Design of an Endoscopic Haptic Display System using an Integrated Ring-actuator

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***Abstract*— Existing virtual reality-based endoscopic simulators lack immersive haptic feedback. We address this need with a one degree-of-freedom haptic display module that can be retrofitted onto an endoscopic simulator. In this paper, we present the design of circumferentially actuated compact ring-mechanisms that provide radial motion for force-reflection on the tube of the endoscope. Both compliant and rigid-body embodiments of the ring-mechanisms are explored in this work. The multi-padded force-reflecting mechanism is designed to apply a maximum force of 5 N and to cover a range of endoscope tubes whose outer diameters range from 10 mm to 15 mm. Design, modeling, electronics, and fabrication of the ring-actuator endoscopic haptic display system are presented in this paper.**

Keywords—Haptics; Endoscopic Simulator; Ring-actuator

I. INTRODUCTION

In this paper, we present the initial stages of development, in particular, the design of the endoscopic simulator equipped with a novel ring-actuator for providing haptic feedback. A brief overview of virtual endoscopy and motivation for the work are presented first.

Endoscopy is a minimally invasive procedure where a flexible tube is inserted through the digestive tract for medical examination, and lately also for surgical procedures. Endoscopic procedures are important diagnostic tools for doctors to detect abnormal tissue, ulcers, polyps, cancers, etc. Gastrointestinal endoscopy, including colonoscopy, is a complex procedure involving high degree of hand-eye coordination. These procedures are generally carried out by highly skilled clinicians. During an endoscopic procedure, care must be taken to reduce pain and trauma and to avoid any injury to the Gastro Intestinal (GI) tract. Consequently, there is a need for clinicians to undergo rigorous and extensive training before they try endoscopy on animals or human subjects. Virtual Reality (VR) training devices have been in existence for long [1]. They are used for training clinicians in endoscopic procedures. VR-based training devices have many advantages that include: economical and usable any number of times; the training model can be changed and designed as per requirements including incorporating in situ cases; they can be used for assessing skill because recorded training sessions can be used for identifying mistakes; and the accessibility to the training environment can be increased.

Development of VR-based medical training systems are of interest in academia and industry. Until recent times, VR-based endoscopic training systems concentrate mostly on visual feedback using medical image processing and graphical rendering techniques [2]. However, apart from visual feedback, it is important for the clinicians to feel the interaction forces [3, 4]. Haptic feedback is known to greatly enrich the user-experience during training [3]. Kinematics and dynamics of the virtual environment and those in user interface are different. Haptic device acts as an interface for creating transparent and more realistic interaction than what is possible in VR without haptics. Efforts towards realizing force feedback in an endoscopic training system have begun, some of them are discussed next.

Ikuta and his team from the Nagoya University developed an endoscopic training system with force feedback [5]. Feedback force was applied using a friction drive that consists of a ball driven by four motors. Approximate deformable models were developed to compute forces of interaction between the colon and the endoscope. However, forces generated by frictional drive are hard to control and are not reliable. Recently, a team of researchers from Ecole Polytechnique Fédérale de Lausanne (EPFL) designed a compact haptic interface for colonoscopy using V-type friction rollers and customized brakes [6]. In this design, the lateral forces due to sideways motion of the endoscope were not included. Researchers at the Georgia Institute of Technology reported a proof-of-concept prototype for their endoscopic force feedback system [7]. Force in this system is produced by reducing the instantaneous radius at the end of endoscope using an air filled balloon. However, only a concept was reported. The accurate control of air-filled balloon to impart force is difficult and is not presented in the paper. Körner and Männer have reported their work on an endoscopic trainer that gives force feedback at the tip of the endoscope [4]. The design of the system to impart forces in all the degreed of freedom is not

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presented. Commercial products from Immersion Corporation (http://www.immersion.com) and Simbionix (http://www.simbionix.com) exist in the market. Force feedback in immersion electronic system is produced by winding the insertion tube around a motor. Endoscopic training systems from Simbionix do not possess active force display and rely only on graphical display.

