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A Multi-Arm Hand-Held Robotic System for Transurethral Laser Prostate Surgery

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Abstract— **Benign prostatic hyperplasia is the most common symptomatic disease in men. A new transurethral surgical intervention is available that has been shown to reduce bleeding, catheterization time, and hospitalization time in comparison to traditional Transurethral Resection of the Prostate (TURP). However, this new procedure, Holmium Laser Enucleation of the Prostate (HoLEP), is so challenging to accomplish that only a small number of expert surgeons are able to offer it. Toward facilitating broader use of HoLEP, we propose a new hand-held robotic system for the purpose of making the surgery easier to perform. In current HoLEP, the only way to aim the laser and/or manipulate tissue is to move the entire endoscope, stretching a large quantity of tissue. In contrast, our new robotic approach provides the surgeon with two concentric tube manipulators that can aim the laser and manipulate tissue simultaneously. The manipulators are deployed through a 5 mm working channel in a 26 French (8.66 mm) endoscope clinically used for transurethral procedures. This paper describes the design of the robot and experiments illustrating its ability to perform the motions expected to be useful in HoLEP.**

I. Introduction

One of the earliest surgeries to which robotics was applied was Transurethral Resection of the Prostate (TURP) by Davies, et al. [1]. Recently, the feasibility of transurethral bladder access and laser resection has been demonstrated by Simaan et al. using a continuously flexible multi-backbone robot [2], [3]. In this paper, we apply a different kind of continuously flexible robot (the concentric tube robot) to facilitate a new approach to the clinical condition that originally inspired Davies et al.'s work. This new procedure is Holmium Laser Enucleation of the Prostate (HoLEP), which is known to have better clinical outcomes than TURP, yet is underutilized because of how challenging it is for the surgeon to perform using conventional endoscopic instruments. The intent of the robotic system described in this paper is to make HoLEP easier to perform so that more patients can benefit from it. Our system concept is illustrated in Fig. 1.

HoLEP is a surgery applied to treat benign prostatic hyperplasia (BPH), or enlargement of the prostate, which is the most prevalent symptomatic disease in men [4], occurring in 8% of men in their 30s, 50% in their 50s, and 90% in their 80s [5]. BPH occurs when the prostate grows large enough that it restricts the flow of urine through the urethra, which passes through the prostate. The goal of a surgical intervention for BPH is to remove prostate tissue surrounding the urethra and thereby enable normal urine flow to resume. TURP is the current standard surgical approach for BPH [6]. It is accomplished endoscopically, through the urethra, and prostate tissue is removed in pieces by either sharp dissection or electrocautery [7]. Although the approach to the prostate is minimally invasive, the tools used to remove tissue can cause substantial bleeding (potentially requiring transfusion), long catheterization time, urethral narrowing, and bladder neck narrowing [6].

HoLEP can alleviate many of these concerns, since the Holmium laser "possess the ideal combination of cutting and coagulation" [8], enabling dissection without significant thermal spread (making HoLEP safer than electrocautery for nearby structures such as nerves), and without substantial blood loss. The reduction in morbidity in HoLEP compared to TURP has been corroborated in a number of clinical

