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Haptic Display for a Virtual Reality Simulator for Flexible Endoscopy

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Abstract

A simulation system for flexible endoscopy is described, based on virtual reality techniques. The physician moves the flexible endoscope inside a pipe, in which forces are applied to it. In addition the navigation wheels provide force feedback from the bending of the endoscope's tip. The paper focuses on the special purpose haptic display which actively generates forces to model the complex interaction of physician, endoscope and patient with high accuracy. Moreover fast algorithms for the force simulation in real-time are presented.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [User Interfaces]: Haptic I/O

1. Introduction

In medicine, minimally invasive procedures like endoscopy play an increasing role in interventional treatment. Endoscopic devices for gastroscopy and colonoscopy are flexible tubes that are inserted into the digestive system. They are equipped with an optical channel to transmit an image to a video display. For navigation, the physician can bend the tip of the endoscope in two orthogonal directions by small wheels attached to the head of the endoscope. Below the three parts of an endoscope are called tip, tube and head (see Figure 1).

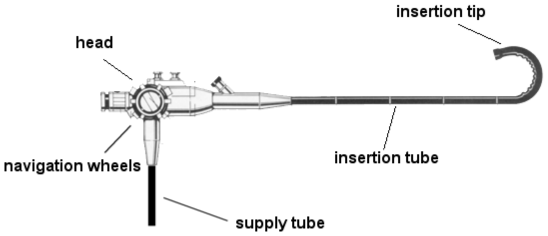

Figure 1: *Schematic setup of an endoscope.*

Due to their limited and constraint environment, minimal invasive procedures are a particularly suited testbed for the development of virtual reality systems that allow to train these procedures in a simulation. The first system of this type developed in our lab allows a virtual eye surgery[5]. The basic technologies developed there were real-time optical tracking of multiple objects, real-time stereo computer graphics, and real-time biomechanical simulation of biological tissue and the interaction with it (e.g. cutting). This system did not use force feedback since the surgeon does not feel forces during the operation.

Based on this experience and using these technologies we began to develop a system for training of flexible endoscopy in 1999. The most important difference is that the doctor feels active forces. After the endoscope has been inserted into a device representing the patient, such forces can be applied to move or rotate the endoscope's tube and to rotate the two navigation wheels. Using a biomechanical model of a patient, these forces are computed in real-time as well as the monitor images that the physician would see during the real endoscopy. This system allows the training of doctors by means of software and the force feedback device only.

First, we describe recent research projects, followed by our approach. Section 4 contains the design of the haptic display, Section 5 algorithms for the force simulation and Section 6 technical details of the implementation.

2. Force Feedback during an Endoscopy

The limited view during endoscopic procedures forces the physician to use haptic clues for orientation. When passing flexures for example, the tip of the endoscope is bent and thus a force can be realized at the navigation wheels on the head of the endoscope. It is important to note that this force is active, i.e. if unhanded, the wheel will turn by itself and thus requires a motor that generates the realistic force feedback. This has to be distinguished from a situation where the doctor applies a force against a resistance as it is the case, e.g., if the endoscope is moved against friction. Here, the movement stops when the force is removed, and force feedback can be realized by brakes only.

Another example for the role of haptics during a colonoscopy is the detection of tension in the endoscope by an increasing force on the navigation wheels (this could be realized using brakes). If the physician is not reacting properly, the endoscope may be partly pushed off the colon (this must be realized using a motor).

So a brake based force feedback system for simulated endoscopy is only capable of generating part of the effects encountered by a doctor. The simulation of particularly difficult situations that require a precise action of the doctor requires a motor based force feedback device. Since a virtual reality simulation system will be used to train complicated situations, we focused on the development of haptic displays with active force feedback to model these subtle yet very important haptic clues.

3. Previous Work

Some research has been done in the area of simulators for endoscopic procedures. We will restrict to recent attributions for the development of computer-based simulators:

In 1991 A. Poon published his doctoral thesis[4] about real-time simulation of colonoscopy. He developed a dynamical model to simulate the behavior of the endoscope in the colon.