All the work on endoscopic haptic display system discussed previously neglect radial/lateral force reflection. Radial forces are commonly encountered in endoscopic procedures as the doctors are more likely to move sideways and collide the endoscope with the GI-tract. Also, It is to be noted that the work in [4, 5, 6, 7] focus on colonoscopy for developing endoscopic haptic display system. However, endoscopic procedures also include upper GI-tract endoscopy. Our interactions with doctors practicing endoscopy revealed the importance of having a comprehensive haptic feedback for effective training in upper GI-endoscopy [8]. Forces encountered in upper GI-tract endoscopy are low when compared to colonoscopy procedures. There is a need to develop efficient endoscopic haptic display system that can efficiently reflect low forces with high fidelity. Thus, the design and development of a haptic display system that caters to this need is the focus of this paper.

A prototype of the designed system is shown in Fig. 1. The compact design of the device uses circumferentially actuated mechanisms for imparting radial forces on the endoscope tube. Apart from the rigid-embodiment of the force-reflecting mechanism, we also designed a compliant circumferentially actuated mechanism. Compliant mechanisms are mechanisms that transfer force or motion using elastic deformations [9]. These mechanisms are free from joints, compact and easy to manufacture, making them more attractive for use in haptic display system. We also develop the dynamic model of the entire endoscopic haptic simulator together with its actuator. The dynamic model can be used to develop and verify feedback controller for the device.

In the remainder of the paper, we give an overview of the endoscopic haptic display system in Section 2. This is followed by Section 3, which contains the description of the design of both rigid-link and compliant force reflecting mechanisms. Actuation and sensing elements used in the system are discussed in Section 4. In Section 5, a dynamic model of the endoscopic haptic display system is developed. Concluding remarks are in Section 6.

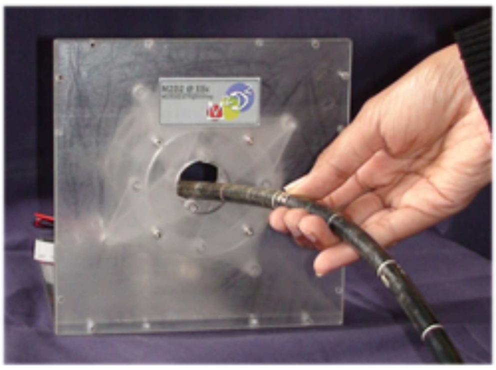

Fig. 1. A prototype of an endoscopic haptic display system.

II. ENDOSCOPIC SIMULATOR

The forces acting on the endoscopic tube during an endoscopic session are the forces applied by the user on the tube, frictional force as the tube slides over tissue lining of the GI tract, and reaction forces as the end-effector deforms the tissue. It is difficult to display all these forces to the user in exactly the same manner. Most of the forces arising in an endoscopic procedure due to different degrees of freedom of the endoscope tube can be approximately modeled as radial force, axial force and torque acting on the endoscope tube. This is physically meaningful because the user usually moves it radially, pushes/pulls along the length of the tube, or turns the endoscopic tube. Hence, it makes sense to provide haptic feedback as a radial force, axial force and turning torque. In this paper, we attempt only the radial force. It should be noted that some of the axial forces can also be simulated in the form of friction using a radial force-reflecting mechanism. However, this requires linear position measurement of the endoscope and is not part of the present prototype.