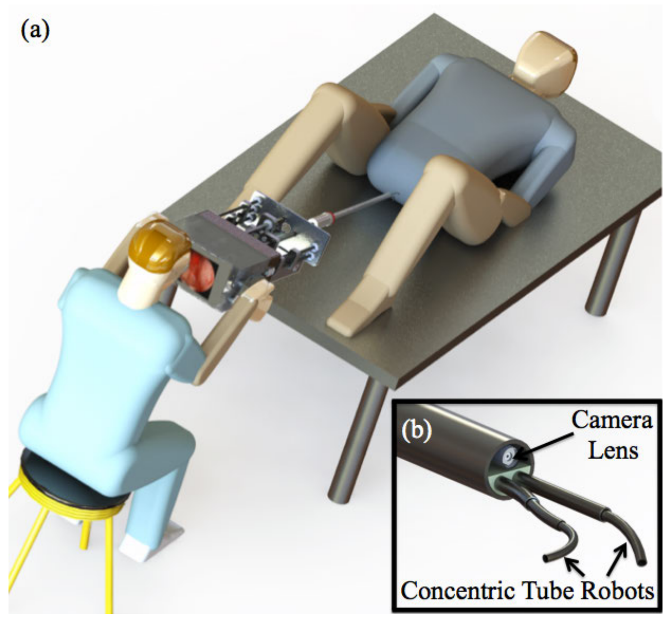

Fig. 1. An illustration of the proposed robotic system for HoLEP. (a) The surgeon is able to position and angle the endoscope while simultaneously controlling two concentric tube manipulators that extend from its tip, as shown in (b). The surgeon controls these manipulators with thumb joysticks and finger triggers, and views the endoscope image on a screen between his/her hands. Note: Not pictured is a passive support arm that counterbalances the robot, relieving the surgeon of the robot's weight.

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studies [8], [9], [10]. These show that HoLEP reduces average catheterization time (2 days to 1 day), hospital stay (3 days to 2 days), and blood loss (eliminates the need for transfusions) [11]. The improvement in outcomes is sufficiently compelling that HoLEP is now generally viewed in the urology community as the superior treatment [6].

In spite of this, HoLEP adoption has been disappointingly slow [12], and it is currently only conducted at a few institutions in the USA [13] (in contrast, TURP was conducted approximately 50,000 times in the United States in 2005 [14]). The best explanation for why HoLEP has not been more widely adopted is that it is extremely challenging for the surgeon [8], [9], [10], [12]. What makes it so challenging is that the laser proceeds straight out of the endoscope and can only be aimed by moving the entire endoscope. Since the endoscope must pass through a great deal of soft tissue on the way to the prostate, its maneuverability is limited. Large forces are required to aim the endoscope and the only way to physically manipulate tissue near its tip is to use the tip of the endoscope itself [8]. It is challenging and physically demanding for surgeons to attempt to accurately aim the laser using the endoscope while simultaneously applying large forces to the same endoscope to deform the tissue.

II. System Concept

In HoLEP (both standard HoLEP and our robotic approach) the patient and surgeon are positioned as shown in Fig. 1. In standard HoLEP, the surgeon manually manipulates the endoscope, which is inserted into the urethra. With our new robotic approach, we keep the same basic setup and work flow, but provide the surgeon with added dexterity via a hand-held robotic system. This enables the surgeon to control gross motions of the endoscope manually as usual, while fine motions of the continuum manipulators at the endoscope tip are accomplished with thumb joysticks and finger triggers near the surgeon's hands. The surgeon can view the endoscope image on a screen placed on the back of the robot, as shown in the Figure. The endoscope that passes into the patient is of the same diameter as that currently used clinically for HoLEP, namely 26 Fr (8.66 mm). It delivers optics for a camera, light sources, and provides a 5 mm diameter working channel through which the concentric tube manipulators are delivered. One concentric tube robot guides and aims the Holmium laser fiber (which runs through it), and the other enables the surgeon to manipulate tissue to expose areas for laser dissection. The major modules of the robot are shown in Fig. 2.

A. The Hand-Held Paradigm

The hand-held paradigm has been usefully applied in surgical robotics in devices such as articulated laparoscopic forceps [15], a hand-held interface for da Vinci tools [16], a knee arthroscopy instrument [17], steerable needles [18], and an articulated endoscopic robot for natural orifice surgery [19], among others. A simple single-tube concentric tube robot has been previously employed as a reach extender in eye surgery [20] and in a flexible neuro endoscope to deliver an electrocautery wire [21]. This is the first time that multiple concentric tube robots have been incorporated into a hand-held device. The concentric tube robot idea provides a means for delivering two articulating instruments through a 5 mm diameter channel in a small endoscope.

B. Concentric Tube Manipulators

Concentric tube manipulators (also called active cannulas), are needle-diameter, tentacle-like robots consisting of multiple concentric, precurved, elastic tubes (typically made of nitinol) that are independently rotated and translated at their respective bases. As these precurved tubes interact with one another, they cause one another to bend and twist, with the tubes collectively assuming a minimum energy conformation. The latest models of these robots account for arbitrarily many tubes, each with general precurvature [22], [23]. The curved shape of the device inside the patient is controlled via linear translation and axial rotation of each tube at its base, outside the patient. These devices are particularly well suited to natural orifice procedures because their small diameter and remote actuation enable them to operate in areas where bulkier actuation systems (e.g. tendons and pulleys) are not feasible. The size of the manipulator is limited only by the size of nitinol tubes available (the smallest nitinol tube on stock lists for NDC, Inc. is 200 μm outer diameter). The Jacobian of this robot can be computed [24], and used to enable teleoperation [25].

