DEVELOPING A NEXT GENERATION COLONOSCOPY SIMULATOR

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Colonoscopy is considered the gold standard for detection and removal of precancerous polyps in the colon. Being a difficult procedure to master, exposure to a large variety of patient and pathology scenarios is crucial for gastroenterologists’ training. Currently, most training is done on patients under supervision of experienced gastroenterologists. Being able to undertake a majority of training on simulators would greatly reduce patient risk and discomfort. A next generation colonoscopy simulator is currently under development, which aims to address the shortfalls of existing simulators. The simulator consists of a computer simulation of the colonoscope camera view and a haptic device that allows insertion of an instrumented colonoscope to drive the simulation and provide force feedback to the user. The simulation combines physically accurate models of the colonoscope, colon and surrounding tissues and organs with photorealistic visualization. It also includes the capability to generate randomized case scenarios where complexity of the colon physiology, pathology and environmental factors, such as colon preparation, can be tailored to suit training requirements. The long term goal is to provide a metrics based training and skill evaluation system that is not only useful for trainee instruction but can be leveraged for skills maintenance and eventual certification.

Keywords: Colonoscopy simulation; physically based models; photorealism; haptics; GPGPU.

1. Introduction

In Australia, colorectal cancer is the most commonly reported cancer affecting both men and women. It is the third most common cause of cancer related deaths with an increasing risk profile from age 43 onwards. Current rates indicate that one in 22 Australians will develop colorectal cancer within their lifetime, one of the highest rates in the world. Treatment and survival rates improve significantly with early detection, but unfortunately, few, if any symptoms are exhibited until the cancer has reached a relatively advanced stage. Consequently, in Australia less than 40% of
To address this problem, the Australian Department of Health and Ageing has set up a trial program which aims to improve early detection rates. This National Bowel Cancer Screening program offers Australians turning 50, 55 or 65 years of age, fecal occult blood tests (FOBT), which test for the presence of blood in the stool. Positive FOBT results are generally referred for a colonoscopy. Not only does colonoscopy offer detection and treatment of colorectal cancer, it allows removal and biopsy of precancerous colonic polyps and flat lesions. Excised tissue can then be sent for identification and histological confirmation. The procedure involves the insertion of a colonoscope (Fig. 1) into a sedated patient’s rectum, generally as quickly as patient comfort and safety allow. The gastroenterologist aims to insert the colonoscope until the tip reaches the cecum, the proximal end of the colon. It is then retracted slowly, and during this time, the colon is inspected closely for the presence of polyps and suspicious tissue. Unfortunately, colonoscopy is a difficult procedure to master with most training occurring on real patients. Studies have shown an increased frequency of minor adverse effects associated with trainee procedures and a direct correlation between adverse effects and patient reluctance to attend follow-up examinations. Training costs for gastroenterology fellows is high due to a reliance on high fidelity training settings and the longer procedure times associated with trainee procedures.

Provision of simulators for training surgical procedures has many benefits including reduced risk to patients, reduced training costs, ability to train difficult and
rare pathologies and the potential for off-patient certification. Unfortunately, existing colonoscopy simulators rate fairly low for haptic and anatomical realism and do not provide a case variety with a level of difficulty to make them useful for anything but novice training.\(^6\)

The project presented here aims to develop a next generation colonoscopy simulator by targeting the deficiencies in existing simulators through dramatic improvement of 4 key features: case complexity, anatomical and physical realism, visual realism, and haptic fidelity. Our long term goal is to provide a metric based training and skill evaluation system that is not only useful for trainee instruction but can be leveraged for skills maintenance and eventual certification.

2. Methods

The simulator consists of two primary components: A computer generated virtual environment mimicking the view the gastroenterologist normally sees during a colonoscopy procedure and a haptic interface which allows the user to interact with the virtual environment.

The virtual environment is based upon a custom developed modular multi-threaded software framework\(^7\) (Fig. 2) for surgical simulation, written in C++. It is capable of running complex simulation scenes at frequencies of up to 1000Hz. The framework is highly configurable and allows development of new components through a plug-in architecture.