Fig. 2 shows a computer model of the endoscopic haptic simulator system being developed in our lab. The complete drive system, actuator and sensor unit are accommodated within a box that fits in a 16-cm cube. The front plate of the box has an opening for inserting an endoscope. As the user inserts the tube, she/he imparts two kinds of motion; axial motion and radial motion to the tube. Axial motion is along the axis of the endoscope and radial motion is along the radius of the tube. In the design presented in this work we are only interested in radial motion and the user is free to push along the axis of the tube. However, any radial displacement input by the user results in radial displacement of the gripping pads of the circumferentially actuated mechanism shown in Fig. 2. The kinematic relation between the gripping pads and the capstan drive is established in Section 3. Once the kinematic relationship is known, the radial displacements input by the user is sensed using an encoder attached to

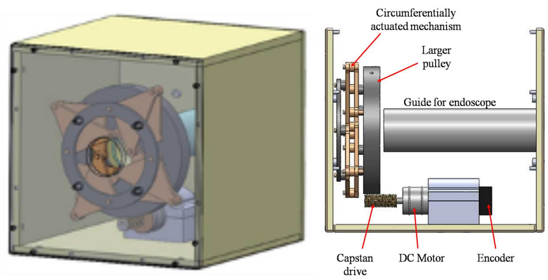

Fig. 2. CAD model of the device.

the drive motor (see Fig. 2). Based on the measured displacements, the virtual tissue interaction model computes the radial forces that are to be applied on to the endoscope tube. These forces are reflected on to the user using an integrated ring-actuator. A ring-actuator consists of a force-reflecting mechanism, a capstan drive, and a motor for actuating the drive. The capstan drive assembly provides for cog-less transmission with good back-drivability. The entire mechanical structure is manufactured using rapid prototyping. All the mechanical parts are assembled using bolts and nuts as fasteners, and pin joints are constrained by e-clips.

An endoscopic simulator is a complex electromechanical system that is controlled using an external computer. Control commands from the computer are sent to the drive system using a Data Acquisition (DAQ) system connected to the computer. This type of modular design has several advantages:

- The haptic display system is compact.
- Endoscopes with different diameters can be used for training.
- Use of removable endoscope is closer to reality, as real endoscopic procedure involves re-insertion.
- Since an actual endoscope is used as a tool handle in the haptic display system, there is no need to provide haptic feedback on the navigation wheel of the endoscope.

III. FORCE-REFLECTING MECHANISMS

A. Rigid-Body Mechanism

Radially deployable mechanisms commonly seen in toys and space applications produce interesting motions. These mechanisms are often kinematically over-constrained. Some examples of radially deployable mechanisms based on generalized angulated elements (GAEs) are reported in [10, 11]. A GAE is simply a ternary body connected to three other bodies. Patel and Ananthasuresh[12] presented the kinematic basis for GAE-based deployable mechanisms by modeling them as prismatic-revolute-revolute-prismatic (PRRP) four-bar linkage or a double-slider linkage. They also presented a special case of GAEs which can be actuated circumferentially. Circumferential actuation was achieved by choosing parameters of GAEs to make the coupler curve of a PRRP linkage trace a circle. Circumferentially actuated rigid-body mechanism is illustrated in Fig. 3. It is to be noted that the radial motion of the pads is achieved by simultaneously actuating both the top and bottom discs in opposite directions. Fixing one of the discs and actuating the other disc makes the pads follow an ellipse rather than a radial straight line. However, this transverse displacement can be ignored for the small operating workspace of the endoscopic haptic device. Hence, in the design presented in this work, we fix one of the plates (front plate) and use the back plate to actuate the mechanism.

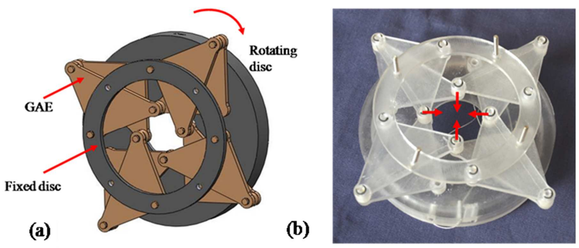

Fig. 3. (a) Computer model for the rigid-body embodiment of the circumferentially actuated mechanism. (b) Physical realization of the circumferentially actuated mechanism with arrows indicating the radial direction of motion.

