Robotic Endoscopic Manipulation System

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INTRODUCTION

This short paper describes the development of a simple, clinically usable robot for manipulating flexible endoscopes for laryngeal surgery. Transoral endoscopic laryngeal surgery aims to reduce the risk of complications such as scarring and infection by utilizing natural orifices when accessing surgical targets. However, despite the many advantages of this approach, it also presents significant challenges, particularly poor sensory feedback, reduced visibility, limited working area, and increased hand tremor due to long instruments.[1]

Robotic surgery systems such as Intuitive Surgical's da Vinci have sought to remedy these problems in other surgical venues, but these solutions do not transfer well to laryngeal surgery. The da Vinci was designed primarily for robotic laparoscopic surgery, in which instrument position and orientation simulate the normal hand position of a surgeon, with widely-spaced large diameter instruments. This results in a large, bulky robot which can be difficult to work around, and can cause additional problems with anesthesia when instruments limit access to the airway.[2]

In transoral laryngeal surgery, this approach has further limitations, since access through the airway requires nearly parallel instrument shafts, which the da Vinci cannot achieve. To partially compensate for these shortcomings, such systems often require highly modified surgical techniques and specialized clinical equipment, resulting in the need for extensive additional training for surgeons and prohibitively high startup and maintenance costs.[3]

Outside of robotic systems, the current state of the art in laryngeal surgery makes heavy use of clinical flexible endoscopes. Current clinical endoscopes are very advanced, offering HD video, working ports, high range of motion tips, and full sterilizability. However, the way endoscopes are currently used has many drawbacks. In a typical surgery, one surgeon holds and actuates the endoscope, which requires both hands, while another uses instruments such as forceps and a laser to manipulate and cut tissue. This leads to a crowded working environment with two surgeons crowded around the patient's head. We also found that coordination between the two surgeons can be difficult and supporting and actuating the endoscope for long periods of time can result in fatigue and inaccuracy.

MATERIALS AND METHODS

We instead propose a relatively simple, small, inexpensive robot that takes full advantage of existing clinical equipment, and requires little modification of existing surgical procedures. We focused on developing a robot to hold and actuate an unmodified clinical endoscope, allowing one surgeon to control the scope with one hand using a SpaceNavigator 3D mouse, and operate with the other hand, or to position the scope using the robot, then operate bimanually. We used the Pentax VNL-1570STK flexible laryngoscope in these experiments, but the system is designed so that any similar clinical endoscope could be used with minimal modification. We found that surgeons generally use three degrees of freedom when manipulating flexible endoscopes: bending of the scope's tip using the scope handle, rotation of the scope about its axis, and translation of the scope along the axis of the airway. To aid in positioning the scope, we also added two passive lockable degrees of freedom (Fig. 1). Both active and passive joints are sealed with corrosion resistant sealed

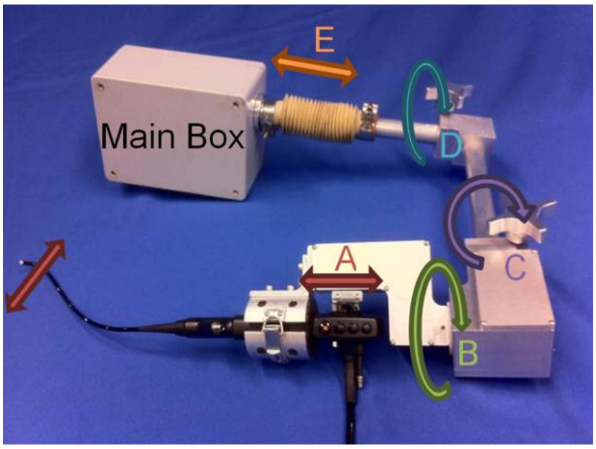


Fig. 1 A) Active scope tip manipulator B) Active axial rotation of the scope C) Passive lockable joints to adjust scope entry angle D) Passive lockable joint to adjust scope height E) Active in-out translation

bearings, o-rings or bellows, allowing the robot to remain fully watertight even when in motion. The electrical connection to the robot is achieved using a Soriau corrosion resistant waterproof electrical connector. All compartments covers are sealed with o-rings.

