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Instrumentation of a Clinical Colonoscope for Surgical Simulation

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Abstract—**This paper describes the instrumentation of a clinical colonoscope needed for a novel colonoscopy simulation framework. The simulator consists of a compact and portable haptic interface and a virtual reality environment to provide real-time visualization. The proposed instrumentation enables tracking different functions of the colonoscope while keeping the ergonomic unchanged.**

I. Introduction

COLONOSCOPY is a minimally invasive endoscopic procedure where the colon of the patient is examined. This technique is performed with a colonoscope, which is a long flexible tube with integrated vision system at the tip. Figure 1 shows the different components of such an instrument. Colonoscopy is addressed to patients complaining of rectal bleeding or unexplained abdominal symptoms, but also as a regular check-up for patients with a risk of developing colon cancer. Colonoscopy allows visual screening of ulcerations and bleeding, but also biopsy, diagnosis and removal of pre-cancerous polyps.

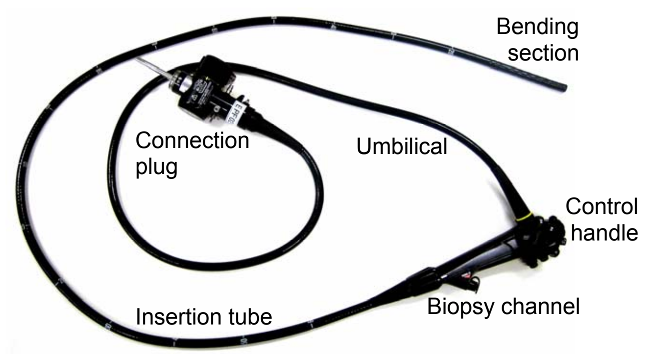

Figure 1: A typical clinical colonoscope (Olympus Corporation, Center Valley, PA). Insertion tube is guided through the colon while the bending section (the tip of the insertion tube) is controlled by the handle. CCD camera and air/water/suction systems are connected to the source by the umbilical and the plug.

During this procedure, the insertion tube of the colonoscope is introduced and guided through the colon from the rectum to the cecum. The colonoscope supports insufflation of air from the tip to expand the colon as well as suctioning of air and obstructing fluids such as blood and mucous. Suspicious tissue and polyps can be removed by using the biopsy channel. The procedure is completed with a slow withdrawal of the insertion tube, ensuring all surfaces and folds are examined carefully [1].

Colonoscopy is a complex procedure performed by highly trained and experienced physicians and requires subtle control of the endoscope during navigation in order to minimize forces. However, it presents moderate risk of colonic perforation to the patient. Thus, training of colonoscopy procedures becomes crucial with the increase of colon diseases. In addition, there is a growing need to screen as a preventative measure. In order to facilitate this training, several solutions may be considered. Practicing on animals or cadavers for instance is of limited effectiveness. Tissue properties and anatomy are different and certain pathologies are rare. A more ethical alternative to the previous one is provided by computer-assisted training systems with virtual reality (VR) visualization and haptic feedback. This approach offers also flexible and repeatable scenarios without risk to the patient.

Recent studies [2-6] have focused on simulation modeling and visualization of colonoscopy with haptic feedback. The outcome of some of these studies is a set of commercial devices [7-9]. However, the main drawbacks of existing simulators for a realistic simulation are: 1. the absence or a weak force feedback [2, 4, 8], 2. the impossibility to remove the colonoscope from the simulator [4, 6], and 3. the coupling of the translational and rotational force feedbacks [7, 9].

In our previous work, we have proposed a differential drive to decouple translation and rotation and a high friction belt to ensure the required forces and the absence of slippage. Although the proposed device was able to render high forces, compactness and portability requirements led us to consider a new device.

To address the need for higher fidelity and complexity in a colonoscopy simulator, we have designed a new haptic interface [10] to integrate it with the software simulation framework for colonoscopy (MILX^{TM} GastroSim) [11]. We propose a device consisting of a standard clinical colonoscope with two customized optical sensors incorporated. The optical sensors are based on analog output encoders. The resulting device permits to train with a very realistic tool in the proposed colonoscopy simulation.

Modules of the simulator are presented in detail in the next subsections. Conclusions and outlook will follow.

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II. COLONOSCOPY SIMULATOR

We have developed a framework for colonoscopy simulation called GastroSim [11] enabling a multi-threaded simulation environment to be interfaced with a real-time colonoscopy haptic device [10]. Figure 2 shows the modular components of the framework, such as virtual reality, haptic interface and data acquisition & control. These components are detailed in the next subsections.