In the circumferentially actuated mechanism, one of the points on the triangular element is made to move along a circle. Fig. 4 shows the two configurations of the circumferentially actuated mechanisms with eight triangular elements. Points abc and $\tilde{a}\tilde{b}\tilde{c}$ correspond to two angulated members hinged together. Hence b and $\tilde{b}$ are coincident. Point c and $\tilde{c}$ move along the circle. Points a and $\tilde{a}$ move along the radial line applying force on the endoscope tube. For every $\pi/2$ rotations of the ring, the end-effector position denoted by x has a displacement of l. Hence, the kinematic relation between angular position of the actuated disc and position of radially moving pads is given by

$$x = \frac{2l\theta}{\pi} \tag{1}$$

where θ is the angular position of the rotating disc. The mechanism prototyped in this work has a length, l =50 mm for one of the sides of the triangular element. The overall diameter of the circular ring is 70 mm.

B. Compliant Circumferentially Actuated Mechanism

The design of the radially deployable compliant mechanism was reported in [13] to develop a pipe-crawling robot. In that, the ring actuator was used to hold and release its grip on the pipe by tightly hugging the pipe by applying radial pressure externally on the pipe and then letting it free by retracting the pads that apply the radial pressure. This feature is utilized here for applying the required radial pressure. However, the mechanism used in pipe crawler was large and had high stiffness for use in endoscopic haptic system. We modify the mechanism by changing the dimensions and shape of the flexible members of the mechanism. To reduce the stiffness, the

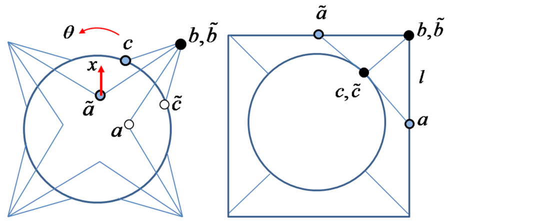

Fig. 4. Two kinematic configurations of the circumferentially actuated mechanism.

number of gripping pads are reduced to three. We also changed the shape of the beam segments to fit the stiffness and geometric constraints imposed by the endoscopic haptics display system.

Some design constraints are laid out for redesign of the compliant ring-mechanism. The mechanism should be able to apply a minimum force of 5 N on the endoscopic tube. The input torque that produces 5 N contact force should be within the maximum torque developed by the motor (which is approximately 170 mN.m). It is intended that the overall dimensions of the mechanism should be similar to the size of the rigid-body mechanism. This allows the same drive system to be used for both rigid-link and compliant mechanisms.

The redesigned mechanism is shown in Fig. 5 (a). It consists of two circular discs, each having three pairs of beam segments. Corresponding beam segments from each circular disc are connected together at the gripping pads. During operation of the mechanism, one disc is fixed and a torque is given to the other disc. As a result of circumferential actuation, the ends of the beam segments connected to the pads move radially inwards. This can be seen in the finite element simulation results shown in Fig. 5(b).

The important dimensions of the designed circumferentially actuated mechanism is shown in Fig. 6 (a). The design is based on Finite Element Analysis (FEA) carried out using COMSOL MultiPhysics software (www.comsol.com) (see Fig. 6 (b)).The properties of polypropylene (Young's modulus = 1.7 GPa, Poisson's ratio 0.33) are used because the prototype was made using this material. The out-of -plane thickness is chosen to be 4 mm, which is one of the standard thicknesses of polypropylene sheets available in market. Fig. 7 (a) shows the plot for input torque versus output displacements. The output port has a displacement in excess of 2.5 mm for input torque of 150 mN.m. Displacement of 2.5 mm on all the pads allows the use of endoscopic tubes with any diameter between 10 mm to 15 mm. From Fig. 7 (b) we also note that the gripping pressure is about 5 N for a torque of 150 mN.m. These FEA simulations show that the torque requirement is below the motor torque and the compliant mechanism can be used as an alternative to rigid-link mechanism.