A group at the Georgia Institute of Technology developed a simulator for gastroscopy[3]. Static force feedback on the tube of the endoscope has been realized using an anatomically formed pipe in which the endoscope is inserted.

Immersion Medical (see http://www.immersion.com earlier HT-Medical Systems) has built a simulator for different endoscopic procedures: flexible bronchoscopy, flexible sigmoidoscopy and colonoscopy. Force feedback is realized using mechanical brakes acting on the tube of the endoscope.

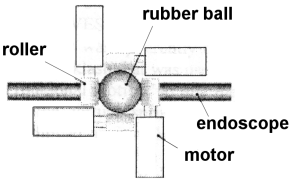

Figure 2: *Force feedback on the endoscope's tube from Nagoya University.*

The University of Nagoya developed some haptic displays for the tube of the endoscope[12]. In the actual version forces are applied to the endoscope's tube by a rubber ball. The rubber ball is driven by several rollers, which are connected to motors (see Figure 2). In a diagram about the force ability are 8N the maximal translational force.

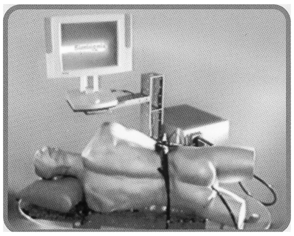

Figure 3: *GI-Mentor from Simbionix.*

The most advanced system, GI-Mentor (see Figure 3), was developed by Simbionix (see http://www.simbionix.com) Ltd. in 2000 and is commercially available. The force feedback is realized by pneumatic brakes acting on the tube of the endoscope.

All these systems except the one from Nagoya University only use frictional forces to brake the motion of the endoscope and thus are not able to produce realistic forces as the doctor feels at the endoscope itself and the control wheels. The system from Nagoya University uses the friction of rubber wheels which we found not sufficient to transmit high enough forces due to mechanical slippage (see Section 4.1). To our knowledge, there does not exist any system with force feedback on the navigation wheels so far.

4. Haptic Display

The term haptic display implies that the human sense of touch is to be stimulated, e.g. by a tool handle. In our case the tool handle is the endoscope.

A flexible endoscope is twistable and has many degrees of freedom. However one can neglect the true state of the endoscope, as long as the endoscope as a tool handle stimulates the user in the wished way. The degrees of freedom can be reduced to:

- Translation of tube
- Rotation of tube
- Bending of tip in local X direction (which turns the respective navigation wheel)
- Bending of tip in local Y direction (which turns the respective navigation wheel)

Thus the haptic display must generate forces in four degrees of freedom. In the following we describe the force generation on the tube and the tip of an endoscope.

4.1. Force Feedback on Tube of Endoscope

A realistic simulation requires that the doctor feels correct forces at the endoscopes head and the navigation wheels. The shape of the endoscope's part inserted into the patient, including the position of the tip, is of no interest as long as realistic forces are generated. The tube of the endoscope can neither be compressed nor twisted along its axis. Thus translational and rotational forces can be applied at any position of the endoscope's part inserted into a straight pipe. One way to generate the translational force on the tube is with rubber wheels on the insertion point of the endoscope like K. Ikuta[2]. He reports about a translational force up to $8N$. However to generate sufficient translational forces ($> 20N$) on such a small contact area, one has to squeeze the tube strongly to overcome the mechanical slippage, which results in spoiling the tube and a too high friction in the forceless mode.

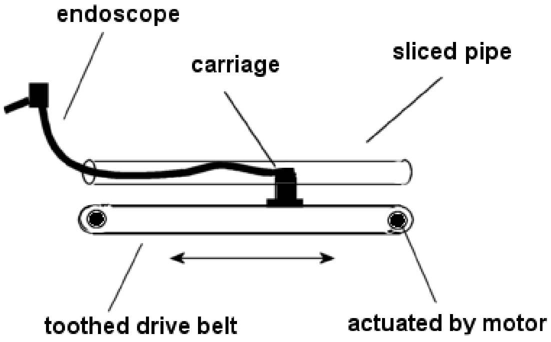

Figure 4: *Force feedback on the endoscope's tube.*

We attached the tip of the endoscope to a carriage connected to a toothed drive belt (see Figure 4). The drive belt is actuated by a motor. The endoscope is threaded through a slitted pipe to prevent shifting aside. Thereby one obtains a closed force transmission that allows generating of sufficiently high translational forces on the endoscope without slippage. On the carriage torques can directly be transmitted with a motor to the tip of the endoscope.

