Colonoscopy Training Simulator

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Abstract: This paper presents a new colonoscopy training simulator that includes a specialized haptic device and graphics algorithms to transfer haptic sensation through a long and flexible tube, and manage large number of polygons. The developed haptic device makes the colonoscope tube move along the two guiding rods in the translational direction. The torque of the roll motion is transferred by a timing belt and pulleys. A special guide is developed, which allows the force and torque from the motors to be transmitted to the user without loss. The haptic device is evaluated by physicians. One of the important skills of the colonoscopy, jiggling is incorporated for the first time by the developed sensor mechanism using photo-sensors. A colonoscope handle that shares the look, feel, and functions with the actual colonoscope, is developed with the necessary electronics inside. The number of polygons is reduced by an edge-collapse algorithm for real-time simulation. The algorithms to import CT data, to segment the colon image, to extract centerline of the colon, and to construct the colon surface, are integrated into a *Colon Modeling Kit* system that performs all these processes in real-time.

Keywords: Colonoscopy, medical simulation, virtual reality, haptic interface

1. INTRODUCTION

Traditional colonoscopy training requires many practices on the patients under the supervision of experts, and carries increased risks to the patients. Colonoscopy training simulator can help trainees practice the necessary skills without any risks to the patients, and supplement the traditional patient-based training to increase the overall efficiency of the curriculum. However, the simulator requires a specialized haptic interface and graphics algorithms to transfer large haptic sensation through a long and flexible tube, and manage large number of polygons of the computer model.

Ikuta et al. [1] developed a mobile system for the flexible endoscope. It provides the force and torque using friction between the tube and rubber balls that are driven by rollers. The tube should be tightly squeezed to overcome the mechanical slippage, and generate sufficient reflective forces within small workspace. This makes its transparency suffer. Interference between the translational and the roll motions are also eminent, which is generic to the mechanism. A haptic device developed by Woo et al. [2] provides decoupled 4-DOF reflective forces. The device does not provide sufficient workspace enough to simulate the colonoscopy. Körner et al. [3] developed a 2-DOF haptic device that attached the tip of the endoscope to a carriage. This mechanism has a large inertia in the translational direction, and cannot provide large torque in the roll direction for complete colonoscopy simulation. Immersion Medical [4] also developed a virtual endoscope simulator. It provides only the translational force-feedback. The reflective force is relatively small, and the response time is slow because it winds the inserted tube on a large wheel. Simbionix Ltd. [5] recently developed the GI-Mentor II that simulates both the upper and lower diagnostic and therapeutic endoscopic procedures. It generates the force-feedback by a braking system using a pneumatic balloon. This mechanism cannot generate accurate reflective forces.

The colonoscopy training simulator presented in this paper has a new 2-DOF haptic interface to provide enough and accurate reflective forces and workspaces. The device is evaluated by physicians because the clinical evaluation is integral to the success of the developed simulators. Aabakken et al. [6] presented a simple questionnaire to assess the virtual-reality-based simulator. They applied this method to evaluate the realism, complexity and usefulness of the Simbionix GI-Mentor [5], and observed that the effectiveness of the training could be discerned by testing the virtual skills in spite of the small sizes of the users.

The virtual colon model extracted from medical images consists of tens or hundreds of thousands of polygons. It is inefficient to compute collision detection and reflective forces using this massive data. Polygon reduction algorithms convert the original model into a smaller one with fewer polygons, yet similar geometric fidelity. Our polygon reduction algorithm is based on the edge-collapse [7]. A pre-computed hierarchical representation using bounding-box trees has been widely used to detect collision [8]. There are several other algorithms for collision detection such as I-Collide, Q-Collide, and V-Clip [9]. However, most of these collision detection algorithms are concerned with collision between volumetric solid objects or cloth-like surface models. Since the colon has a long and hollow inner space, they are not directly applicable. The developed simulator extracts a centerline from the virtual colon model. Collision detection and reflective-force computation [10, 11] are carried out using this centerline.