IV. ACTUATION AND SENSING

A DCX series brushed DC motor manufactured by Maxon Motors, Switzerland, is used to apply torque on

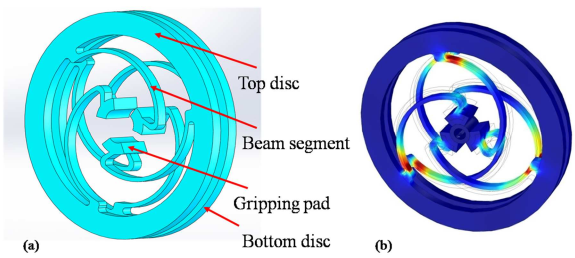

Fig. 5. (a) Computer model of the compliant ring-mechanism. (b) Deformation characteristics of the compliant ring-mechanism.

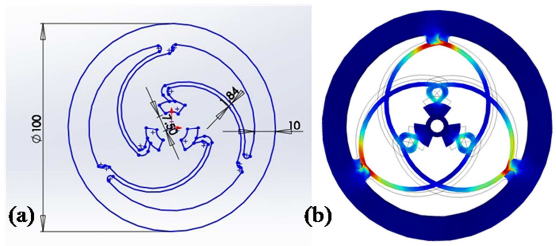

Fig. 6. (a) Important dimensions and (b) deformed configuration obtained from of the compliant ring-mechanism.

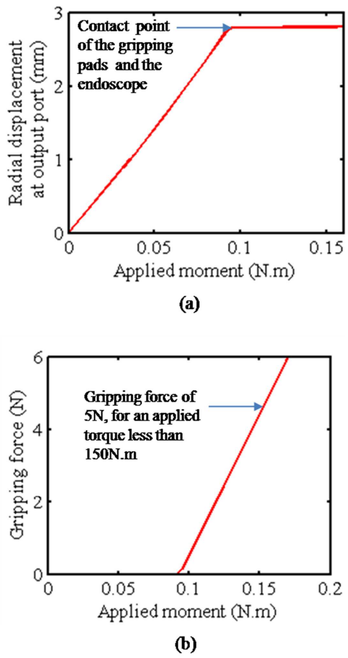

Fig. 7. (a) Displacement characteristics of the compliant ring-mechanism. (b) Gripping force due to applied moment.

the ring-actuator. The motor is coupled to the capstan drive that actuates the circumferentially actuated mechanism. DC motor was customized to have low inertia and high torque by the vendor as per our specification. Further increase in torque is achieved by incorporating a 1:16 reduction gearbox that takes the nominal operating torque to 170 mN.m. Sensing device of the endoscope is a 500 counts per revolution (CPR) optical encoder. This roughly translates to 0.116^{o} resolution. All the control prototyping is done on a PC with MATLAB/SIMULINK windows real-time target. The computer communicates with the driver circuit and encoder using a National Instrument PXI 6221 data acquisition system (DAQ). The important characteristics of the actuation and sensing system are summarized in Table 1.

A. *Drive Electronics*

Impedance type haptic devices are designed to apply desired forces on to the user. Torque from the DC motor drives the force-reflecting mechanism to impart controlled forces onto the user. The motor produces a torque that is proportional to the current in the circuit. To control the

Table I

SENSING AND ACTUATING CHARACTERISTICS

Instruments	Physical property	Value
DC motor	Nominal voltage	12 V
	No load Speed	387 RPM
	Nominal torque	176 mNm
	Nominal current	0.818 A
Encoder	Counts per revolution	500
DAQ	Correlated DIO	1 MHz
	Resolution	16-Bit
	Output voltage range	-10 V , +10 V
	Counter resolution	32-Bit

torque in the motor, the motor has to be operated in the current control mode. However, the DAQ used to send control input to the motor can only apply voltage in the range -10 V to + 10 V with a maximum current of 5 mA. To control the current in the motor, a custom current driver circuit based on LM 675 was designed. LM 675 IC is a power operational amplifier that can drive up to 3 A of current. The transfer function for the inverting amplifier is given by

