Computational Analysis of Design Parameters for a Bimanual Concentric Push-Pull Robot

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INTRODUCTION

Colorectal cancer is a pervasive disease: an estimated 4.3% of men and 3.9% of women will suffer from it in their lifetime [1]. Precancerous polyps can be small (<5 mm), medium (6-9 mm), or large (>10 mm) [2]. Small polyps are most frequent, but polyps too large for immediate endoscopic removal during screening occur 148,000 times per year in the US alone [3]. There are two primary options for removing these polyps: endoscopic removal or partial colectomy. Endoscopic procedures, such as endoscopic submucosal dissection (ESD), are less invasive and reduce the risk of infection, recurrence, and other adverse events [4]. Despite this, approximately 54,000 patients each year undergo partial colectomies for polyps that could have otherwise been removed endoscopically [3].

A primary obstacle to the wider adoption of endoscopic procedures is how challenging they are for physicians to perform, due to the limited dexterity of existing trans-endoscopic tools [4]. To enable tools to move more dexterously, we propose an endoscopically deployable, flexible robotic system, as shown in Fig. 1. This system deploys a dexterous sheath through each channel of a standard 2-channel colonoscope. Each dexterous sheath is composed of an outer sheath followed by an inner sheath, with each sheath built using a concentric push-pull robot (CPPR) [5]. The outer sheath will move to a fixed pose and remain in the pose, while the inner sheath will perform the movements required in a surgical operation. Each dexterous sheath has a hollow central lumen through which tools (e.g. forceps, electrosurgery probes, etc.) can be passed. This design adds dexterity and provides the physician with two independent manipulators, with the goal of making ESD easier to perform.

In this paper, to inform the design of the system, we computationally analyze the relationship between the reachable workspace of the dexterous sheaths and their design parameters. We note that there are inherent trade-offs in the design parameters, e.g., increasing the length parameters of the outer sheaths increases the distal reachable workspace but may limit the proximal reachable workspace. For a candidate design, we evaluate the reachable workspace by calculating forward kinematics over a wide range of actuatable configurations and compare the resulting reachable workspace to the field of view of an endoscopic camera. We conduct this evaluation for a wide range of candidate designs. This work will inform future work on tube design for the proposed surgical robot.

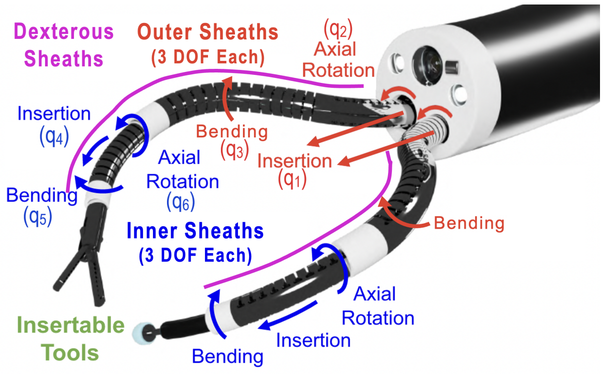

Fig. 1 Degrees of Freedom of a Bi-manual Concentric Push-Pull Robot (CPPR) composed of two dexterous sheaths.

MATERIALS AND METHODS

The proposed bimanual system includes two dexterous sheaths, each composed of an inner and outer sheath. Each of these sheaths is a CPPR, which is composed of a nested pair of Nitinol (NiTi) tubes which are asymmetrically laser patterned to offset the neutral bending axes from each other and joined at their tips such that relative translation of the tube bases results in bending [5].

Each outer sheath includes proximal and distal segments, enabling actuation into an "S" shape. The proximal segment will have a length L_1 and curvature q_3. The distal segment will have a length L_2 and the same curvature in the opposite direction, $-q_3$. The two curved segments are separated by a short straight segment of length L_s.

For the outer sheaths, the design parameters are the following geometric properties:

- Max curvature of the outer sheaths ($q_3 < \kappa_{max}$),
- Length of the curved proximal segment (L_1), and
- Length of the curved distal segment (L_2).