Immersion Medical and Simbionix Ltd. have commercialized the colonoscopy simulators. However, they do not simulate various scenarios of the colonoscopy because of limited patient sample. A simulator with a large number of patient cases can provide enhanced experiences of the colonoscopy to the trainees. The colonoscopy simulator presented in this paper also has a *Colon Modeling Kit* to import and process the patient CT data.

2. SIMULATOR ARCHITECTURE

Fig. 1 and 2 show the colonoscopy simulator and its configuration, respectively. The GUI (Graphic User Interface) that is built on MFC (Microsoft Foundation Classes) library and OpenGL API (Application Programming Interface) provides the endoscopic view, the position of the tip, and various help messages during the colonoscopy simulation. The colon model is constructed from the CT data obtained from real patients. As shown in Fig. 1, the graphic user interface consists of three views, i.e., model view, navigation view, and message view.

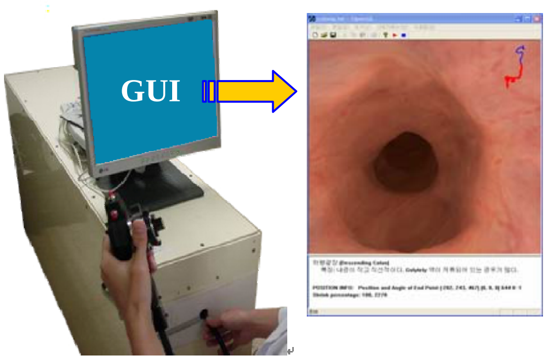

Fig. 1 The developed colonoscopy simulator.

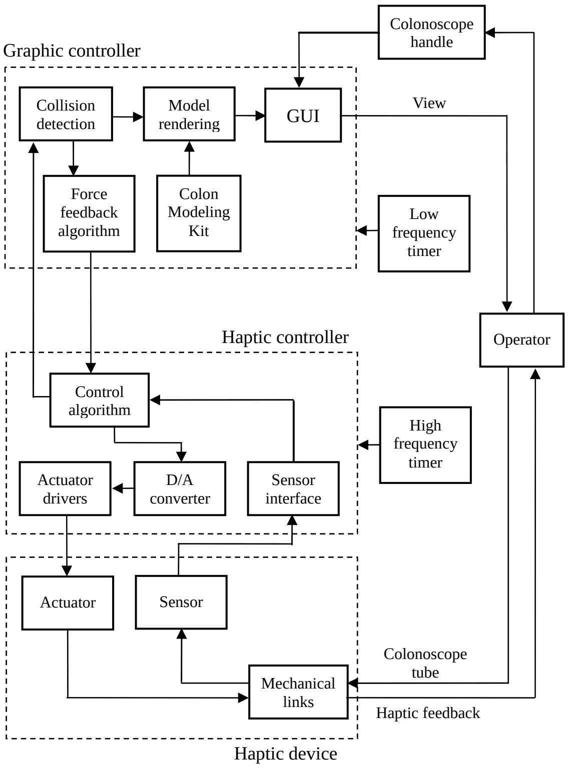

Fig. 2 Configuration of the simulator.

3. THE HAPTIC INTERFACE

Fig. 3 depicts the decoupled 2-DOF haptic device of the developed colonoscopy simulator. The translational motion is implemented with a wire-driven mechanism. The colonoscope tube, fixed on the pulley mechanism, moves along the two guiding rods in the translational direction. The torque of the roll motion is transferred by the timing belt and pulleys. Special guide is used to maintain the tube straight. This helps the force and torque generated by the motors be transmitted to the user without loss. The guide folds and expands as shown in Fig. 4. The guide panels are connected with wires so as to ease the folding motion, and endure the stretching force. The distance between the guide panels is limited to approximately 5cm to keep the tube straight.

