Two-Dimension Guidance Control and Simulation of a Colonoscopic Robot

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Abstract—**Continuum robots feature continuously deformable backbone as opposed to traditional robots featuring rigid links and identifiable rotational joints. Due to their compliance and high dexterity, continuum robots have good potential application in minimally invasive surgery(MIS). In order to develop a colonoscopic robot which can perform inspection of human colon and do MIS but much less discomfort for the patient, a novel continuum robot for colonoscopy is designed. The robot consists of 5 sections, and each section has 2 degrees of freedom(DOF) and is 12mm in diameter and 120mm in length. This paper briefly introduces the mechanical structure and kinematics of colonoscopic robot first. For simplicity but without loss of generality, a 2-D model of human colon is built according to the anatomy of human colon. In order to achieve a semiautomatic guidance, the guidance control algorithm and implemention method for single section and multiple section colonoscopic robot is developed based on the 2-D colon model. Finally, the simulation is carried out to verify the kinematics and guidance control algorithm. This study lays a foundation for the clinic application of robotic colonoscopy.**

Keywords- continuum robot; colonoscopy; guidance control; simulation

I. INTRODUCTION

With the population aging, the incidence trend of colon diseases is on the increase because the incidence rate rises sharply for the people whose age is above of 50[1]. In industrialized countries, cancer of the colon and the rectum is the second most malignant tumor[2]. Nevertheless, the colon diseases cannot be diagnosed reliably by indirect methods such as X-Rays. As a direct method, the conventional colonoscope is more reliable and allows visual screening of ulcerations and bleeding. Besides, it can be used to perform minimally invasive surgery (MIS) such as biopsy and removal of pre-cancerous polyps. Thus the colonoscope is an important tool not only for the diagnosis of colon diseases, but also for the regular check-up of patients with risk of developing colon cancer. However, only the 10cm-length bending tip of conventional colonoscope can be bent manually. Due to the lack of active bending ability, the bending of other bending sections is realized passively by the contact pressure between the tube and the colon wall. The colon is thus usually changed to be unintended loop formation [3], giving the doctor fairly severe difficulties, causing the patient a great deal of discomfort and pain and even presenting a moderate risk of colonic perforation to the patient.

These disadvantages of conventional colonoscope motivate the development of colonoscopic robot, and several prototypes are developed. A kind of capsule-type endoscope is developed: the M2A[4]. This capsule-type endoscope can realize the inspection of small intestine and the examination is painless and relatively safe, but no active inspection and MIS is possible due to its lack of a locomotive mechanism[5]. Accordingly, its application is limited. Several robotic endoscopes having active bending capability are developed. Simaan and Xu developed a hybrid 8 Degrees-of-Freedom (DOF) snake-like unit for tele-operated MIS of the throat and upper airways using super-elastic NiTi backbone[6-8]. Peirs, et al. proposed a flexible distal tip which is used for endoscopic robot surgery and consists of a superelastic NiTi tube which can be bent from -90° to +90° in 2 directions by 4 cables[9-10]. Choi, et al. also designed a micro endoscope with spring backbone. It can realize 3 DOF motion including compression and two rotational motions[11]. Chen, et al.[12] presented a pneumatic-driven flexible robotic manipulator. It is a kind of continuum robot[13-15] with 2 DOF and actuated by 3 active pneumatic chambers regularly disposed at 120° apart. Breedveld developed a rolling stent endoscope which adopts a new locomotion method based on a rolling donut positioned around the endoscope tip. It is not to push the tip from behind but to use the friction with the intestinal wall to pull the tip forward[16].

In order to develop a colonoscopic robot which can perform inspection and MIS of human colon but much less discomfort for the patient, a colonoscopic robot with multi-section continuum structure is developed. In our previous work[17-18], we have analyzed the principle of the cable-driven continuum robot, introduced its control system and briefly described the single-section kinematics. The focus of this paper mainly lies in the two-dimension guidance control algorithm and simulation of the colonoscopic robot with 5 continuum sections. The rest of this paper is organized as follows: mechanical structure and kinematics is introduced briefly in the next section, section 3 presents the guidance control algorithm, section 4 shows the simulation results and the concluding remarks are given in the last section.

II. MECHANICAL STRUCTURE AND KINEMATICS

A. *Mechanical Structure*

The continuum robot adopts a new type of biologically inspired structure: continuum structure. This kind of robot features continuously deformable flexible structure as opposed to the traditional robot featuring rigid links and identifiable rotational joints. It can bend continuously along its length and produce motion through the generation of smooth curve,

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similar to the snake and the elephant trunk. The continuum structure of this colonoscopic robot offers enhanced environmental interaction by deforming to fit the environmental constraints of colon tract.