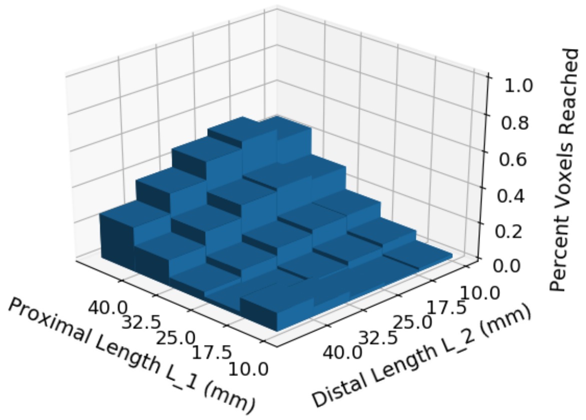

Fig. 2 This plot shows the percentage of workspace voxels reached with a maximum outer sheath curvature of 0.4mm^{-1} as a function of the two outer sheath curvature lengths.

i	1	2	3	4	5
L	q_1	L_1	L_s	L_2	q_4
κ	0	q_3	0	$-q_3$	q_5
ϕ	q_2	0	0	0	q_6

TABLE I Parameters used for Evaluation of each constant curvature transformation matrix $T_{cc,i}(L, \kappa, \phi)$

For the inner sheaths, greater curvature and insertion capabilities will improve the reachability in the workspace of the robot, so we assume maximal values. The limits for curvatures and lengths were selected based on prior experience with maximum manufacturable values.

The robot can actuate the DOF shown in Fig. 1. For the outer sheaths, the DOF are base insertion (q_1), axial rotation (q_2), and curvature (q_3). For the inner sheaths, the DOF are insertion (q_4), curvature (q_5), and axial rotation (q_6). The target workspace is determined by the field of view for a commercial colonoscope. Based on the Olympus CF-2T160I, the field of view is 140 degrees and depth of field is 3-100 mm respectively. We discretized the resultant volume into cubic voxels with edge length 5 mm. To evaluate the reachable voxels of each design, we iteratively computed the results of the forward kinematics.

The forward kinematics $T_{\text{base}}^{\text{tip}} = \overset{\frown}{\prod}_{i=1}^{5} T_{cc,i}$ is based on a constant curvature model with a transformation matrix T_{cc} allowing for length L, curvature κ, and axial rotation ϕ as denoted in Table I [6].

We computed the resulting tip location for each combination of design parameters and actuation variables. The voxels containing these tip locations were marked as reached. The best design was determined by the highest coverage percentage of reachable voxels in the workspace.

RESULTS

Figure 2 illustrates the trends in the reachable workspace as a function of each design parameter. The plot shows that increases in the length of the proximal section generally lead to a larger proportion of the target workspace being reached. The largest reachable workspace was achieved with an outer sheath having a proximal segment length of L_1 = 40 mm and a distal segment length of L_2 = 10 mm. Fig. 3 shows the workspace and example configurations of this design, which is able to reach 50.1% of the camera's field of view.

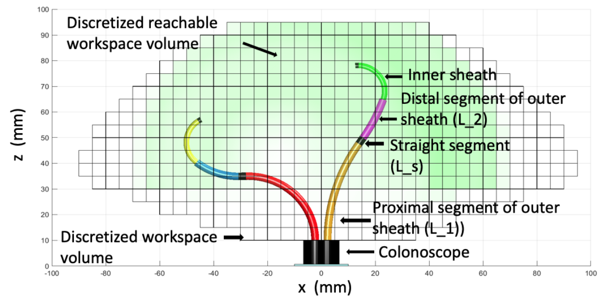

Fig. 3 Bi-manual CPPR system and its workspace. The boxes show a 2D slice of the voxels of the workspace. The green indicates the voxels that are reached. Darker green regions indicate higher sampled point density.

A maximum outer sheath curvature of 0.04 mm^{-1} was chosen as an estimated maximum based on previous work on tube cut pattern designs. Further experiments showed that more voxels are reached with a higher maximum curvature up to 0.10 mm^{-1}, beyond which there are diminishing returns.

DISCUSSION

This paper outlines early work toward designing a bi-manual CPPR capable of completing ESD. Proceeding with the resulting design parameters of tubes, we can continue work on modeling, actuation, and control of the robotic manipulators. Future work will involve implementing intuitive controls for surgeons, modeling the robotic system, and optimizing the transfer of actuation actions through the length of the colonoscope. Additionally, testing in live porcine models is planned for validation of in-vivo ESD performance. With this work as a cornerstone, we ultimately hope to realize the potential benefits of ESD and improve surgical outcomes.

Acknowledgement: This research was supported by the National Institutes of Health (NIH) award R01EB032385.

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