III. System Design

Our robotic system for HoLEP consists of the modules shown in Fig. 2. The tip of the endoscope is shown in Fig. 3. The rear ends of each tube of the concentric tube robots are grasped by carriers in the transmission section of the device, which is pictured in Fig. 4. An individual carrier is shown in Fig. 5. The motor pack is a modular attachment that is housed between the surgeon's control handles as shown in Fig. 6. This design follows the general modularity and sterilization approach introduced in [26]. In this design paradigm, the motors are isolated from the transmission, with the sterile barrier between the two, and the transmission is designed to be biocompatible and autoclavable. Motors are coupled to transmission elements using oldham couplings, the same basic concept used by the da Vinci robot to transmit rotary motion through a sterile barrier.

In our robot we have designed the two concentric tube manipulators to have different numbers of tubes and hence

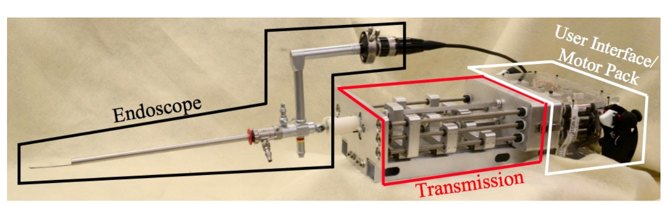

Fig. 2. The robotic system for HoLEP surgery consists of an endoscope, a transmission, and a combined user interface and motor pack. These components are described in more detail in Section III.

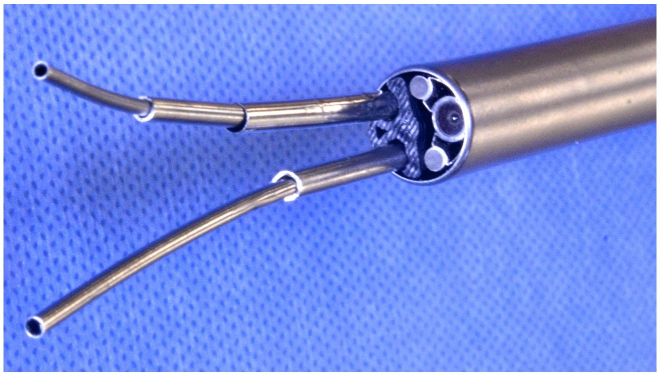

Fig. 3. Distal end of endoscope showing concentric tube manipulators, camera, and light sources.

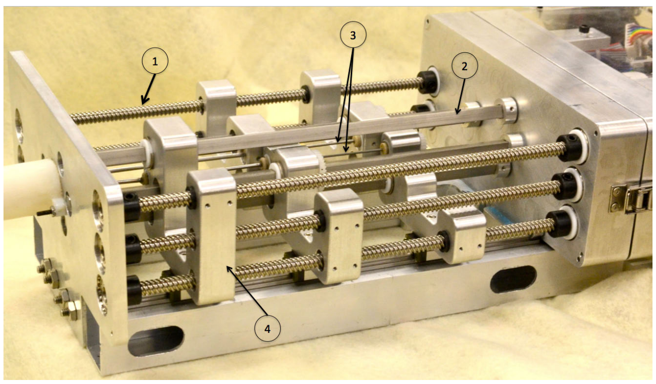

Fig. 4. The transmission section carriers grasp each concentric tube at its base and apply linear translational and axial rotational motions. 1 Lead screws connect translational motors in the motor pack to each carrier. 2 Square shafts connect rotational motors to tube bases through gear trains. 3 Tubes of the concentric tube manipulators can be seen here. 4 Tube carrier – see exploded view in Fig. 5.

degrees of freedom (DOF). One has two tubes with the outer tube straight, and hence 3 DOF. The other has three tubes, all of which are curved providing an additional 6 DOF. The reason for this design choice is that it is currently unclear how many DOF will be needed to accomplish the surgical objectives with the laser manipulator and with the tissue manipulator. This configuration will enable us in future studies to explore these questions experimentally.