The mechanical structure of colonoscopic robot comprises the colonoscope body, the bending control device and the propulsion device. The bending control device is mainly used to realize the multi-degree of freedom bending control and to clamp the colonoscope body; the advancement of colonoscopic robot is driven by the propulsion device.

The colonoscope body with continuum structure is 12mm in diameter and 600mm in total length. Fig. 1 shows the mechanical structure of single section. It is composed of universal joint, rivet, spring tube, drive cable and metal mesh. The universal joint is made of stainless steel and manufactured with sheet forming technics. Two 1.0mm-length guide tubes in the inner surface of universal joint are used to guide the cables. With the connection of universal joints, a 120mm-length single section which can realize 2-DOF bending motion is built. The spring tube which is 0.6mm in diameter is not only used to guide the cable properly along the length of colonoscope body, but also to bear the axial force produced by the multi-section coordinated motion. Due to the fact that cables can only exert pulling and not pushing forces, 4 cables located 90 degrees apart and divided into two pairs are used to provide 2-DOF actuation for each section. In order to increase the bending stiffness and provide the overall form, a metal mesh is used to cover the whole body of the colonoscopic robot.

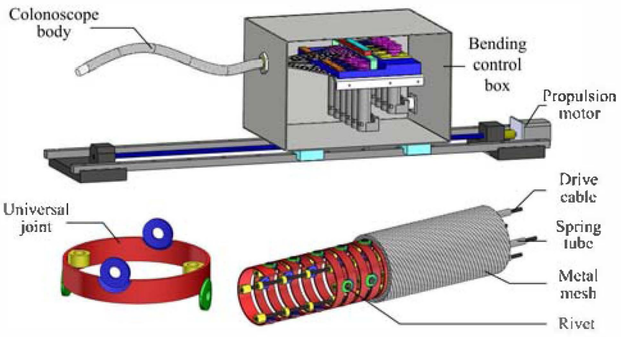


Fig. 1. Mechanical structure of colonoscopic robot

The bending control box is used to realize the coordinated motion control of these sections of the colonoscopic robot. As the colonoscope has a total of 10 DOF and is driven by 20 cables, 10 DC servo motors are needed and each is used to actuate a pair of cables. Each motor has a photoelectric encoder which can provide the real-time feedback of velocity and position. A gearbox whose reduction ratio is 231:1 is used to increase the rated torque of each motor.

In order to realize the advancement of the colonoscopic robot in the colon tract, a propulsion device is designed. It mainly consists of DC servo motor, coupling, lead screw and guide. With the drive of the propulsion device, the bending control box and the colonoscope body can move forward or backward dexterously.

B. Kinematics

The Denavit-Hartenberg (D-H) method is usually adopted to realize the kinematics analysis of traditional discrete robot. However, unlike traditional robots composed of spherical joints and rigid links, the standard D-H method is not applicable for the kinematics analysis of continuum robots which contain no prismatic or revolute joints. The structure of colonoscopic robot is a kind of continuum structure which contains no discrete links or joints, thus the kinematics analysis based on geometry analysis method instead of the standard D-H method is more concise and efficient. The kinematics transformation from base coordinate to tip coordinate can be realized by following four steps:

- translating the center O_{k-1} of base frame to the center O_k of tip frame;
- rotating the local frame around its Z_{k-1} axis for angle φ_k;
- rotating the local frame around its Y_{k-1} axis for angle θ_k;
- rotating the local frame around its Z_{k-1} axis for angle $-\varphi_k$.

Thus, the homogenous transformation matrix can be expressed by (1).

$$
\begin{aligned}
{}^{k-1}_{k}\boldsymbol{T} &= Trans\left(\frac{l}{\theta_k}C\varphi_k(1-C\theta_k), \frac{l}{\theta_k}S\varphi_k(1-C\theta_k), \frac{l}{\theta_k}S\theta_k\right)\cdot Rot(z,\varphi_k) \\
&\cdot Rot(y,\theta_k)\cdot Rot(z,-\varphi_k) \\
&= \begin{bmatrix}
c^2\phi_k c\theta_k + s^2\phi_k & c\phi_k s\phi_k c\theta_k - c\phi_k s\phi_k & c\phi_k s\theta_k & \frac{l}{\theta_k} c\phi_k\cdot(1-c\theta_k) \\
c\phi_k s\phi_k c\theta_k - c\phi_k s\phi_k & s^2\phi_k c\theta_k + c^2\phi_k & s\phi_k s\theta_k & \frac{l}{\theta_k} s\phi_k\cdot(1-c\theta_k) \\
-c\phi_k s\theta_k & -s\phi_k s\theta_k & c\theta_k & \frac{l}{\theta_k} s\theta_k \\
0 & 0 & 0 & 1
\end{bmatrix}
\end{aligned} \tag{1}
$$