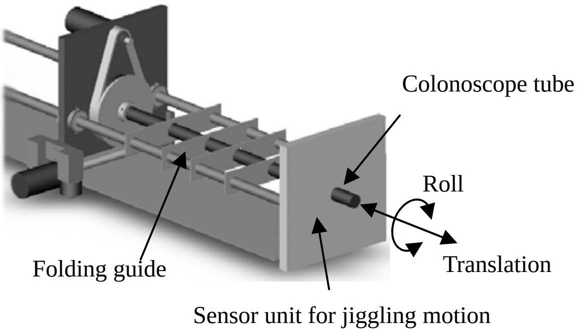

Fig. 3 The 2-DOF haptic device.

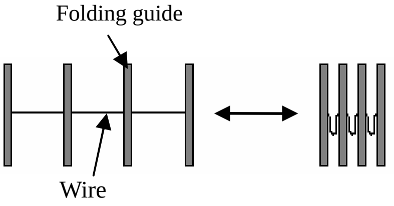

Fig. 4 The folding guide.

The continuously exertable force, maximum force, workspace, sensitivity, and inertia are the commonly used specification to measure the performance of the haptic device, and are shown in Table 1.

Table 1 Specification of the 2-DOF haptic device.

	Translation	Roll
Maximum exertable force and torque	60.25 *N*	1.028 *N*m
Workspace	98 cm	Infinite
Sensitivity	0.0139 mm	0.045°
Inertia	1100 g	$1.1\times10^5\ g\cdot mm^2$
Force bandwidth	50 Hz	57 Hz

The new 2-DOF haptic device can generate enough force and torque for the colonoscopy simulation [3]. The colonoscope tube is 160cm in length and the colon of adults is 150~160cm. If the user properly keeps the colon linear while doing colonoscopy, 80cm of the tube is sufficient to inspect from anus to cecum. The workspace of the 2-DOF haptic device is enough to simulate the entire range of colonoscopy. The average human orientational JND (Just Noticeable Difference) is 2.0° and the Cartesian JND of the hand is 1mm. It is generally recommended that the haptic device have four times higher positional resolutions than the average human JND. Table 1 shows that the developed 2-DOF haptic device has sufficient resolutions. The force bandwidth is 50Hz in the translational direction and 57Hz in the roll direction. Shimoga [12] reported that human hand can be actuated at 5~10Hz, and the haptic device should produce position and force feedback at more than 20~30Hz. Ellis [13] recommended 50Hz as the force bandwidth of the haptic device. The translational inertia is relatively large because the moving part of the device has 2 DC motors and 2 timing pulleys, and the developed mechanism also has a small friction. Therefore, a control scheme is applied to compensate the friction and inertia.

The 2-DOF haptic device is assessed by physicians. The subjects completed colonoscopy simulation after a brief introduction. The subjects are then asked to fill out a questionnaire regarding the experience. The questionnaire consists of closed-ended questions using the Likert scale. The subjects are asked to express agreement or disagreement on a five-point scale, that is, strongly disagree, disagree, neither agree nor disagree, agree, and strongly agree. Each degree of agreement is given a numerical value from one to five. The total numerical value is calculated from all the responses.

The Cronbach's α, a coefficient of reliability or consistency, is used to assess the results. It is defined as the mean correlation between each set of items, and computed as in Eq. (1).

$$\alpha = \frac{N \cdot \bar{r}}{1+(N-1)\cdot \bar{r}}. \tag{1}$$

The N is the number of items and $\bar{r}$ is the average inter-item correlation among the items. The Cronbach's α can be considered as the probability that the same result is acquired from the repeated surveys. The coefficient α can take values between 0 and 1. It is accepted that the questionnaire is reliable if the coefficient of 0.8 or higher is obtained. Table 2 shows the results of the surveys. All the subjects agree that the 2-DOF haptic device is effective and realistic for the colonoscopy simulation. The Cronbach's α is 0.8209, meaning that the questionnaire is suitable and reliable to measure the effectiveness and realism of the 2-DOF haptic device.

Table 2 Results of the questionnaire surveys.

