Area-Based Total Length Estimation for Position Control in Soft Growing Robots

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INTRODUCTION

Recently, the use of eversion-based movement in robotics has gained popularity. Eversion mechanisms enable objects to turn inside out, similar to flipping a sock, allowing them to move through narrow spaces without making direct force on the environment. This type of movement can be used for medical devices such as catheters and endoscopes [1], where the use of soft growing robots with appropriate length is critical for safe and successful navigation through the human body. For instance, an autonomous colonoscope is required to navigate through narrow and curved spaces in the colon. Eversion movement is a suitable solution that allows the colonoscope to move more safely. However, the length of the soft growing robot is a critical factor in determining its ability to navigate through the colon without causing damage to surrounding tissue. To address this challenge, implementing feedback control based on real-time total length information can enhance the accuracy and efficiency of the examination process.
This paper introduces a method for calculating the total length of the everted portion based on area and the number of motor rotations. The model was validated using an optical tracking camera and compared with four other methods for calculating the total length in roller mechanisms [2], [3].

MATERIALS AND METHODS

The total length of the eversion portion (L) is typically controlled by a spool-based reel mechanism consisting of tightly wrapped plastic tubing [4]. The plastic layflat tubing on the roll is assumed to be in the shape of an Archimedean spiral rather than a logarithmic spiral and has a uniform thickness (h). One end of the plastic tubing is glued to the spool. At a specific rotation angle (α), the tubing's end comes into contact with the portion of the wrapped layflat tube. This point forms the tangent (A2) to the cylinder, marking the final point of contact with the cylinder as shown with read line in Figure 1. The following layers of the wrapped sheet consist of a cylindrical section around the spool and a flat section between the layers.
The entire radius of the spool (R) with the inner radius

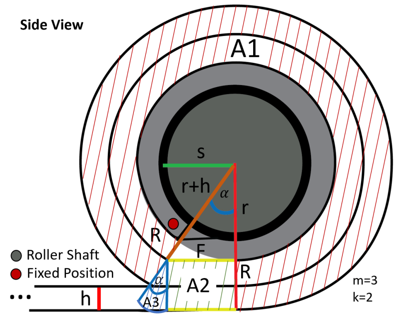

Fig. 1 Diagram of area based calculation for reel mechanisms: Light gray area is the inner radius(r), Dark gray represents the rotating shaft (s)

(r) is calculated by $R = r + kh$, where k is the number of rotations. The inner radius is denoted by $r = (m - k)h + s$, where m is the total number of layers around the shaft, s is the radius of the spool. The flat section's length (yellow line), denoted as F, between the glued end and the second layer is calculated as $F = \sqrt{(r+h)^2 - r^2} = \sqrt{(2r+h)h}$. The angle (α) between red line and orange line in the Figure 1 is calculated by:

$$\alpha = \arccos \frac{r}{r+h} \tag{1}$$

The area of entire roll is divided into three parts (A_1, A_2, A_3) [5], where A_1 represents the cylindrical section of the roller, A_2 refers to the rectangular area of the roller, and A_3 represents the sector between the layers as follow:

$$\begin{aligned} A_1 &= \left(\pi - \frac{\alpha}{2}\right)\left(R^2 - r^2\right) \\ A_2 &= (R - r - h)\sqrt{(2r+h)h}. \\ A_3 &= \frac{\alpha}{2}(R - r - h)^2 \end{aligned} \tag{2}$$

The total length (L) is calculated by dividing the total area by the thickness of the sheet, as

$$\begin{aligned} L =& \frac{1}{h}(A_1 + A_2 + A_3) \\ =& k(R+r)\pi + (k-1)\sqrt{(2r+h)h} \\ & - \left(k(r+h) - \frac{h}{2}\right)\arccos\frac{r}{r+h} \end{aligned} \tag{3}$$

The reel mechanism was equipped with a DYNAMIXEL motor (MX-24), which is controlled through USB communication using a U2D2 device. The Matlab script was utilized to control the rotation times by extended position control mode. The robot's tip was with a passive optical marker. An optical tracking camera (fusionTrack 500, Atracsys) was employed to provide the system with feedback on the tip's coordinates, as depicted in Figure 2b. The Cartesian coordinates of the maker were recorded at each step $k = (1, 2, .., 10)$. The plastic tubing ($h = 0.13mm$) was wrapped around the shaft ($r = 7.7mm$) in total of 15 layers ($m = 15$). The experiment was repeated 5 times ($n = 5$) with different rolls of tubing. Additionally, the pressure in the experiment was set to 0.5 bar, which is below the maximum bearing pressure of the plastic tubing. The experiment was repeated five times to calculate the standard deviation of the results.