Where, $S\theta=sin\theta$, $C\theta=cos\theta$, the range of the bending angle θ is $[0, \pi]$; $S\varphi=sin\varphi$, $C\varphi=cos\varphi$, the range of the rotation angle φ is $[0, 2\pi]$, and l represents the length of the section.

The kinematics transformation for 5 sections continuum robot can then be generated by the producing of 5 matrices of the form given in (1). The homogenous transformation matrix of the colonoscopic robot with 5 sections can be calculated as:

$$ {}^{0}_{5}T = {}^{0}_{1}T \cdot {}^{1}_{2}T \cdot {}^{2}_{3}T \cdot {}^{3}_{4}T \cdot {}^{4}_{5}T \tag{2} $$

III. GUIDANCE CONTROL

For more simplicity but without loss of generality, a common 2-D colon model is built according to the anatomy of human colon. The guidance control algorithm presented in this section is based on this common colon model. Yao, et al. proposed a method of curve fitting with equal length arc for NC processing[19] and Chen, et al. introduced a sensor-based guidance control algorithm for a silicone-based robotic manipulator driven by pneumatic actuators[20]; however, their guidance algorithms are limited to the single section and not applicable for the guidance control of the multiple section colonoscopic robot.

A. Bending Model of Human Colon

According to the anatomy of larger intestine, the human colon is a tortuous "tube" and about 120cm in total length. It bends like a question mark "?" with several bends such as splenic flexure, hepatic flexure and sigmoid flexure. Generally the human colon is divided into four segments: ascending colon, transverse colon, descending colon and sigmoid colon. The length of ascending colon is 12~20cm and the diameter reach 6cm. The length and the diameter of transverse colon is about 40~60cm and 5.2cm respectively; the position of this segment is easy to be changed. The same as the ascending colon, the position of descending colon is comparatively unchangeable, and its length and diameter is 25~30cm and 4.4cm respectively. The average length of sigmoid colon is 38cm and the diameter is 4.2cm. For more simplicity but without loss of generality, a simplified 2-D colon model is developed with VC++ and OpenGL. As illustrated in Fig. 2, the colon model is 120mm in length and 45mm in diameter, and whose center curve consists of lines and circular arcs.

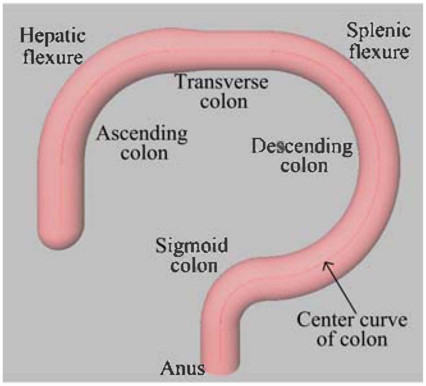


Fig. 2. Simplified bending model of human colon

B. Guidnace Control Algorithm of Single Section

As illustrated in Fig. 3, the system coordinate frame is OXY and the base coordinate frame of the single section is defined coinciding with the system frame. The parametrized equation for the center curve of 2-D model can be written as:

$$\begin{cases} x = f(t) \\ y = g(t). \end{cases} \tag{3}$$

Assuming O_1 (x_{O1}, y_{O1}) is a random point of the curve and a relative coordinate frame $O_1X_1Y_1$ is built at that point. The direction of axe Y_1 coincides with the curve's tangent at point O_1 and the direction of axe X_1 coincides with the outer normal. Based on the relative coordinate frame $O_1X_1Y_1$, the center curve is transformed as:

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} \cos\beta_1 & -\sin\beta_1 \\ \sin\beta_1 & \cos\beta_1 \end{bmatrix} \cdot \begin{bmatrix} f(t) - x_{O1} \\ g(t) - y_{O1} \end{bmatrix} \tag{4}$$