The threading of the endoscope trough the pipe makes it impossible to use a real endoscope, since there is no place anymore for bending the tip. One has to rebuilt the tube of the endoscope and attach it to the carriage.

4.2. Force Feedback on Tip of Endoscope

The "endoscope" used in the simulation system does not use a mobile tip, it is fixed (see Fig. 4). The forces generated by movements of the tip could be applied by motors directly on the navigation wheels. However with bowden wires (respectively twines) for force transmission one can avoid to place motors in the small cavity of the head of the endoscope (see Figure 5). The wires/twines are twisted around threaded bolts to link the wheel with the motor via the supply tube.

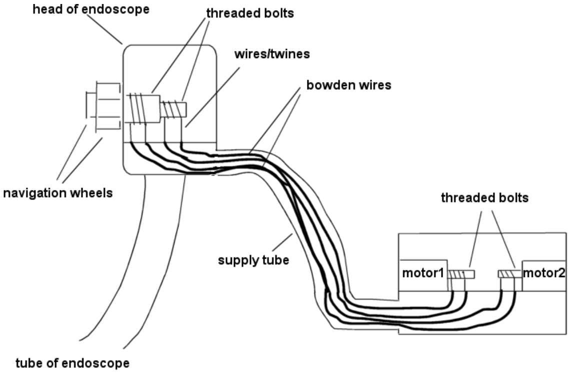

Figure 5: *Force feedback on the navigation wheels.*

The force transmission in a real endoscope works in the same way. When the tip of the real endoscope collides with the wall of the colon, the repulsive force is transmitted by the wires to the navigation wheels. Therefore with the use of bowden wires one already gains a realistic damping and latency on the wheels for free, that alternatively would have to be simulated.

5. Haptic Rendering

For the force calculation one needs a biomechanical simulation of the endoscope in the colon. There are two contrary approaches[6]:

Physical modelling using physical laws and physical parameters to model the functionality of the process.

Descriptive modelling using free parameters to obtain a desired behavior.

A. Poon[4] presents an algorithm for the biomechanical modelling of the endoscope in the colon. He uses an implicit function for the representation of endoscope and colon and considers all contact points of the endoscope with the colon, which is a very time-consuming process. A similar model with multi contact calculation is used by K. Ikuta[2] to calculate the translational and rotational forces acting on the endoscope's tube.

Both use descriptive models without any physical parameters. In order to cope with the real-time demand we present a descriptive model as well. But in contrast to the others, we regard only collisions of the tip with the colon and the curvature of the colon, since collisions between tube and colon are integrated in reality as well.

In the following, we first describe the collision detection of the tip and then the force calculation on tube and tip.

5.1. Collision Detection/Response

With the inclusion of haptics to the virtual environment, one combines the continuous real and the discrete virtual world.

As in computer graphics, one usually detects a collision of virtual objects, when they already penetrate each other. But, one can not simply shift the position of the objects in computer haptics, since at least one object corresponds to the tool handle in the real world. Therefore, one has to distinguish between the visual and the real position of the objects. It is necessary to determine the surface-contact-point, e.g. with the god-object-algorithm from C. Zilles[7]:

1. regard triangles as planes
2. specify planes between new and previous position
3. clip each plane to its triangle
4. calculate surface-contact-point at closest triangle

In edges and corners the algorithm has to be repeated with the new position and the previous calculated one. The distance between the real position and the surface-contact-point quantifies a static repulsive force vector $\vec{F}_{rep}^{static}$.

5.2. Translational Repulsive Force on Tube

The translational repulsive force F_{rep} on the endoscope is calculated from the static repulsive force F_{rep}^{static} by the collision response of the tip and a dynamic repulsive force F_{rep}^{dyn} by the friction of the endoscope in the colon.

