM Cortex-M4 microcontroller (Teensy 3.2, PJRC.COM, LLC) that communicates with the high-level controller over TCP/IP using a WIZ850io Ethernet module (WIZnet Co., Ltd.). Each motherboard is connected through a managed switch (Cisco SG-300). Thus, the computer running the high-level control requires only a single Ethernet connection to drive all 21 motors.

A diagram of the low-level control loop is shown in Figure 11. Each daughterboard contains a servo controller (Maxon Motors, ESCON Module 50/5) which drives a single motor in current control mode. Motor current is set via an analog input by a 16-bit digital-to-analog converter (Analog Devices, AD5761R). A quadrature converter (LSI Computer Systems, LS7366R) monitors motor position via an optical encoder (ELESTA, E OI R007). The daughterboards also provide an input for a limit switch, which is utilized for both emergency stopping and joint homing.

The microcontroller firmware is written using a state machine (event-driven) architecture. Separate proportional-integral-derivative (PID) controllers...
enable independent position control of its six motors at a rate of 1 kHz. High-level configuration and relevant data input/output (e.g., position commands) is provided over ROS topics. Creating this layer of abstraction means the motor boards become agnostic to the specific type of high-level controller used, making them much more flexible. For example, our system comprises multiple types of limit switches (optical/mechanical), encoders (optical/magnetic), and motors; however, all components of the same type appear identical to the high-level controller. Additionally, each daughterboard PCB uses the same design so they can be swapped between motherboards without requiring changes to the firmware. Since all identifying information (i.e., IP/MAC address and ROS namespace) is configured and stored to non-volatile EEPROM in the microcontroller, any power/Ethernet cable can be used with any motor control module; it is not possible to connect the modules incorrectly. It is the combination of all of these features that enabled us to create a modular, yet robust and safe, surgical robotic system.

3.4 Surgeon Interface Console

The custom surgeon console, shown in Figure 12, is a mobile cart, which houses the high-level control computer and human-machine interfaces (PHANTOM Omni haptic devices, 3DSystems, Inc.). Each pen-like device accepts 6-DOF input poses from the surgeon and is capable of providing force feedback. The surgeon console and robot actuation unit are connected via Ethernet.

A 42-inch high-definition monitor (NEC Corp.) is mounted to the surgeon console on a hinge and can be folded down for transport. The monitor displays endoscope video footage and a GUI that provides the surgeon information on the robot’s status, as well as the ability to change various teleoperation settings during a procedure (e.g., level of motion scaling, which user input controls which tool, etc.).

3.5 Tube Parameters

Each of the tube sets used for the experiments in Section 5 had an overall outer diameter (OD) of 1.9 mm with an inner lumen diameter (ID) of 0.77 mm, and was capable of extending from the tube collimator by up to approximately 110 mm. The full set of tube parameters for each tool is summarized in Table 1. These parameters were heuristically selected to provide a stable workspace of the desired size with qualitatively good dexterity.

Figure 13 shows the achievable workspace of the gripper arm within the orbit (not including configurations which would interact with the bony anatomy) for one approach angle selected as clinically reasonable by an otolaryngologist. This volume was generated by sampling the joint space in simulation. The workspace shown in the figure represents a conservative estimate for the overall achievable working volume, since some amount of interaction with the bony anatomy is acceptable in practice, and...
Table 1. Summary of the tube design parameters used in experiments.

<table>
<thead>
<tr>
<th></th>
<th>OD (mm)</th>
<th>ID (mm)</th>
<th>L_straight (mm)</th>
<th>L_curved (mm)</th>
<th>( \kappa ) (mm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gripper</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube 1</td>
<td>1.01</td>
<td>0.77</td>
<td>66.7</td>
<td>287.0</td>
<td>6.7</td>
</tr>
<tr>
<td>Tube 2</td>
<td>1.52</td>
<td>1.29</td>
<td>50.7</td>
<td>245.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Tube 3</td>
<td>1.90</td>
<td>1.70</td>
<td>30.0</td>
<td>180.0</td>
<td>9.1</td>
</tr>
<tr>
<td><strong>Curette</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube 1</td>
<td>1.01</td>
<td>0.77</td>
<td>49.3</td>
<td>308.0</td>
<td>7.35</td>
</tr>
<tr>
<td>Tube 2</td>
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<td>1.292</td>
<td>55.4</td>
<td>242.0</td>
<td>8.2</td>
</tr>
<tr>
<td>Tube 3</td>
<td>1.90</td>
<td>1.70</td>
<td>29.0</td>
<td>182.0</td>
<td>10.6</td>
</tr>
</tbody>
</table>

the approach angle can be readily adjusted by the surgeon as needed. Optimization of the tubes is also possible, and has been demonstrated with a variety of objectives, such as reaching anatomical targets [Bergeles et al., 2015], covering volumes [Burgner et al., 2013], and preventing elastic instability [Ha et al., 2014; Hendrick et al., 2015]. Tube optimizations may be used to provide even better dexterity and workspace characteristics for this system, but these optimizations are outside the scope of this paper and are left to future work. It is worth noting that selecting tubes which are capable of 'snapping' (due to elastic instabilities) within the intended joint space is only practical when a snap-avoiding controller, such as the one described in Section 3 is employed.