Where, β_1 represents the rotation angle from the coordinate frame $O_1X_1Y_1$ to coordinate frame OXY and can be computed as follows:

$$\beta_1 = \operatorname{atan}(y_{O1}/x_{O1}) \tag{5}$$

Note that because the coordinate frame $O_1X_1Y_1$ is a 2-D frame, the rotation angle ϕ of the colonoscopic robot is defined to 0. According to the homogenous transformation matrix from (1), we obtain the locus curve of the end point of single section:

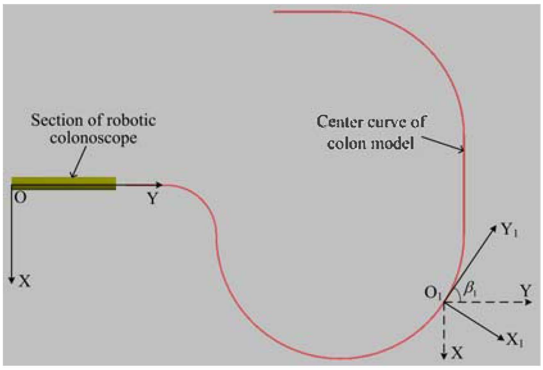


Fig. 3. Guidance control model of single section

$$\begin{bmatrix} x'_{O2} \\ y'_{O2} \end{bmatrix} = \begin{bmatrix} \pm\dfrac{l}{\theta_1}(1-\cos\theta_1) \\ \dfrac{l}{\theta_1}\sin\theta_1 \end{bmatrix} \tag{6}$$

If we adopt the relation

$$\begin{cases} x'_{o2} = x_1 \\ y'_{o2} = y_2 \end{cases} \tag{7}$$

and substitute (5) into (6), then the bending angle θ_1 of single section can be derived. As the intersection point between the center curve and the locus curve of the end point of single section, the position of O_2 with respect to the relative frame $O_1X_1Y_1$ can be obtained from (6). And its position relative to the system frame OXY can be computed as follows:

$$\begin{bmatrix} x_{O2} \\ y_{O2} \end{bmatrix} = \begin{bmatrix} x'_{O2} \\ y'_{O2} \end{bmatrix} + \begin{bmatrix} x_{O1} \\ y_{O1} \end{bmatrix} \tag{8}$$

C. Guidnace Control Algorithm of Multiple Section

Assuming the center curve of 2-D model is expressed by (3), and the start point is O_1 (x_{O1}, y_{O1}), then we can finish the guidance control of the first section using the algorithm proposed previously and obtain the bending angle θ_1 and the position of the intersection point $O_2(x_{O2}, y_{O2})$.

Similarly, the guidance control of the other sections can be realized as following steps:

First, the rotation angle β_i (i={2,3,4,5}) from the relative coordinate $O_iX_iY_i$ to the system coordinate OXY can be computed as follows:

$$\beta_i = \operatorname{atan}(y_{Oi}/x_{Oi}) \tag{9}$$

Where the point O_i (x_{Oi}, y_{Oi}) in the center curve is the start point for guidance control of the section i and the end point of the section i-1.

Second, the equation of center curve with respect to the coordinate $O_iX_iY_i$ can be written as:

$$\begin{bmatrix} x_i \\ y_i \end{bmatrix} = \begin{bmatrix} \cos\beta_i & -\sin\beta_i \\ \sin\beta_i & \cos\beta_i \end{bmatrix} \cdot \begin{bmatrix} f(t) - x_{Oi} \\ g(t) - y_{Oi} \end{bmatrix} \tag{10}$$

Third, according to the homogenous transformation matrix from (1), the locus curve of the end point of section i is expressed as follows:

$$\begin{bmatrix} x'_{O(i+1)} \\ y'_{O(i+1)} \end{bmatrix} = \begin{bmatrix} \pm \frac{l}{\theta_i}(1-\cos\theta_i) \\ \frac{l}{\theta_i}\sin\theta_i \end{bmatrix} \tag{11}$$

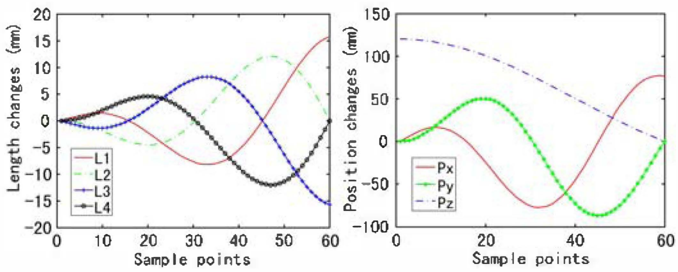
Fourth, substituting (9) into (10) and according to the equivalence of the corresponding elements of (10) and (11), we can obtain the bending angle θ_i. Then, the position of O_i with respect to the system coordinate frame OXY can be obtained by (12).

$$\begin{bmatrix} x_{O(i+1)} \\ y_{O(i+1)} \end{bmatrix} = \begin{bmatrix} x'_{O(i+1)} \\ y'_{O(i+1)} \end{bmatrix} + \begin{bmatrix} x_{Oi} \\ y_{Oi} \end{bmatrix} \tag{12}$$

Finally, as the end point of section i is the start point of section i+1, the guidance control of next section can be realized by jumping to the first step to start next loop.