Friction will mostly occur in bends due to the stiffness of the tube. Thus, bending of the endoscope in the colon is a measure for the expected friction. Supposing the course of endoscope and colon are roughly the same, a first approximation of the friction can be done by integrating the curvature of the colon up to the tip of the endoscope. The curvature C is a measure of the local variance of a curve $\vec{r} = \vec{r}(s)$ from a straight line:

$$C(s) = \left| \frac{d^2\vec{r}}{ds^2} \right|$$

Assuming a lubricant friction of the endoscope in the colon, the friction is proportional to the velocity v and the normal force. Since the normal force increases with the bending, the repulsive force F_{rep}^{dyn} is approximately proportional to the velocity v of the translation and the integration of the curvature along the course of the colon:

$$F_{rep}^{dyn} \sim v \int C(s) ds = v \int \left| \frac{d^2\vec{r}}{ds^2} \right| ds$$

Moving from continuous integral to a discrete summation we get

$$F_{rep}^{dyn} \sim v \sum \left| \frac{\Delta^2\vec{r}}{\Delta s^2} \right|$$

and for equal delta

$$F_{rep}^{dyn} \sim v \sum_i |\vec{r}(i) - 2\vec{r}(i+1) + \vec{r}(i+2)|$$

Furthermore the curvature can be used to deform the course of the endoscope/colon. Most parts of the colon are fixed in position relative to each other. Only the sigmoid and transverse colon are mere limited by their connections to the mesenteries.

We have not considered a calculation of the torque on the tube here, since it is not that relevant during a colonoscopy as it is during a gastroscopy.

5.3. Torque on Navigation Wheels

A repulsive torque on a navigation wheel can have two reasons: it is either an indication for (A) a bending of the tip due to a collision with the colon, or an indication for (B) a strong bending of the tube of the endoscope, which often occurs when the endoscope is about to form a loop.

A) The repulsive torque T_{rep} on the navigation wheels is proportional to the projection of the static repulsive force vector $\vec{F}_{rep}^{static}$ to the viewing direction $\vec{n}_{tip}$ of the tip of the endoscope:

$$T_{rep}^{collision} \sim \vec{n}_{tip} \cdot \vec{F}_{rep}^{static}$$

B) The navigation wheels are connected by wires to the tip of the endoscope. An acute bending of the tube extends the outer wire and therefore generates a torque on the tip and the navigation wheels (see Figure 6).

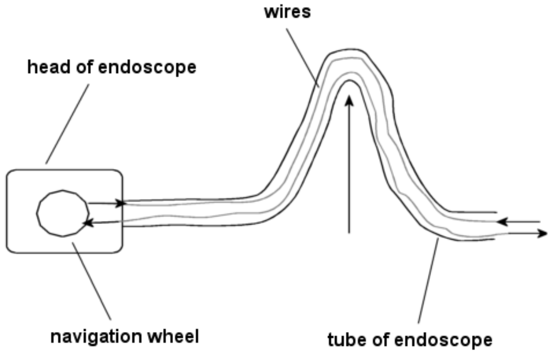

Figure 6: *Acute bending of endoscope causes tension on navigation wheels.*

The length L of a wire can be calculated by

$$L = \int \left| \frac{d\vec{r}}{ds} \right| ds$$

Then the difference in the length of the two wires becomes

$$\Delta L = \int \left[\left| \frac{d\vec{r}_1}{ds} \right| - \left| \frac{d\vec{r}_2}{ds} \right| \right] ds$$

Since, $\left|\frac{d\vec{r}}{ds}\right| = \frac{d\vec{r}}{ds} \cdot \vec{n}_{dir}$ with $\vec{n}_{dir}$ as the normalized direction vector and $\vec{n}_{dir_1} = \vec{n}_{dir_2} =: \vec{n}_{dir}$ we get

$$\Delta L = \int \vec{n}_{dir} \cdot \left[\frac{d\vec{r}_1}{ds} - \frac{d\vec{r}_2}{ds}\right] ds$$