Colon shape data is extracted from patient abdominal CT scans (Fig. 3) and two surface meshes of each colon are generated. The first is a low resolution mesh

![Fig. 2. Our modular simulation framework allows integration of many components at haptic rates (300–1000 Hz).](image-url)
upon which a physically based model is based, which is solved at haptic rates (300–1000 Hz). The second is a high resolution visualization mesh capturing the detail of the colonic surface and is mapped onto the physical model at rendering rates (30 Hz). The physically based model of the colon is constrained by models of the surrounding tissue and organs, and deformed through the interaction with the colonoscope model, which is controlled by the user via the haptic device. To account for the large variety in patient anatomy and pathology, a case generator has been created to provide randomized scenarios sufficient to deliver a complete training program to a high level of competence. Each step is described in more detail in the following sections.

2.1. Data acquisition

Abdominal CT colonography scans, courtesy of Dr. Richard Choi, Virtual Colonoscopy Center, Walter Reed Army Medical Center, are processed using custom software to extract geometric models of the colonic lumen (Fig. 3). The acquisition protocol for the images included ingestion of contrast agents to improve the contrast of solid-stool and luminal fluid. Air and stool/fluid regions are labeled through voxel intensity thresholding and merged. The colon is identified manually and other air filled structures are discarded. The surface of the raw binary colon image is smoothed and a marching cubes algorithm is used to extract a high density surface mesh. Successive Laplacian smoothing and quadric decimation filters are applied until a high resolution surface mesh of an appropriate density is obtained,
balancing anatomical realism and rendering performance. A lower resolution mesh is generated through further decimation of the high resolution surface mesh.

2.2. Visualization

Texture coordinates for surface texturing and shading are required to obtain realistic tissue rendering of the surface mesh. A novel technique for generation of surface texture coordinates\textsuperscript{12} creates correspondences between the colon surface and the colon centerline by tracing equipotential streamlines, generated by solving Laplace’s equation.\textsuperscript{13–15} The process results in a surface mesh with smooth texture coordinates which exhibit minimal stretching or tearing artifacts.

Realistic organ and tool visualization is obtained via an OpenGL GLSL shader pipeline.\textsuperscript{16} Triangular surface mesh texture coordinates are used to determine the position of multiple textures on the mesh surface. These include blood vessels, Perlin noise, mucus, pathology and normal mapping textures. Several render passes are required to create a complete scene comprising realistic organ and tool surfaces, soft shadows and post-process lens effects including lens flushing and camera occlusion artifacts.

2.3. Mesh mapping

The size and complexity of the physically based colon model is limited by the fact that a high solution frequency is required for accurate haptic feedback. However, for visualization, a high resolution mesh with as much detail as possible is desired. Therefore an algorithm has been developed to map the high resolution mesh onto the low resolution mesh by replacing every vertex with a mass and every connection between vertices with a spring with incorporated damping. The acceleration of each mass, due to the forces applied to it by the attached springs, is integrated using explicit Euler integration to obtain the mass position. Stability of the system is maintained by setting the solution frequency such that the time step between solutions satisfies the constraint described by Bhasin and Liu.\textsuperscript{17}
To speed up solution times and ensure the model can be solved at the required rate for haptic feedback, a solver has been developed using NVIDIA’s Compute Unified Device Architecture (CUDA)\(^8\) to leverage the parallel processing power of the graphic card’s Graphics Processing Unit (GPU).