A. Mechanical Design

The carriers shown in Fig. 5 grasp the bases of the tubes in the concentric tube robot. Motors in the motor pack are coupled to the carriers via lead screws and square shafts to apply linear and angular motions, respectively as shown in Fig. 4. One useful feature of this design was the incorporation of a ball bearing block and guide rail (THK America, Inc. part number HSR8R) which can sustain significant moment loads while continuing to slide freely.

Previous concentric tube robot designs have been designed to be statically mounted, so weight was not an issue. In contrast, since this is intended to be a hand-held device, compactness and lightness are priorities. Because of this, due to their high power to weight ratio, we selected brushless

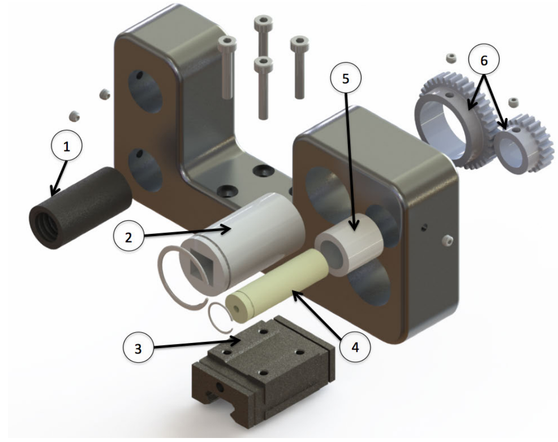

Fig. 5. Design of a single carrier: 1 Lead nut 2 Square bore sleeve 3 Bearing block 4 Tube holder 5 Sleeve bearing 6 Gear train.

8 Watt DC motors (Maxon Motor, Inc.), equipped with 29:1 planetary gearheads. All nine motors were arranged within the motor pack to axially align with the nine shafts of the transmission.

In this system we incorporate a Storz, Inc. 27292 AMA endoscope which is currently used clinically for prostate surgery. The endoscope contains integrated optics and light sources, which can be seen in Fig. 3, as well as a 5 mm working channel through which we introduce the concentric tube robots. This size specification implies that the outside diameters for the largest tube of each concentric tube manipulator can be approximately 2 mm in diameter each. The diameters, curvatures, and lengths of the tubes have not yet been optimized for this application. Future studies similar to those described in [27] will be useful for selecting optimal tube parameters.

B. User Interface Design

To control the robot, we provide the surgeon with two contoured handles, as shown in Fig. 6. Each has a thumb joystick with pushbutton capability, as well as an analog index finger trigger. Using coordinated motion of both hands, the surgeon can control gross motion of the endoscope. Fine motion of the concentric tube manipulators is accomplished using the joysticks and triggers. The analog signals from these were mapped to velocities of the concentric tube robot tips, with respect to the endoscope tip frame. The trigger was mapped to the insertion direction and the two joystick degrees of freedom were mapped to the lateral directions. To change the direction of motion (insertion vs. retraction) controlled by the trigger, the surgeon clicks the joystick push button. We note that this mapping has not yet been studied in depth or via user studies, and that that these will be the subject of future work. It is possible that alternate thumb and finger controls will be desirable.

IV. Modeling and Control

Real-time control was implemented using xPC Target and Simulink (MathWorks Inc.). A block diagram of the interface

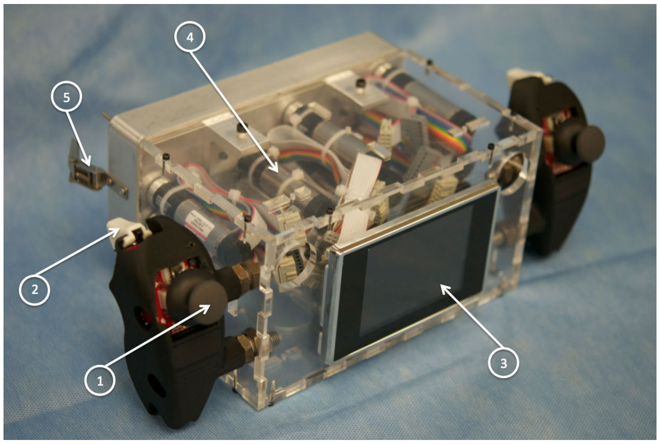

Fig. 6. User interface of system: (1) Analog joystick (2) Analog trigger (3) Endoscopic display (4) 8W brushless DC motor (5) Latch. This unit is intended to be bagged for sterility, and the intent is that the handles would be sterile and coupled to the motor pack housing through the bag around the user interface, although the current prototype handles are rigidly mounted and not yet made from sterilizable components.