$$\frac{V_0(s)}{V_i(s)} = -\frac{Z_2(s)}{Z_1(s)} \tag{2}$$

Where V_i is the input is control signal and V_0 is the output voltage across the power resistor. Z_1 and Z_2 are the input and feedback impedances respectively. Ignoring the small capacitors used for DC filtering and expressing equation (2) to give current through the power resistor, we write

$$i(s) = -\frac{Z_2(s)\, V_i\,(s)}{Z_1(s)\; R} \tag{3}$$

Impedances are chosen to be static elements with values $Z_1 = 100K\,\Omega$, $Z_2 = 3.3K\,\Omega$. The power resistor, R has a value of $0.33\,\Omega$. Substituting these values in (3) makes the current in the power resistor to be one tenth of the input voltage. By neglecting the small current in the feedback loop of the power amplifier and considering the range [-10, 10] V as command input voltage from the DAQ, the controllable current through the motor is obtained as [-1, 1] A. This is roughly the range of the current for the motor used in the device. It is to be noted that this method of using power amplifiers is a low-cost solution and does not take into account back emf induced by the motor. For accurate current control through the motor, one has to use Pulse Width Modulation (PWM) based motion control drives. The PWM motion control drives have inbuilt current sensor and feedback loop for accurately maintaining current in the circuit. Fig. 8 (a) shows the circuit diagram and Fig. 8 (b) shows its practical realization.

V. MODELLING AND CONTROL

A. Dynamic Model

The dynamic model for the rigid-link embodiment of the integrated ring-actuator is developed in this section. A simple sketch of the actuation system for the haptic display system is shown in Fig. 9. Equation of motion for the mechanical and electrical part of the motor can be written as [14].

$$\frac{J_m}{K_t} R\, \ddot{\phi} + \left(\frac{b_d}{K_t} R + K_v \right) \dot{\phi} = V(t) \tag{4}$$

where J_m is the motor rotary inertia, b_d is the damping coefficient in the motor. K_t, K_v *and* R are the motor electrical components namely torque constant, speed

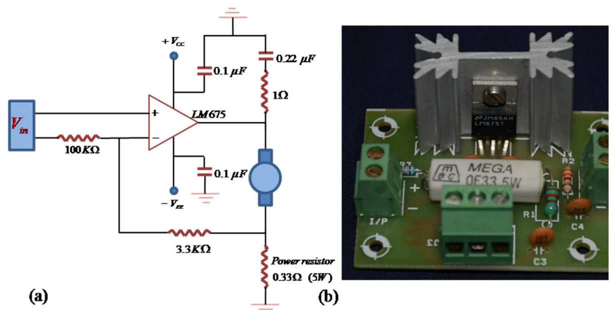

Fig. 8. (a) Current driver circuit diagram and (b) the physical realization of the circuit.

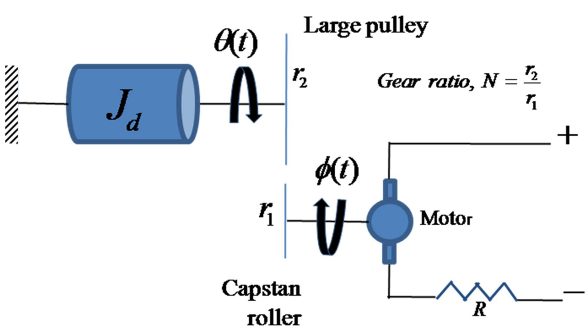

Fig. 9. Schematic of the integrated ring-actuator.

constant, and resistance respectively. The symbol ϕ denotes the angular position of the motor shaft, and V is the input voltage. The endoscopic haptic display system is an impedance type haptic device where force control is achieved by controlling motor torque. Making the non-homogeneous term of (4) to be motor torque using the relation, $\tau_m = K_t\ i(t)$ we get:

$$J_m\ \ddot{\phi} + \left(b_d + \frac{K_t K_v}{R} \right) \dot{\phi} = \tau_m \tag{5}$$