Items	Average of responses	α
Q1. Realism of the reflective forces	3.67	0.8209
Q2. Realism of the free motion	4.33	
Q3. Sufficient workspace of the translational motion	4.33	
Q4. Realism of the tactile sense of the colonoscope tube	3.83	
Q5. Effectiveness of the 2-DOF haptic device	4.67	

Physicians sometimes jiggle the tube to get it inside the colon, and wrinkle the colon along the endoscope. This is one of the skills of colonoscopy. The sensor unit to incorporate the jiggling motion into the simulator is developed with a veil plate and 4 pairs of photo sensors as shown in Fig. 5. The photo sensors are located with particular intervals to identify decoupled directions. A crescent support plate prevents the colonoscope tube from drooping below the center. This mechanism is attached to the entrance hole for the tube. This mechanism identifies the jiggling motion of 2.5Hz and above.

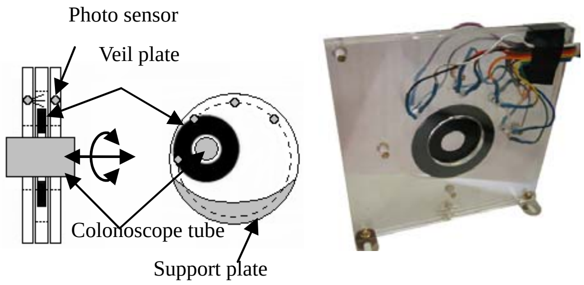

Fig. 5 The sensor mechanism for the jiggling motion.

Colonoscopy requires not only the translational and roll motions of the colonoscope tube but also the yaw and pitch motions of the tube tip to navigate the colon. A colonoscope handle is developed, which shares the look, feel, and functions of the actual colonoscope, and the necessary electronics inside as shown in Fig. 6. The user can navigate and interact with the virtual colon using the developed colonoscope handle and 2-DOF haptic device. For example, the angle knobs change the view angle of the graphics, and the relative position and orientation of the colonoscope model and the virtual colon model. The user can also simulate the suction and injection of air or water, and see the corresponding graphics.

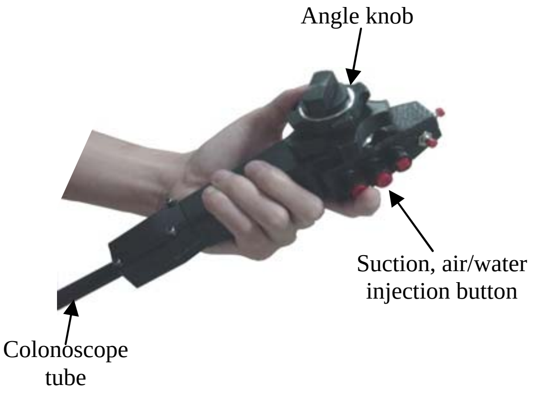

Fig. 6 The colonoscope handle.

4. GRAPHICS CONTROL

The polygon reduction algorithm converts the original model into a reduced one that has similar geometric fidelity but fewer polygons. The polygon reduction algorithm used for the colonoscopy simulator is based on the edge collapse method [7]. Fig. 7 shows the basic idea of the edge collapse algorithm. The first step is to select removable edges, and the next step merges two vertices of the edges into one vertex. This is repeated until a manageable size of the model is obtained. The removable edges are those that are relatively short in thin triangles.

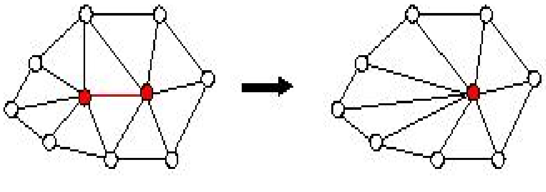

Fig. 7 Edge collapse.

The polygon reduction algorithm is applied to the colon model. The algorithm reduced the original model consisting of 55,572 vertices and 111,068 polygons to one with 18,713 and 37,382, respectively. Although the number of vertices and polygons are reduced up to 66%, the model maintains similar fidelity as shown in Fig. 8.