### 2.5. Physically based model for the colonoscope

The physically based model for the simulated colonoscope is based on classical beam theory, with the colonoscope divided into a finite number of nodes and elements. We have implemented a real-time solver using a chain based approach, similar to the technique presented by Pai,\(^9\) which does not require composition and inversion of large matrices. We use an iterative approach where the current element deformation is calculated by adding the change in element deformation to the element deformation from the previous time step. At each time step the external load \(F_i^{\text{ext}}\) on the node \(n_i\) at the end of an element \(e_i\) is calculated node by node from the tip \((i = m)\) through to the base \((i = 0)\) of the virtual colonoscope by adding up all environmental contacts \(F_i^{\text{env}}\) acting on the node or downstream from it (i.e. towards the tip):

\[
F_i^{\text{ext}} = F_{i+1}^{\text{ext}} + F_i^{\text{env}}. \tag{1}
\]

Next, the internal load \(F_i^{\text{int}}\) on node \(n_i\) due to previous deformation \(\Theta_i\) of the element \(e_i\) attached to the node is calculated and subtracted from the external load \(F_i^{\text{ext}}\), expressed in the element’s local coordinate space \(C_i\), to determine the net load \(F_i\) on the node:

\[
F_i = C_i F_i^{\text{ext}} - F_i^{\text{int}}, \tag{2}
\]

where \(k\) is the stiffness of the element. Then the change in element deformation caused by the load on the node at the element’s end is calculated and added to the element deformation from the previous time step:

\[
\Delta \Theta_i = F_i/k, \tag{3}
\]

\[
\Theta_i^{\text{new}} = \Theta_i^{\text{old}} + \Delta \Theta_i. \tag{4}
\]

Finally, new nodal positions \(u\) are calculated iteratively from the base towards the tip of the colonoscope by adding the dimensions \(L_i\) of the deformed element to the position \(u_{i-1}\) of the previous node in the chain to obtain the position \(u_i\) of the node at the element’s end:

\[
u_i = u_{i-1} + L_i(\Theta_i)C_i, \tag{5}\]

\[
C_{i+1} = C_i R_i(\Theta_i), \tag{6}\]

where \(R_i(\Theta_i)\) is the transformation matrix that transforms element \(e_i\) from its undeformed state \((\Theta = 0)\) to its current state \((\Theta = \Theta_i)\).
Developing a Next Generation Colonoscopy Simulator

The colonoscope is approximated as a homogenous material, with flexural and torsional rigidity properties determined during experiments on an Olympus CF-Q160AL colonoscope. Additionally, shear and elongation are assumed to be negligible. The model includes a controllable tip, which the user controls via encoded dials on the handle of the modified colonoscope while it is inserted into the haptic device. In the model, the tip deflection angles set by the control dials are superimposed upon the deflection angles calculated from the beam formulations. Our approach provides a fast and stable technique for realistic modeling of the clinical colonoscope at haptic frequencies over 300Hz.

2.6. Physically based models for the surrounding organs

A key aspect in the training of colonoscopy is the recognition of the formation of loops (bent and looped sections) in the colonoscope. These loops generally need to be resolved before insertion of the colonoscope can progress. Their occurrence is a result of insertion technique in combination with the mechanical properties of the colonoscope and the colon, and the constraints the colon and surrounding environment apply to the colonoscope. This environment consists of structures directly attached to the colon such as the mesentery and adhesions, and other organs restricting the places the colon can move to. Currently the mesentery and adhesions, as well as the other organs, are modeled as mass-spring systems, similar to how the colon is modeled.

2.7. Haptic interface

A novel haptic device\textsuperscript{20} (Fig. 4) has been developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL) which allows insertion of an encoded clinical colonoscope.\textsuperscript{21} The device is capable of providing both linear and rotational force feedback (up to 25 N and 1 Nm respectively) and acquisition of colonoscope linear position and rotation with an accuracy of 0.2 mm and 0.18° respectively. The novel device design also allows motion in one direction with impedance in another within an unlimited workspace. Modifications to the clinical colonoscope include addition of encoders for all control handle buttons as well as optical encoders to read rotation of the control knobs and thus support modification of the tip orientation of the virtual colonoscope.

2.8. Case generation

Current commercially available colonoscopy simulators do not provide a rich, variable set of complex training cases. A static number of cases, usually with an increasing difficulty profile, are provided for selection by the trainee. Our simulation framework attempts to avoid this problem through randomized case generation. Complete cases are represented in the simulator by XML documents containing both patient and simulation data. Patient details, including gender, age, name and
body characteristics can be randomly generated using a configured set of software components. Additionally, the probability for the presence of a particular pathology is determined using population statistics for the generated patient's age and gender. A suitable colon mesh is selected and properties for the physical model, including mesentery fixations and surface properties are tuned according to factors including the patient's body mass index, age, gender as well as any randomly selected pathology. To ensure repeatability, randomly generated patient scenarios are stored after generation.