Equation (5) is the torque equation for the DC motor. However, the DC motor is also coupled to the force reflecting mechanism through a capstan drive. By reflecting all the torques in the system onto the motor shaft, we get

$$\tau_m = \frac{1}{N}\ \tau_d + J_m\ \ddot{\phi} + b_m\ \dot{\phi} + \frac{1}{N}\ \tau_f \tag{6}$$

where N is the transmission ratio and τ_f is the torque due to friction. The torque, τ_d due to dynamics of the force-reflecting mechanism can be modeled as $\tau_d = J_d\ \ddot{\theta}$. Where J_d is the inertia of the large pulley and θ is its angular position. It should be noted that this is a simplified model where inertia due to angulated elements and damping at the joints are neglected. This simplification is reasonable as the mass of angulated members are smaller in comparisons to the mass of the large pulley. Equation (6) now reduces to

$$\tau_m = \left(\frac{1}{N^2}\ J_d + J_m \right)\ \ddot{\phi}\ +\ b_m\ \dot{\phi}\ +\ \frac{1}{N}\ \tau_f \tag{7}$$

Now consider the kinematics discussed in Section 3. The position of the end-effector (pads applying radial forces), x can be expressed in terms of motor angular position and one of the sides of angulated member, l.

$$x = \frac{\pi\phi}{4\,l\,N} \tag{8}$$

After substitution, the equation of motion for the equivalent system can be expressed as,

$$m_e\ \ddot{x} + b_e\ \dot{x} = \tau_{me} + \tau_{fe} \tag{9}$$

Where m_e is the equivalent mass and b_e is the equivalent damping in the system. τ_{em} and τ_{fe} are the equivalent motor torque and torque due to friction.

B. Feedback Control

Fig. 10 shows the closed loop operation of the endoscopic simulator. The developed haptic display

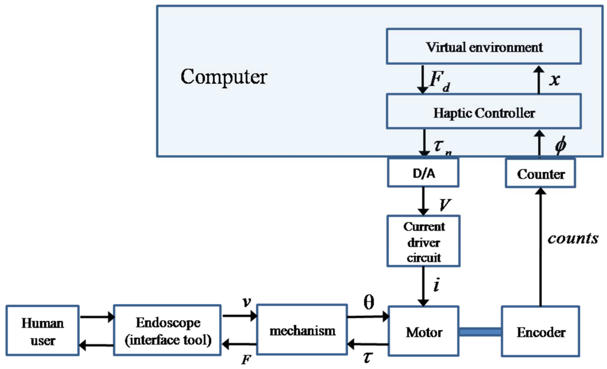

Fig. 10. Block diagram for the closed loop operation of the endoscopic haptic device.

system is an impedance type haptic device that take displacement as input and reflects forces to the user. The desired force F_d is estimated from the virtual environment model using position information. A haptic controller computes the necessary torque for the motor based on the estimate sent by the virtual environment. The forces are rendered on to the user using force-reflecting mechanism. We implemented a Proportional Integral (PI) controller for the model developed in previous section [15].

The haptic display model was simulated using MATLAB/SIMULINK software. Fig. 11(a) shows the response of the closed loop system to a step input in force. We note that the controller responds quickly with a time constant of 0.12 s. We also tested the controller for tracking (see Fig. 11(b)) and note that the tracking error is within ± 0.5 N. The maximum error for tracking was 0.5 N. It should be noted that these simulations were carried out by taking the dynamics of the environment (user with endoscope) to be a simple linear spring. However, in reality, variation in mass of human users, grasping force and neuromotor skills, all influence the user dynamics. Determination of these factors is difficult and an average estimation has to be done based on numerous experiments. Due to all these uncertainties, the controller is not tested on the actual system and is the future direction of this work.