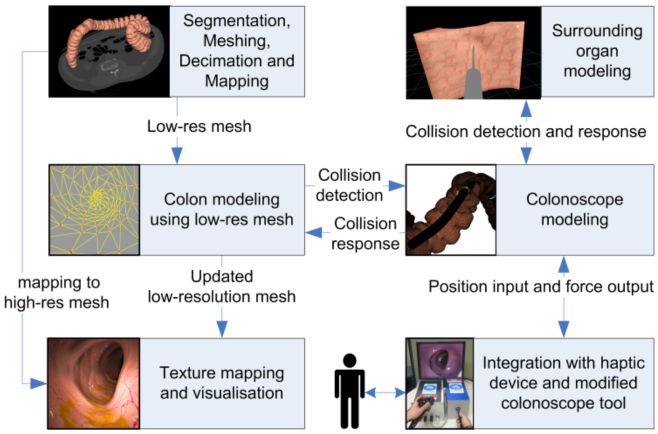

Figure 2: MILX[TM] GastroSim Simulator Framework providing integration between all areas of research.

A. Virtual Reality

GastroSim framework includes a rendering environment with a high degree of realism and an accurate lighting model. Figure 3 illustrates the realism of the simulator (b) compared to a snapshot of a real colon (a). General-purpose computing on graphics processing units (GPGPU) is used to create realistic physical models of the colon and surrounding organs. Life-like texturing is applied to a decimated mesh of the colon that is mapped to a high-resolution mesh on the GPU for real-time visualization.

(a) (b)

Figure 3: Visual Realism: (a) A snapshot from a real colonoscopy session, (b) Simulated colonoscopy.

B. Haptic Interface

The haptic interface acquires position of the colonoscope and provides force feedback in linear and rotational directions. Figure 4 shows the proposed haptic device and components. Combined electrical motors and passive brakes are used to cover a large range of forces. Estimated forces and torques for a procedure performed with a regular size colonoscope are in range of about ±44N and ±1Nm respectively [12]. DC motors are used to simulate the natural friction of the colonoscope when inserting through the colon. A powder brake and a mechanical brake are used if respectively torques or forces applied on the colonoscope are too strong to be maintained by the motors. The haptic interface provides 75N maximum translational force and 1Nm maximum rotational torque. This novel design allows motion in one direction while impeding the other. The interface has an unlimited linear and rotational workspace and the tool insertion and removal are also possible.

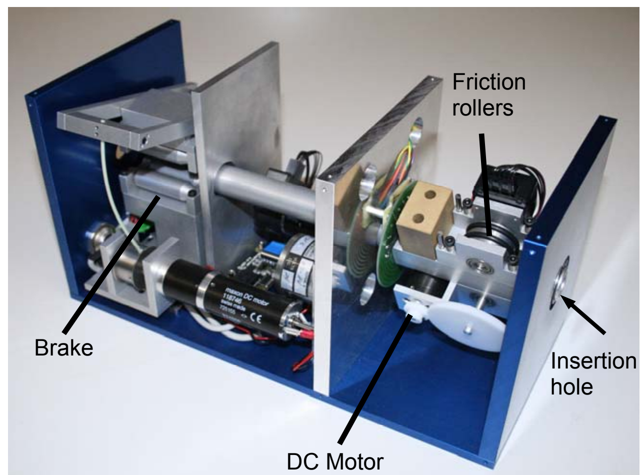

Figure 4: 2-DOF Haptic Interface: Friction rollers tracking the linear displacement of the colonoscope and imposing linear force feedback, DC motors for active force feedback and friction compensation, and brakes for high force rendering.

C. Data Acquisition & Control

Haptic interfaces for surgery simulation require a compact real-time system with sufficient precision for online control and data acquisition. A Linux based USB-port data acquisition card, USBDUX, with USB2.0 communication is used for I/O between a PC running Linux and the device. The card has four D/A and eight A/D channels with 12-bit resolution. The D/A channels are used to drive the motor/brake system through four amplifiers (Maxon 4-Q-DC Servoamplifier LSC) working in current control mode. In addition, all the functionalities of the colonoscope are tracked by the A/D channels. For position data acquisition via quadrature encoders, a USB-based card (Phidget Encoder) is connected in parallel to the data acquisition card by a USBHUB. Two optical position encoders for linear and rotational displacements are tracked individually by the Phidget encoders. This USB-based data acquisition and control approach allows transmission at haptic rates with a plug-and-play solution [13].