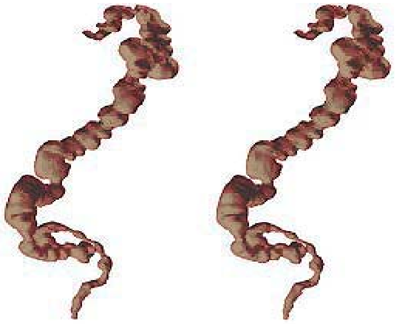

Fig. 8 Colon model before and after the reduction.

The 2-DOF haptic device simulates the translation and roll motions, and the angle knobs of the colonoscope handle simulate the yaw and pitch motions as illustrated in Fig. 9. These 4-DOF motions sufficiently allow the user to navigate the inside of the virtual colon.

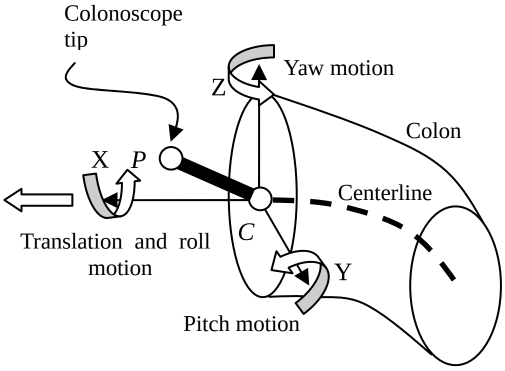

Fig. 9 Defined coordinates and motions.

The centerline of the colon model consists of numbers of nodes. Each node has its position and predefined local coordinates representing the orientation with respect to the world coordinates as shown in Fig. 10. The tip position of the colonoscope, C, that is a function of the inserted depth of the colonoscope, *s*, is determined by Eq. (2).

$$C(s) = C\left(\frac{S}{D}\cdot d\right). \qquad (2)$$

The *S* is the total length of the centerline. The *D* and *d* are the maximum and the current translational input value of the haptic device, respectively.

The tip of the colonoscope is bent in the yaw and pitch directions by rotating the angle knobs. This is reflected by the rotation of the viewpoint, *P*, around *C* within a range of fixed peak angles. Hence the viewpoint is determined by Eq. (3).

$$P = C(s) + T(s)R(\alpha,\beta,\gamma)\begin{bmatrix} l \\ 0 \\ 0 \end{bmatrix}. \qquad (3)$$

The *R* is the 3-by-3 rotation matrix determined by the roll, yaw, and pitch angles. *T(s)* is the 3-by-3 transformation matrix from the local to the world coordinates. The *l* is the length of the bendable tip of the colonoscope tube.

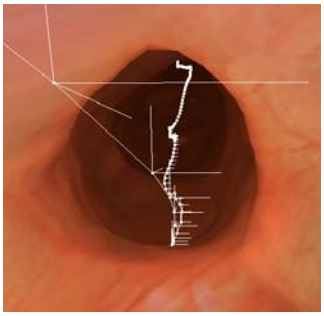

Fig. 10 Predefined local coordinates along the centerline of the colon model.

Fig. 11 shows the GUI of the developed *Colon Modeling Kit* with 4 panes. The CT images are displayed in the middle pane when the user loads and selects CT dataset. The user, then, chooses the sequential processes in the left pane as shown in Fig. 12.

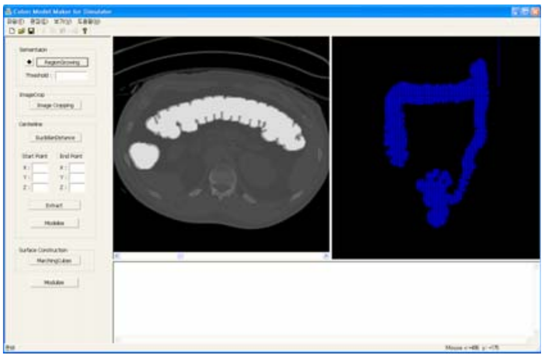

Fig. 11 GUI of the *Colon Modeling Kit*.