VI. CLOSURE

In this paper, we presented the design and development of a novel haptic display device for

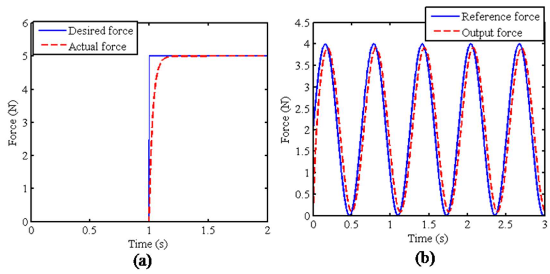

Fig. 11. (a) Step response and (b) tracking response of the endoscopic haptic display system.

endoscopic training. The main contributions of this paper are*:*

- Initial prototyping of an endoscopic haptic display system.
- Design of both rigid-link and compliant force-reflecting mechanism.
- Dynamic modeling for radial forces and preliminary controller simulation is shown for integrated ring-actuator.

We note that the developed device is compact and can apply radial force in excess of 5 N. In this work we only presented the design of the compliant ring-actuator. The complete system model and integration of the compliant ring-actuator as an endoscopic haptic display are yet to be carried out. Controller testing and complete characterization of the prototyped device comprise the future course of this work.

References

[1] F. Mantovani, "12 VR Learning: Potential and Challenges for the Use of 3D Environments in Education and Training," *Towards CyberPsychology: mind, cognition and society in the internet age*, vol. 2, pp. 207, 2001.

[2] S. Haque and S. Srinivasan, "A meta-analysis of the training effectiveness of virtual reality surgical simulators," *Information Technology in Biomedicine, IEEE Transactions on*, vol. 10, pp. 51-58, 2006.

[3] T. R. Coles, D. Meglan, and N. John, "The Role of Haptics in Medical Training Simulators: A Survey of the State of the Art," *Haptics, IEEE Transactions on*, vol. 4, pp. 51-66, 2011.

[4] O. Koerner and R. Maenner, "Implementation of a haptic interface for a virtual reality simulator for flexible endoscopy," presented at Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003.

[5] K. Ikuta, M. Takeichi, and T. Namiki, "Virtual endoscope system with force sensation," presented at Proceedings of International Conference on Robotics and Automation, 10-15 May 1999, Piscataway, NJ, USA, 1999.

[6] E. Samur, L. Flaction, and H. Bleuler, "Design and Evaluation of a Novel Haptic Interface for Endoscopic Simulation," *IEEE Transactions on Haptics*, vol. 5, pp. 301-11, 2012.

[7] J. W. Peifer, W. D. Curtis, and M. J. Sinclair, "Applied virtual reality for simulation of endoscopic retrograde cholangio-pancreatography (ERCP)," presented at Proceedings of Medicine Meets Virtual Reality IV: Healthcare in the Information Age - Feature Tools for Transforming Medicine, 17-20 Jan. 1996.

[8] Dr. Nageswara Reddy and Dr. Pradeep Rebala, "Private communication." Asian Institute of Gastroenterology, Hyderabad.

[9] L. L. Howell, *Compliant mechanisms*: Wiley-Interscience, 2001.

[10] C. Hoberman, "Radial expansion/retraction truss structures," U.S. Patent, 1991.

[11] Z. You and S. Pellegrino, "Foldable bar structures," *International Journal of Solids and Structures*, vol. 34, pp. 1825-1847, 1997.

[12] J. Patel and G. Ananthasuresh, "A kinematic theory for radially foldable planar linkages," *International journal of solids and structures*, vol. 44, pp. 6279-6298, 2007.

[13] P. Singh and G. K. Ananthasuresh, "A compact and compliant external pipe-crawling robot," *IEEE Transactions on Robotics*, vol. 29, pp. 251-60, 2013.

[14] N. S. Nise, *Control systems engineering*, vol. 5: Wiley Hoboken, NJ, 2008.

[15] C. R. Carignan and K. R. Cleary, "Closed-loop force control for haptic simulation of virtual environments," *Haptics-e*, vol. 1, pp. 1-14, 2000.