IV. SIMULATION

The simulation of the single section includes the length changes of drive cables and the position changes of end-effector. At the initial state, the rotation angle, the bending angle and the length changes of each cable are equal to 0 and the position of the end point is [0, 120] (unit: mm). Define the range of rotation angle and bending angle to be [0, 2π] and [0, π] respectively, and program using MATLAB to calculate the length changes of drive cables and the position changes of end-effector according to the robot kinematics presented previously. The simulation results of single section are shown in Fig. 4.



(a) Length changes of cables (b) Position changes of end-effector

Fig. 4. Kinematics simulation of single section

In order to validate the planning and guidance capability of the colonoscopic robot, a simulation platform based on VC++ and OpenGL is developed. The mechanical model of colonoscopic robot with 8 sections is built and the simplified bending model of human colon is imported into the simulation platform. Using the guidance control algorithm presented previously, the sections of colonoscopic robot bend automatically in the advancement within the colon model and the simulation result is shown in Fig. 5. The middle point of the second section of colonoscopic robot is selected as the reference point and the position error between the trajectory of reference point and the central axis of the colon model is shown in Fig. 6. It can be seen that the movement of the colonoscopic robot can avoid contacting with the colon wall.

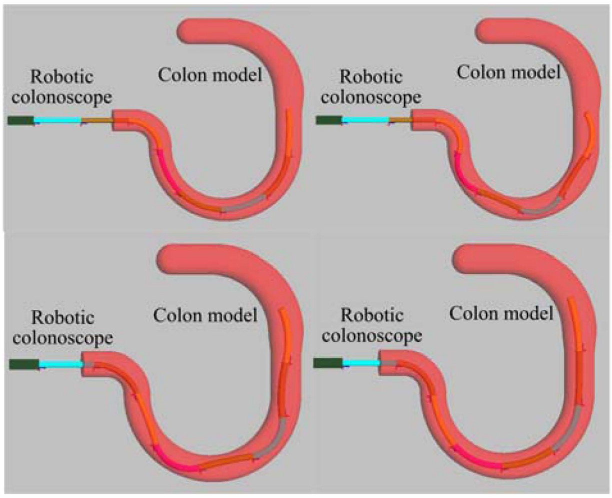


Fig. 5. Guidance control simulation

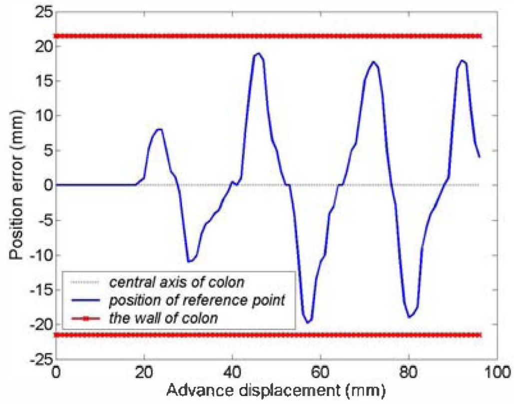


Fig. 6. Position error simulation of guidance control

V. CONCLUSIONS

According to the disadvantages of conventional colonoscope, a colonoscopic robot for colonoscopy is presented, which consists of 5 continuum sections and each section has 2 DOF and is 12mm in diameter and 120mm in length. The mechanical structure and the kinematics based on geometry analysis method are introduced. In order to achieve a semiautomatic guidance, a guidance control algorithm for multiple section colonoscopic robot has been presented based on a simplified 2-D colon model which is built according to the anatomy of human colon. The results of the simulations and the prototype experiments with a colon-like tube validated the feasibility of the system and verified the effectiveness of kinematics and guidance control strategy. The continuum robot has good potential for colonoscopy. The work of this paper laid good foundation for the semi-autonomous guide control in 3-D colon model and for the clinic application of robotic colonoscopy in the future.

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