If we express $\vec{r}_1 - \vec{r}_2$ by $\Delta r * \vec{n}_{wires}$, where Δr is the distance and $\vec{n}_{wires}$ the normalized direction between the two corresponding points on the wires, we get

$$\Delta L = \Delta r \int \vec{n}_{dir} \cdot \frac{d\vec{n}_{wires}}{ds} ds$$

Moving from continuous integral to discrete summation results in

$$\Delta L = \Delta r \sum_i \left[\vec{n}_{wires}(i+1) - \vec{n}_{wires}(i)\right] \cdot \vec{n}_{dir}(i)$$

The repulsive torque is proportional to the difference in the length of the two wires.

$$T_{rep}^{tension} \sim \sum_i \left[\vec{n}_{wires}(i+1) - \vec{n}_{wires}(i)\right] \cdot \vec{n}_{dir}(i)$$

In the computer model, the direction $\vec{n}_{wires}$ between the two corresponding points on the wire can be calculated by incrementally rotating an initial vector according to the curvature.

The repulsive torque on a navigation wheel consists of the sum of $T_{rep}^{collision}$ and $T_{rep}^{tension}$. Fine tuning by a physician is still necessary to quantify these effects.

6. Implementation

The simulator uses the same polygon mesh for graphic and haptic rendering. Similar to the portal technique in game engines only the necessary parts of the colon are rendered (see screenshot in color section).

The system is work in progress. Figure 7 shows the current prototype of the force feedback device for the tube.

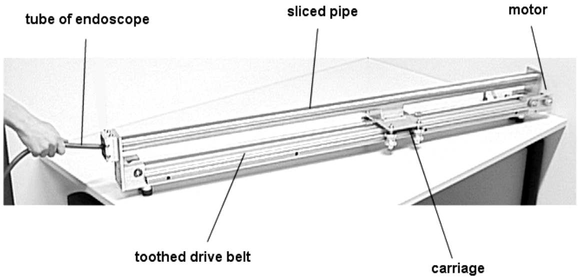

Figure 7: *Haptic display for the endoscope's tube.*

The actuators have to be carefully chosen. Usually brushless motors are more powerful than brushed motors. When using in standstill brushed motors have the disadvantage that only part of the coil holds the current and they overheat faster. But a brushless motor needs a more complex control especially when used in standstill.

For a realistic force interaction, translational force should be more than $20N$. With a radius of $1.5cm$ on the gearwheel, this results in a necessary motor torque in standstill of $0.3Nm$ and higher.

We choose a brushless DC motor for the translational force, controlled by the PC via USB.

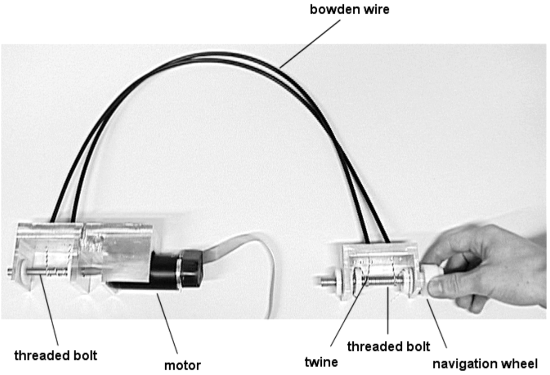

Figure 8: *Force transmission for a navigation wheel.*

Figure 8 shows a prototype of the force feedback device for the navigation wheel. Here, we use brushed DC motors with a maximal torque of $0.1Nm$, which is sufficient. The motors are controlled by the PC via RS232 serial communication.

The update rate so far is around $100Hz$, which is sufficient, since there are no stiff walls and no need for high position accuracy.

7. Results

We have proposed the design of an active haptic display for the tube and the tip of a flexible endoscope and its implementation. As well we presented the necessary algorithms for a real-time force calculation by investigating the mechanical behavior of the endoscope in the colon and estimated the emerging forces during an operation.

8. Conclusion and Future Work

All necessary technical parts for the simulator with a sophisticated haptic display are now available. The next step thus is to fill the simulator with the medical content, i.e. different pathologies and training modules. Then, an evaluation of the simulated effects has to occur. Therefore we intend to precalculate the behavior of the tube of the endoscope in the colon in relevant situations with the finite-element-method and physical parameters to fine tune our haptic rendering algorithms.