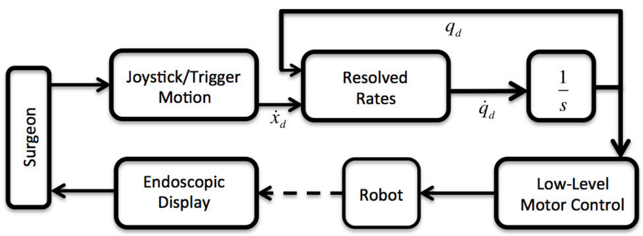

Fig. 7. Block diagram outlining the control methodology. The user interface commands a velocity in task space which is translated into joint space via resolved rates, integrated, and sent to a low level controller.

is shown in Fig. 7. The surgeon specifies a desired velocity in task space via displacement of the triggers and joysticks. The desired velocity is converted into a desired joint space velocity using a resolved rates algorithm as discussed in the next subsection. These velocities are then integrated to obtain desired joint positions for low-level control.

Note that one of our concentric tube manipulators consists of two tubes and has three DOF. In this case, the forward kinematics and hybrid Jacobian can be calculated in closed form, as shown in the next subsection. In contrast, our other manipulator has three tubes and six DOF. Here, the forward kinematics are solved via the model described in [22], and the Jacobian is computed according to [24]. These models are implemented in C++ and sent via UDP to the main controller in Simulink. Note that the six DOF manipulator requires a redundancy resolution method since only the three-DOF tip position is to be controlled. As an initial approach, we resolve redundancy by locally minimizing joint speeds, though we have not yet experimentally compared this to alternate redundancy resolution approaches.

A. Kinematics of the Three-DOF Manipulator

The forward kinematics of the two-tube robot with a straight outer tube and a constant curvature inner tube can be written in closed form [28]. Here, we assume that the outer tube is sufficiently stiff that the inner tube does not bend it significantly. The inner tube is elastic with constant precurvature κ. The actuation variables are α_1, which denotes the angular position of the inner tube, $\beta_1 \in s$ (where s measures arc length), which is the location where the inner tube is held by its carrier, and $\beta_2 \in s$, which is the location where the outer straight tube is held by its carrier. We define $s = 0$ to be where the tubes exit the tip of the endoscope, with positive s toward the prostate. Further, let us define ℓ_1 and ℓ_2 to be the physical lengths of the tubes. Consider a fixed frame at the endoscope tip, with its z-axis tangent to the endoscopic axis, and its x-axis defined as the direction about which the inner tube curves at $\alpha_1 = 0$. Let us also place a body frame at the tip of the robot with its z-axis tangent to the central axis of the robot at its tip, and its x-axis in the direction about which the tube curves (note that the body frame moves with the robot's tip as the robot deforms). Using these definitions, the forward kinematics, g_{st}, is given by:

$$
\begin{aligned}
g_{st} &= \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix} \\
R &= \begin{bmatrix} c_{\alpha_1} & -s_{\alpha_1} c_\gamma & s_{\alpha_1} s_\gamma \\ s_{\alpha_1} & c_{\alpha_1} c_\gamma & -c_{\alpha_1} s_\gamma \\ 0 & s_\gamma & c_\gamma \end{bmatrix} \\
d &= \begin{bmatrix} -r s_{\alpha_1}(c_\gamma - 1) \\ r c_{\alpha_1}(c_\gamma - 1) \\ l_2 + \beta_2 + r s_\gamma \end{bmatrix},
\end{aligned} \tag{1}
$$

where $\gamma = \kappa(\beta_1 - \beta_2 + \ell_1 - \ell_2)$ and $r = \frac{1}{\kappa}$. Using the methodology outlined in [29], the spatial Jacobian J_s can be defined from the forward kinematics as,

$$
J_s = \left[\left(\frac{\partial g_{st}}{\partial \alpha_1} g_{st}^{-1} \right)^\vee \quad \left(\frac{\partial g_{st}}{\partial \beta_1} g_{st}^{-1} \right)^\vee \quad \left(\frac{\partial g_{st}}{\partial \beta_2} g_{st}^{-1} \right)^\vee \right]. \tag{2}
$$