3. Results

The simulator is implemented in C++ on an Intel Dual Core Xeon PC (3.0GHz, 2 GB RAM) with an NVIDIA 8800GTX (768MB) graphics card. On the CPU solving a mass spring system of the colon with 1,872 masses took 10.6 ms. By making use of the parallel processing power of the GPU, this has improved to run at haptic rates. The high resolution colon mesh used for visualization consists of 54,000 vertices. Mapping of this mesh onto this physical model took 8.5 ms on the CPU. On the GPU the same mapping took 0.88 ms on average. It should be noted that the mapping is only required at the visualization frequency (30 Hz). The colon model supports realistic deformation behavior, such as air insufflation. The model of the colonoscope, consisting of 80 nodes and using 50 iterations per time step to ensure a stable response to collisions, is solved in less than 3 ms on the CPU. Figure 5 shows the colonoscope model, driven by the haptic device, interacting with a deformable colon model. By placing anatomically accurate constraints on the colon to simulate its attachment and interaction with its environment, it behaves naturally when interacting with the colonoscope, including causing the loop formations also observed during real colonoscopy procedures and described in literature, for example in Sato et al.22
Fig. 5. The physically based model of the colonoscope interacting in a stable fashion with a simplified deformable colon model. Loops observed in real colonoscopy procedures are also occurring naturally in our simulator. Clockwise starting top left: N loop, alpha loop, reverse alpha loop, U loop, gamma loop, splenic loop.

Figure 6 compares our visualization to a screen capture from an actual colonoscopy. Visualization effects include blood vessel texturing, red out when colliding with the colon wall, soft shadows, realistic light attenuation, specular highlights due to submucosal reflections, surface mucous and bleeding, lens distortion and flushing, and fine surface details via normal mapping.
Fig. 6. A comparison of (a) an actual colonoscopy and (b–d) our simulated colonoscopy, including (b) blood vessel texturing, specular highlights due to submucosal reflections, surface mucous, (c) surface bleeding caused by tool interaction and (d) pathology texturing (simulating a case of ulcerative colitis and poor bowel preparation).

4. Discussion and Conclusion

The project presented here aims to develop a next generation colonoscopy simulator which has the potential to provide a real alternative to on-patient training, by improving the deficiencies in existing simulators through dramatic improvement of 4 key features: case complexity, anatomical and physical realism, visual realism, and haptic fidelity. Expert gastroenterologists have already rated our visualization
Developing a Next Generation Colonoscopy Simulator

and anatomical realism as a significant improvement over existing simulators. Using the GPU to solve the complex physically based models of the colonoscope, colon and surrounding organs and their interaction allows us to provide accurate physical realism at interactive rates. This includes the natural occurrence of loop formations in the colonoscope resulting from the physical interaction with the colon, rather than resorting to predicting and then mimicking the occurrence of loops based on an assessment of parameters such as insertion depth of the colonoscope versus actual position within the colon. This accurate physical behavior affords generation of an endless number of training scenarios where the simulator will always provide a natural haptic response to the user’s input.

An evaluation trial of the system is planned in collaboration with the Queensland Health Skills Development Centre at the Royal Brisbane and Women’s Hospital, upon completion of our first prototype. Using expert gastroenterologists, the trial will assess medical impact and relevancy as well as comparisons to existing simulators. Once the prototype reaches its final stages, an extensive trial is planned to provide a quantitative assessment of the simulator’s impact on training outcomes. This will involve the comparison of the competencies of two trainee cohorts, where the training program of only one of the two cohorts will have included training on our simulator. This extensive assessment will form part of the commercialization process of the simulator and hence is expected to extend over the next 3 years.

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References


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