III. COLONOSCOPE

In order to provide the same ergonomics as in an actual procedure, an original clinical colonoscope, Olympus CF-140L (Olympus Corporation, Center Valley, PA), is integrated into the simulation framework. The instrument has been modified to be able to track all the functions of the colonoscope. Special focus has been given to robustness, durability and ergonomics of the instrument.

A. Functions

A typical colonoscope control handle (Figure 5) is designed with an Up/Down (U/D) and a Right/Left (R/L) angulation knobs enabling positioning the tip of the insertion tube (Figure 1).

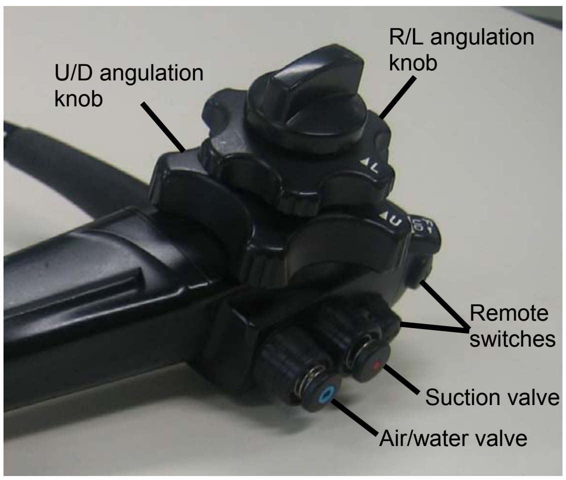

Figure 5: Main functions of the colonoscope handle.

The Up/Down (U/D) and Right/Left (R/L) angulation knobs actuate two gears, which bend a section of the insertion tube. The knobs are mechanically limited to 360 degrees of rotation resulting in ± 180 degree angulation of the bending tip in both xy and yz planes (Figure 6). A set of remote switches for video display control in real time, air/water valve and suction valve are also present on the control handle.

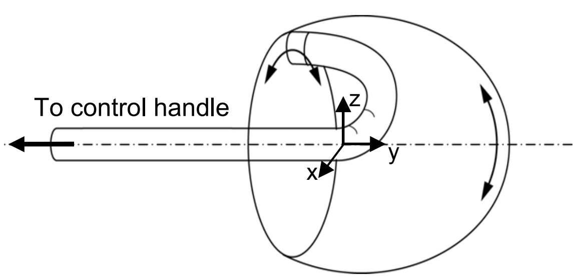

Figure 6: Workspace of the bending section. The tip can cover the partial ellipsoid surface.

Based on these existing functions, the aim is to provide tracking of the colonoscope bending tip position when actuating the angulation knobs as well as the air/water and suction valves and switches. We have assumed that there is no need of force feedback on the knobs as long as the mechanical actuation of them is maintained. This assumption is consistent with the fact that many physicians will not notice force feedback on the angulation knobs. In this case, stiffness force seems to be higher than that resulting from the contact with intestinal wall.

B. Proposed design

Instrumentation has to be performed with minimal modification of the tool in order to maintain the practice as realistic as possible. Several functions of the actual colonoscope are unnecessary in simulation as they are considered in the virtual reality. This is the case of the air/water and biopsy/suction channels, CCD signal cables and the light guide bundles. The volume available inside the handle of the colonoscope after removing the above mentioned functions is ($45x30x18mm^3$). This volume is sufficient for the integration of sensors.

The proposed design consists of two customized optical sensors based on analog output encoder (AEDR-8320, Avago Technologies) that employs optical reflective technology coupled with metal codewheel (HEDS-5120-A, Avago Technologies) making the solution space-saving. Figure 7 shows a schematic of the integration principle. Sensors are placed on each side of the gears actuating the bending tip so that mechanical function and therefore the feeling while actuating the angulation knobs remain unmodified. The first sensor is placed inside the tool and points to the U/D angulation knob. A customized codewheel (modified inner diameter) is fixed on the U/D knob. The second sensor tracks the gear actuated by the R/L knob.

The tracking of the air/water and suction valves is provided by on/off switches. Signals are sent to the data acquisition card through the existing umbilical, though the connector had to be replaced.