In [29], the relationships between the spatial, body, and hybrid Jacobians are defined as,

$$
\begin{aligned}
J_s &= Ad_{g_{st}} J_b \\
J_h &= \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} J_b,
\end{aligned} \tag{3}
$$

where $Ad_{g_{st}}$ is the adjoint transformation, J_h is the hybrid Jacobian, and J_b is the body Jacobian. Using (1) and (3), the hybrid Jacobian can be shown to be

$$
J_h = \begin{bmatrix} r c_{\alpha_1}(1 - c_\gamma) & s_{\alpha_1} s_\gamma & -s_{\alpha_1} s_\gamma \\ r s_{\alpha_1}(1 - c_\gamma) & -s_\gamma c_{\alpha_1} & s_\gamma c_{\alpha_1} \\ 0 & c_\gamma & 1 - c_\gamma \\ 0 & \kappa c_{\alpha_1} & -\kappa c_{\alpha_1} \\ 0 & \kappa s_{\alpha_1} & -\kappa s_{\alpha_1} \\ 1 & 0 & 0 \end{bmatrix}. \tag{4}
$$

Using this Jacobian, a singularity robust resolved rates algorithm is implemented, based on [30]. The update step in this algorithm is given as

$$
\dot{q} = (J_h^T J_h + \lambda^2 I)^{-1} J_h^T \dot{x}, \tag{5}
$$

where λ^2 is given by,

$$\lambda^2 = \begin{cases} 0, & \sigma_m \geq \varepsilon \\ (1 - \frac{\sigma_m}{\varepsilon}^2)\lambda_{max}^2, & \sigma_m < \varepsilon \end{cases}, \tag{6}$$

where ε determines how close to singularity one wishes the system to be before implementing the damping factor, λ_{max} is the maximum damping factor, and σ_m is the minimum singular value of J_h, which indicates how well conditioned the Jacobian is [31].

V. Experimental Illustration of HoLEP Maneuverability

Rigorously demonstrating a functional benefit to our new system on the benchtop is challenging, since tissue deformation is such a significant factor in HoLEP. Hence, we plan future cadaver studies to evaluate this. However, here we provide two anecdotal illustrations of capabilities that we anticipate will lead to a benefit in those future cadaver studies. First, if our system can reduce the angle that the surgeon must apply to the endoscope during surgery, it will reduce the force that the surgeon must apply, and thereby potentially the physical demands on the surgeon.

As can be seen in Fig. 8, the surgeon must apply just under 30 degrees of deflection to reach all reachable points on an ellipsoid representing the desired resection volume with no tissue deformation (here, the laser fiber is held a fixed distance from the endoscope tip, representing roughly the maximum extension typically used - extending the fiber too far with no support can damage it). In contrast, our robot can reach even more points on the ellipsoid surface, with no endoscope angulation. We are assuming here that anatomy roughly enforces a pivot point at the urogenital diaphragm, which we have simulated with a mechanical pivot point mounted above the ellipsoid.

As a second experimental illustration of system functionality, we sought to explore the ability of surgeons to use the system to scan the surface of the ellipsoid representing the desired resection volume. Of particular interest were the points on the "back" of the ellipsoid that would be inaccessible to a standard scope without tissue deformation. Fig. 9 shows a series of images illustrating how the surgeon was able to use the robot to scan the surface of the ellipsoid, in comparison to a standard endoscope without robotic assistance.

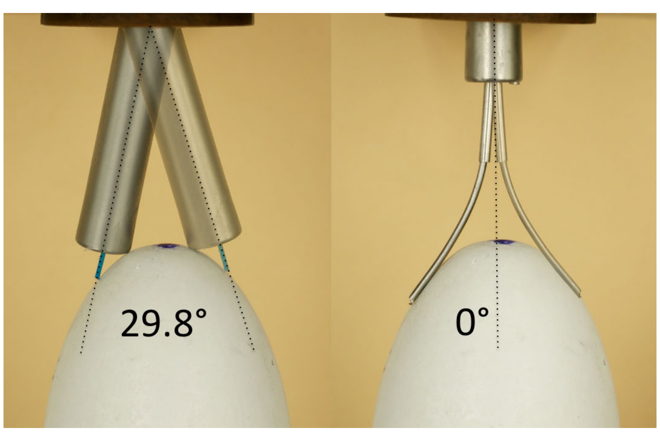

Fig. 8. Operating through an anatomically constrained center of motion, and without deforming the prostate tissue with the endoscope, the surgeon must manipulate the endoscope almost 30° in plane to access the reachable area an ellipsoid representing the desired resection volume of the prostate. With the two-tube active cannula, the surgeon can reach a larger area without angling the endoscope.