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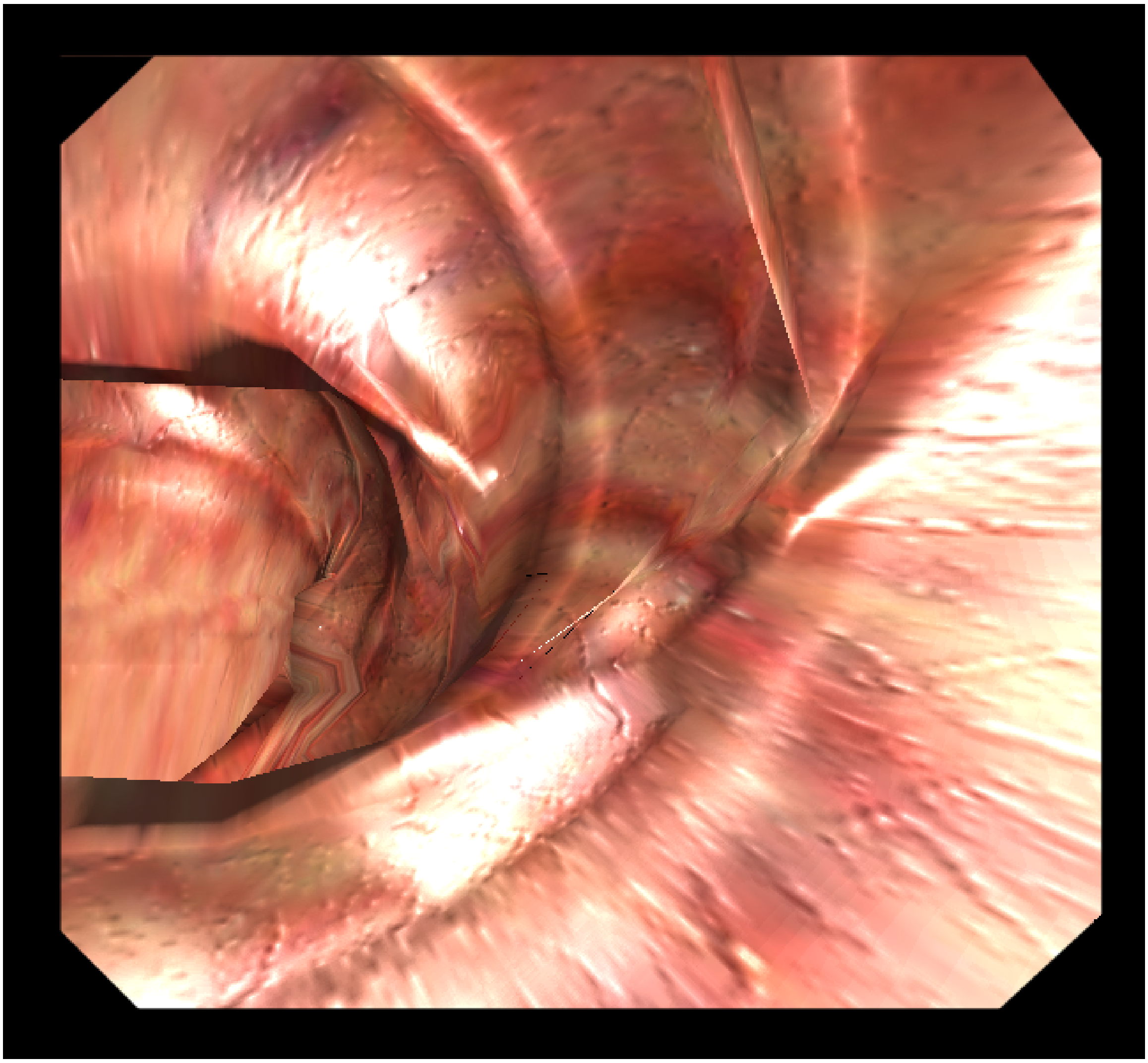

Figure 9: *Screenshot of the monitor image of the virtual reality simulator for flexible endoscopy.*