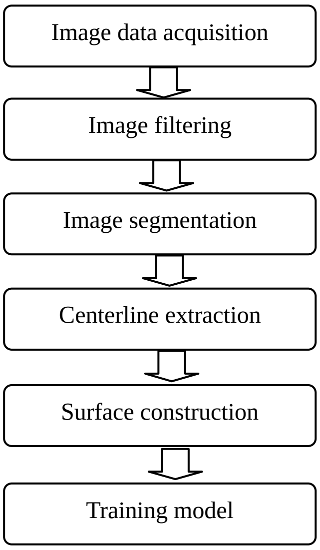

Fig. 12 Colon model construction.

Since the abdomenal CT dataset contains other internal organs and bones as well as the colon, appropriate image processing is necessary to segment the colon, and construct the 3D model. Fig. 13 shows the histogram of the CT dataset which represents the relationship between the number of voxels and the 8 bits grayscale light intensity of voxels. The first and second peaks indicate air, and the third and forth peaks correspond to the mixture of fat and soft tissues. A threshold value is derived from the histogram to identify the regions filled with air. Since only the colon interior among other internal organs contains air, segmentation of colon can be achieved using a seeded region growing algorithm [14] with the threshold value. The centerline of the colon model plays an important role in computing collision detection and reflective force. Wan et. al.'s method [15] is used to extract the centerline. The surface of the colon model is constructed by the marching-cube algorithm [16] that connects the patches from all the cubes on the iso-surface boundary. The middle pane changes to the navigation view showing the interior of the colon after the model is constructed. The right pane shows the entire colon and its centerline, and also indicates the current position of the colonoscope tip as shown in Fig. 14.

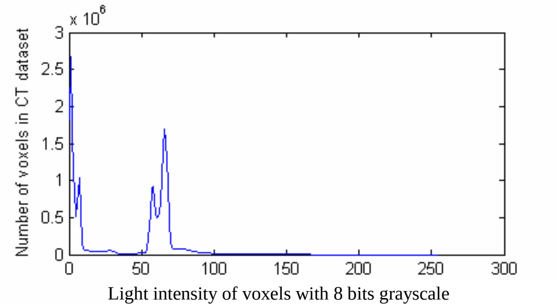

Fig. 13 Histogram: the number of voxels vs. the light intensity of voxels.

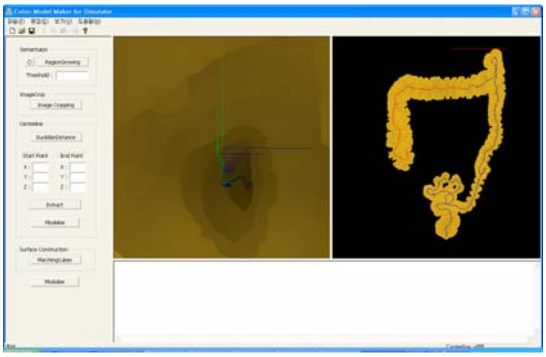

Fig. 14 GUI of the *Colon Modeling Kit* after completion of modeling.

5. CONCLUSION

A new colonoscopy training simulator is developed with the specialized haptic interface and graphics algorithms. The new 2-DOF haptic device, the jiggling sensor mechanism, and the colonoscope handle are developed to provide the user with the increased realism and fidelity of the simulation. Assessment by physicians shows that the developed devices are suitable and reliable to simulate the colonoscopy. The developed graphics algorithms enable the simulator to compute the deformation and the corresponding reflective force in real-time, and provide immersive graphics to the user. The developed *Colon Modeling Kit* allows the simulator to provide various scenarios and types of colons. The future research includes the extension of the simulator to integrate the endoscopic therapeutic procedures such as polyp removal, and clinical evaluation of the simulator for its roll in the overall curriculum.

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