4 Teleoperation Approach

The kinematic model used in this system is the widely used mechanics-based model for concentric tube robots based on Cosserat rod theory, described in [Rieker et al., 2010] and [Dupont et al., 2010]. This model is computed by integrating constitutive equations for the collection of tubes over arc length, given certain known boundary conditions. Evaluation of this model provides a full pose of the robot for any location along its arclength \( (g(s)) \), along with the Jacobian relating tip velocities to joint velocities \( (J) \). For teleoperation, we use the damped least squares resolved-rates approach [Wampler, 1986], as applied to concentric tube robots by [Burgner et al., 2014] and [Hendrick et al., 2015]. In this approach, the manipulator Jacobian is computed at each servo cycle, and used to map the surgeon’s desired velocity to the joint velocities that create a corresponding robot tip velocity. The joint velocities are determined by minimizing a weighted cost function (see [Chan and Dubey, 1995] for a description of the use of weighted cost functions) that balances tracking the surgeon’s desired tip velocity with secondary objectives such as avoiding robot joint limits.

In the experiments that follow, we also incorporate elastic instability avoidance as a term in the cost function using the method proposed in [Hendrick, 2017] and demonstrated in [Anderson et al., 2019]. This relies on computing the stability metric, \( S \), as defined in [Gilbert et al., 2016], which decreases to zero as an unstable configuration is approached. The full cost function used is:

\[
H = \frac{1}{2} ( (J\dot{q} - \dot{x}_{\text{des}}) ^T W_{\text{tracking}} (J\dot{q} - \dot{x}_{\text{des}}) \\
+ \dot{q}^T W_{\text{damping}} \dot{q} + \dot{q}^T W_{\text{joint limits}} \dot{q} \\
+ (\dot{q} - v_S)^T W_{\text{stability}} (\dot{q} - v_S) )
\]  

In this expression, the \( W \) matrices represent weighting functions for the objectives of task space tracking, joint velocity damping, joint limit avoidance, and instability avoidance, respectively. The joint velocity vector is represented by \( \dot{q} \), and \( v_S \) represents a joint space velocity ascending the gradient of the stability metric \( (v_S = \alpha \frac{\partial S}{\partial q} \) where \( \alpha \) is a positive scalar). Appropriate definition of these weighting functions enables intuitive teleoperation while avoiding joint limits and unstable configurations as they are approached. Note that alternative approaches to redundancy resolution and elastic instability avoidance within a resolved rates framework have also been proposed and studied in simulation by [Leibrandt et al., 2017].

The addition of instability avoidance into the control law enables the use of more highly curved tubes that result in the manipulator having elastic instabilities in its workspace, which would have been ruled out a priori by some prior design algorithms (e.g. [Hendrick et al., 2015]). The set of tubes we use in the experiments in this paper have curvatures high enough that elastic instabilities exist in the manipulator’s workspace. These could not be safely used in our application without this elastic instability avoidance approach.

Lastly, note that the above approach is facilitated by selecting variables with computational efficiency in mind. It has been shown that it is possible to convert the forward kinematics problem for concentric tube robots from a boundary value problem (as it was traditionally formulated) to an initial value problem which was first mentioned by [Bergeles and Dupont, 2013] and is described in detail by [Gilbert, 2016]. The increased computational efficiency from this perspective shift is a key to enabling advanced control algorithms, such as real-time instability avoidance, within a resolved rates framework.
5 Orbital Tumor Resection Experiments

We began by creating a phantom model for cavernous hemangioma orbital tumors (see Figure 14). This consisted of a portion of the skull 3D-printed in plastic, an eyeball with attached extraocular muscles, and a 2.5 mm thick string to simulate the optic nerve, with an ellipsoidal tumor. The eyeball, muscles, and tumor were made from silicone. Ballistics gel was cast to surround the eyeball, tumor, nerve, and muscles to simulate orbital fat and connective tissues.

To create the 3D printed eye socket and skull, a cranial CT scan was segmented in 3D Slicer [Fedorov et al., 2012]. The resulting volume was then smoothed and downsampled in Meshlab [Cignoni et al., 2008] and cropped to the eye socket and surrounding anatomy using Autodesk MeshMixer. The skull model was then 3D printed in ABS plastic using a Stratasys F170 FDM 3D printer. An area of the simulated bone was recommended for removal by an experienced rhinologist, to match what is typically removed to access the surgical site during this type of surgery.