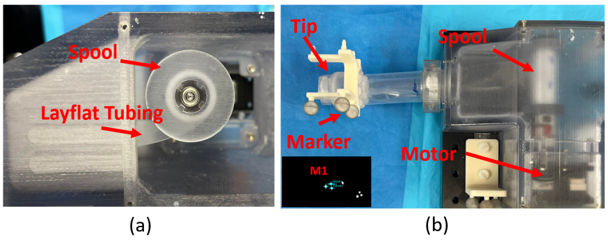

Fig. 2 Soft Growing Robot: a) Side view of the robot with a spool and layflat tubing, b) Top view of the robot with marker at the tip of the robot.

RESULTS

The 3D Euclidean distance between the starting and stopping points at each step was calculated as follow:

$$D = \sqrt{(x_k - x_s)^2 + (y_k - y_s)^2 + (z_k - z_s)^2} \qquad (4)$$

where k is stopping positions and s denotes the starting position at $n = 0$. The results were plotted and compared to the calculations from four different models, including the proposed method, the common roll model [3], the Archimedean spiral model, and Dehghani's method [2], as shown in Figure 3. Additionally, the position at the tip (x^*) of everting structure is equal to the total length divided by 2 as $x^* = \frac{L}{2}$. The root mean square error (RMSe) between the total length from the calculations and Euclidean distance from the experiment are in Table I. The maximum standard deviation in the experiment across multiple samples was approximately 2.1585 mm, significantly lower than the step commands.

DISCUSSION

The proposed method was found to yield the best prediction, with a maximum RMSe of approximately 2.534 mm in estimating the tip position (x^*). Compared to Dehghani's model [2], the proposed approach was, on average, 2 times more accurate ($k > 1$) in RMSe. In general, the maximum difference in RMSe between the proposed method and the other approaches was approximately 1.5% of the total length. Considering a typical colonoscopy with a length of 170 cm, the difference in RMSe corresponds to 2.55 cm, which is much larger than the size of a small polyp. Additionally, this difference was attributed to the thickness of the plastic tubing used (0.13 mm), which did not result in significant differences between the models. The design of the side chambers for steering in the growing structure can lead to an increase in the overall thickness of the tubes, thereby enhancing the disparities between the models. As a result, the approach has the potential to significantly improve the accuracy of endoscopic interventions that employ a soft-growing (everting) device.

k	Mean $\pm SD$	**Proposed**	Roll	Spiral	Dehghani
1	31.284 ±1.967	**0.898**	1.172	5.157	0.559
2	62.958 ±1.471	**1.381**	3.142	8.293	2.121
3	94.103 ±0.821	**1.575**	4.992	10.731	3.562
4	124.077 ±0.688	**2.123**	6.079	13.115	4.649
5	153.372 ±0.687	**2.534**	6.895	14.954	4.649
6	182.684 ±1.377	**2.110**	8.137	15.550	5.482
7	210.941 ±1.227	**1.925**	8.733	15.975	5.671
8	238.070 ±1.589	**2.051**	8.608	16.304	5.137
9	265.247 ±2.158	**1.313**	8.940	15.360	5.060
10	290.067 ±1.973	**2.112**	7.324	15.546	3.035

TABLE I The Mean and SD Euclidean distance (D) of tip position at number of rotation (k) from Different Samples (n = 5) and Comparison of Root Mean Squared Error (mm) in Total Length between the Experiment and Models.

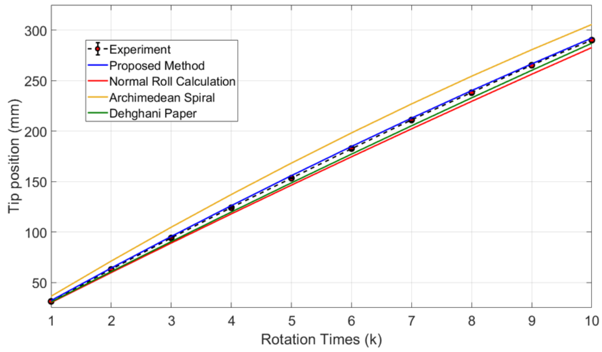

Fig. 3 The tip position (mm) of the everting portion from the 4 different models and Euclidean distance at each step (k), as obtained from the experiment.

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