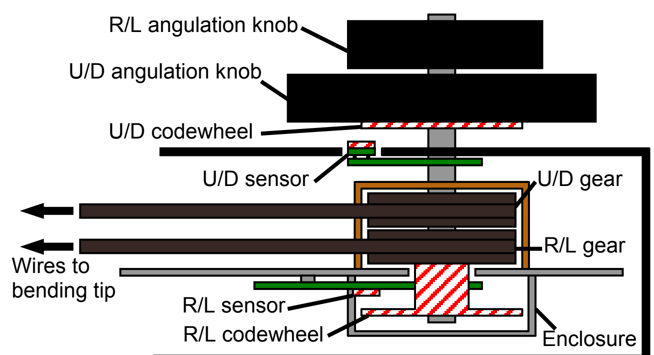

Figure 7: Schematic of the sensors integration (not to scale): red dashed items represent the sensors made of optical encoder and codewheel.

Integration has been completed on an Olympus CF-140L colonoscope as shown in Figure 8. It enables tracking of the bending section and the air/water and suction valves.

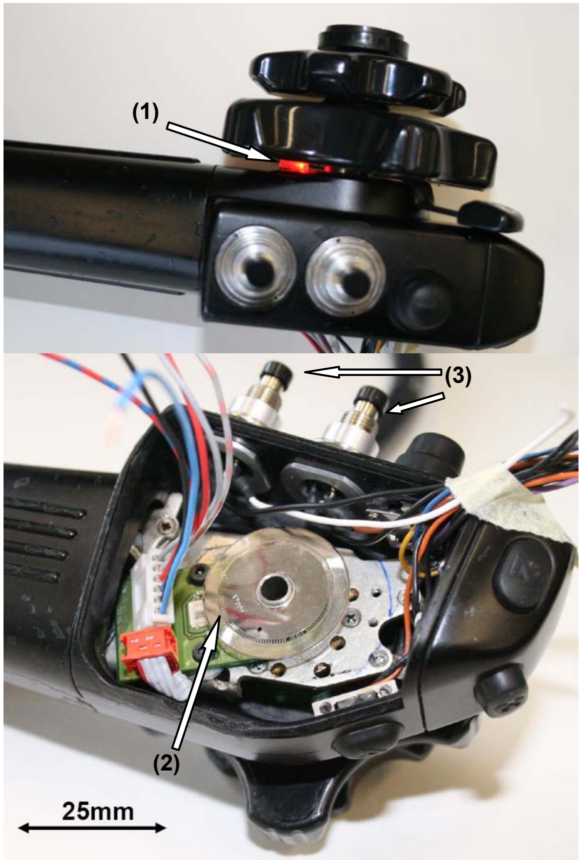

Figure 8: Views of the optical sensors integrated: (1) U/D sensor, (2) R/L sensor and its codewheel, (3) On/Off switches simulating the air/water and suction valves.

Output signals are acquired by means of the USBDUX data acquisition card already applied for the colonoscopy haptic device [10, 13]. The resolution of the angulation tracking is given by the resolution of the codewheels, which is 500 CPR (Cycles/Rev).

Figure 9 shows the proposed setup containing the virtual reality, the colonoscopy haptic device and colonoscope. This solution offers a compact and transportable platform for training goals.

IV. Conclusion

The outcome of this work is an unchanged handling of a colonoscope both in aesthetical and tactile way. This device enables the measurement of the colonoscope tip flexion as well as the air/water and suction valves and switches status. In addition, it permits a high shelf life because of the contactless optical sensors.

The proposed device is now ready to be integrated into colonoscopy simulator. Next step in the development will be the validation of the colonoscopy simulator by physicians.

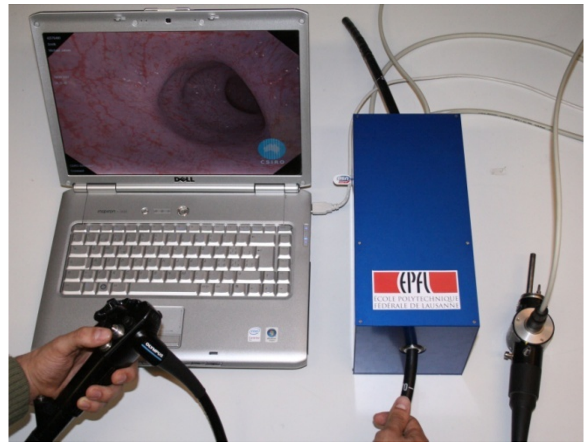

Figure 9: The instrumented colonoscope setup connected to the simulation via the colonoscopy haptic device.

Acknowledgment

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