Silicone eyeballs were molded using DragonSkin 10 Fast Platinum-Cure Silicone (SmoothOn, Inc.) in 3D-printed molds. The eyeball is represented by a one-inch diameter sphere, consistent with anatomical size ranges [Bekerman et al., 2014]. A string was embedded into the eyeball before curing, protruding from the back of the eye to represent the optic nerve. The same type of silicone was then used to create the extraocular muscles and a 7 mm spherical tumor, each of which was molded separately. All of these components were placed into the orbit of the skull model, with the tumor situated between the optic nerve and medial rectus extraocular muscle (i.e. the muscle closest to the nasal passage, see Figure 17 for a CT scan of the phantom after construction). Finally, a ballistics test medium (SIM-TEST, Corbin Manufacturing & Supply, Inc.) was heated and mixed at a 30% concentration by weight with water, to achieve mechanical properties similar to fat. The SIM-TEST mixture was then injected into the skull around the eye structures to fill the space of the orbit and allowed to set. Each component (eyeball structure, tumor, and skull) was weighed separately during assembly to facilitate measurement of the amount of fat removed during the experiments.

Figure 15 shows the experimental setup. A total of ten orbital tumor resections were performed with the robot, with two otolaryngologists performing five resections each. In each case, the percentage of fat removed from the phantom during the trial was recorded and measured by weight. Surgeons seek to minimize unnecessary fat removal, as the orbital fat helps to hold the eye in its proper place and provides better cosmetic results. Resection was then carried out with two tools (one gripper and one curette) controlled by two haptic devices, using the foot pedals to clutch in and out of each tool as desired.

All ten resection trials resulted in the successful removal of the tumor without damage to the muscles or optic nerve. The average amount of orbital fat removed by mass was 3.9% ± 2.1% (0.8 g ± 0.5 g). In each individual case, the level of fat removal was judged to be clinically reasonable for good expected patient outcomes by the participating surgeon. Still images
from the endoscope are shown in Figure 16. Slices from CT scans of a representative phantom before and after resection are shown in Figure 17.

6 Discussion

The system described in this paper and the experimental studies in the preceding section represent promising steps toward enabling transnasal resection of orbital tumors using concentric tube robots. We have demonstrated the ability of the robotic arms, under the control of an expert surgeon, to perform the required manipulation tasks within the geometric constraints of the anatomy. While this is a promising first demonstration of the procedure, there remains much more work to be done. In particular, cadaver studies will be useful for simulating many of the aspects of this surgery which are difficult to recreate in phantom models, such as the cartilaginous features of the nose and septum. It will also be useful to perform future experiments comparing performance of the procedure with our robot versus with manual hand tools. We suspect our robot will make the procedure easier to perform, but the experiments in this paper assessed feasibility only, not ease of use.

Along similar lines, the tube precurvatures used in our experiments demonstrate feasibility, but are by no means optimal. Thus, it will be useful in the future to computationally optimize tube shapes for optimal reachability and dexterity. For an example of how computational design optimization can be carried out for a specific clinical procedure see Burgner et al. (2013).

In addition, incorporating image guidance software that is currently used in the operating room is a useful potential direction for further improving the system. Such navigation software typically involves tracking the tool tips relative to the patient’s anatomy using electromagnetic or optical tracking systems along with registration to preoperative imaging. Incorporating electromagnetic sensors into the tips of concentric tube manipulators is one simple way to achieve tracking, and can facilitate integration of existing image guidance methods into our system.

7 Conclusion

In this paper we have presented a new concentric tube robotic system for transnasal surgical procedures. The primary goals with this new system were to take several specific steps from initial proof-of-concept lab systems that have been described in the literature previously, toward a future complete, clinically practical system.

Toward this goal, we integrated a sterile draping concept for non-sterile components, and a complementary cartridge-based tool change approach that facilitates intraoperative instrument swaps. We also designed a new mobile surgeon interface console that is portable and durable, enabling the system to be easily transported between operating rooms. We integrated a variable view-angle endoscope for more adaptable views of the surgical field, and described custom modular motor control electronics developed for this system. Another system-level advancement was the integration of elastic instability avoidance algorithms for the first time in a physical prototype in a practical application. This facilitated the use of a higher curvature tube set with elastically unstable configurations in its workspace, which would not otherwise have been possible to use safely.

Lastly, we also introduced a new application that has not previously been approached with any surgical robot—the removal of orbital tumors via a transnasal approach. We designed a phantom for orbital cavernous hemangiomas, and demonstrated the ability to remove
these phantom tumors using our concentric tube robot system. While there remains much work left, the advancements in this paper represent several important steps toward bringing concentric tube robots from the academic lab to real-world operating rooms.

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