INTRODUCTION

Transurethral laser surgery using a flexible multi-backbone robot was recently demonstrated by Simaan et al. for bladder resection [1]. For transurethral prostate resection, thinner flexible manipulators are desirable. We have developed a hand-held system that transurethrally deploys two concentric tube robots through an 8.3 mm diameter rigid endoscope [2], as shown in Figs. 1 and 2. The purpose of this system is to facilitate Holmium Laser Enucleation of the Prostate (HoLEP), a surgery that is rarely used despite its demonstrated clinical benefits, because it is so challenging for the surgeon to perform [3]. The objective of the surgery is to remove prostate tissue transurethrally with a laser, and the challenge arises from the need to angulate the entire endoscope (impeded by a great deal of soft tissue) to aim the laser. Our system assists by providing one manipulator to aim the laser and a second to retract tissue, exposing desired targets to the laser.

The purpose of this paper is to explore optimal design of the concentric tube manipulators. We define an optimal design as one in which there is maximal overlap between the workspace of the manipulator and the space viewable by the endoscope. Here, we restrict our attention to the special case in which the concentric tube robot consists of two tubes, where the outer tube is straight and the inner tube is circularly curved. We note that more complex concentric tube manipulators are possible, such as the three tube robot shown in Fig. 2, but leave more complex cases to future work. Based on this, our objective is to choose (1) the curvature of the inner tube, and (2) the distance behind the camera lens inside the endoscope where the base of the workspace should occur.

Fig. 1 This system is made up of three sections: a rigid endoscope that the manipulators pass through, a transmission where rotation and translation are applied to tube bases, and a user interface enabling the surgeon to control the endoscope and both manipulators. See [2] for a detailed description of this robot.
angle subtended by the curved portion of the inner tube with $\theta$, and the critical angle at which the inner tube collides with the boundary as $\theta_c$. This angle and the distance behind the tip of the endoscope where the straight tube should end to achieve it, $d$, are given by:

$$
\theta_c = \cos^{-1}\left(\frac{cK - 1}{pK - 1}\right)
$$

$$
d = \kappa^{-1}\sin(\theta_c).
$$

From this, the trumpet-like workspace boundary, $b$, can be shown to be

$$
b = \left(\frac{-\kappa^{-1}\sin(\alpha)(\cos(\theta) - 1)}{\kappa^{-1}\cos(\alpha)(\cos(\theta) - 1) - \kappa^{-1}\sin(\theta) - d}\right),
$$

where $\alpha \in [0\ 2\pi]$, $\theta \in [0\ \pi/2]$, and an origin on the tube axis at the endoscope tip is assumed. The closed curve defined at $\theta = 90^\circ$ forms the bottom of a cylinder which extends out axially and forms the remainder of the workspace boundary (the cylindrical space can be accessed by extending both tubes together).

RESULTS

To choose the optimal curvature for the curved tube within a range of 20 to 70 m$^{-1}$ we began by discretizing this range into 100 evenly spaced values. For each, the workspace was computed and the percentage of the visualization volume covered was determined. This was done by discretizing the visualization cone into 0.5 mm isotropic voxels, and counting as “covered” those voxels whose centers were inside the manipulator's workspace. Three different example cases of overlaid workspace and view volume are shown in Fig. 3 and view volume coverage as a function of curvature is shown in Fig. 4.

DISCUSSION

The value of optimizing tube design is illustrated by the ability to access a greater percentage of the endoscope visualization volume than the initial tubes in [2] could achieve. The most noteworthy result from this study is that placing the base of the workspace a short distance inside the endoscope is useful for reaching the maximum percentage of the visualization volume. To extend this design framework, one could consider also optimizing the exit location in the endoscope cross section, adding additional curved tubes to the manipulators, or using arc lengths beyond $\theta = 90^\circ$. One could also consider using an endoscope with a different angle of view. Before studying these additional parameters, we intend to rigorously test the system in benchtop and cadaver experiments, to determine whether additional optimization variables are needed, and whether 3 DOF manipulators are sufficient to accomplish the surgery effectively and easily.

REFERENCES


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