VI. Conclusions

Despite demonstrated clinical benefits, HoLEP has been hindered from becoming the gold standard for BPH surgery due to the difficulty for the surgeon of accomplishing the procedure. This paper has described the design of a multi-arm, hand-held robotic system motivated by the objective of making HoLEP easier to perform and shortening the learning curve.

The system described in this paper increases the dexterity of the surgeon in HoLEP, and we believe this dexterity enhancement will make the procedure easier to perform and thereby enable more surgeons to offer it to their patients. Whether or not the system as constructed in this paper actually does make the surgery easier to perform remains to be proven in future user studies.

Other topics we intend to explore in future work are optimal tube design, alternate redundancy resolution algorithms, and the number of degrees of freedom needed for each manipulator. We also plan to conduct experiments with biological tissues so that tissue deformation effects can be accurately included in experiments. Ultimately, we will seek to show that a robotic approach can reduce procedure times and make the procedure easier to learn and easier to accomplish.

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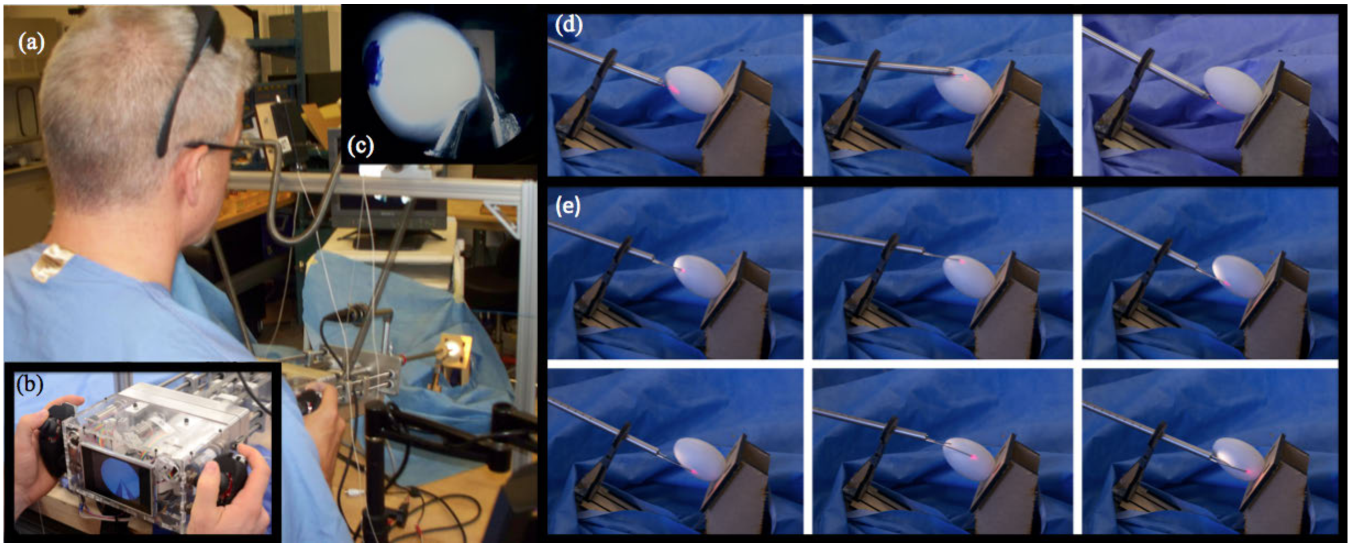

Fig. 9. (a) A surgeon teleoperating the system, operating on the prostate model through the center of motion. (b) The surgeon's user interface. (c) An endoscopic view of concentric tube robots operating on prostate. (d) With a traditional straight scope, the surgeon can only access a portion of the desired resection surface. (e) The robot enables the surgeon to access more of the surface with the laser fiber.

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