In order to minimize the weight over the patient, we designed the system so that the largest motors, for the scope translation and rotation degrees of freedom, are located in the main box. To transmit power from the main box to the scope rotation joint, a cable-pulley mechanism was used. We used 12 V servo motors with planetary gearheads and integrated magnetic encoders for all active degrees of freedom. We also installed potentiometers on each active degree of freedom for added safety and more precise control.

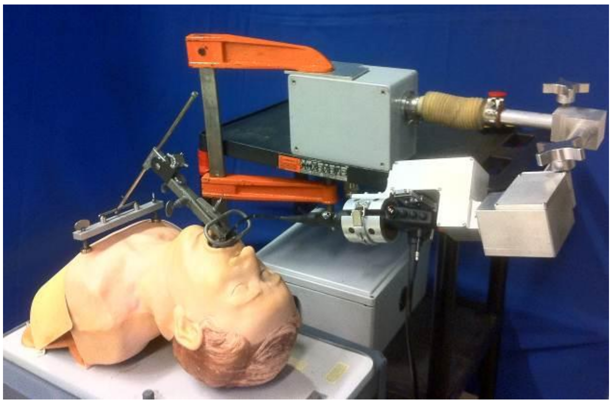


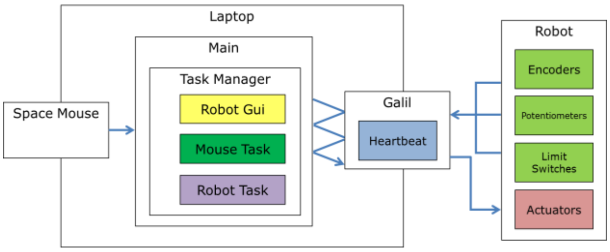
Fig. 2 Robo-ELF mounted on cart with phantom.

The robot grips the scope with custom molded urethane rubber inserts, and uses a quick release latch to hold the scope in place. The scope shaft is highly flexible, so we added a malleable wire scope shaft support to stiffen it for more precise control. The entire robot is built with Johns Hopkins Hospital clinical engineering specifications in mind, including waterproof seals, operating room safe materials, proper electrical grounding with fusing, and an isolated power supply with no voltages greater than 12V. The robot is operable in wet environments and is awaiting a final clinical engineering inspection.

Our surgeons (Hillel and Richmon) have tested the system using two fresh human male cadavers. We suspended each cadaver with a Steiner laryngoscope to allow visualization of the endolarynx, in a configuration similar to Fig 2. First, we performed standard microlaryngoscopy using 0, 30, and 70 degree rigid scopes, taking representative photographs of the endolarynx with each scope for comparison. We then evaluated the Robo-ELF with the following three tasks: 1) comparable field of view; 2) visualization of challenging anatomical areas with precise biopsy sampling; and 3) bimanual surgery with the Robo-ELF in a fixed position.

SYSTEM OVERVIEW

The system consists of 1) the robot, 2) the Galil Motor Controller, 3) the Space Mouse and 4) the Laptop.

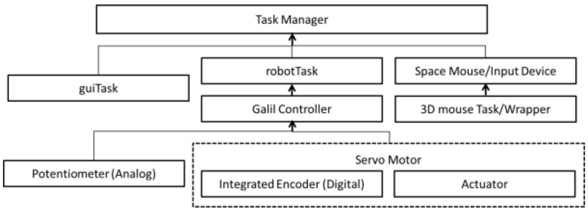


The robot consists of 3 servo motors which are controlled by the Galil Controller. Each of the motors have built in optical encoders giving digital input to the Galil. For each motor that are reverse and forward limit switches which stop any joint from going past its limits. Each motor is also equipped with a linear potentiometer which asks as a redundant sensor, feeding analog input into the Galil. Thus, if the encoder fails, it should be seen by comparison with the analog input, allowing the robot to be shut down safely.

The Galil motion controller is a DMC 3040 which has 3 axes for each of the robots 3 degrees of freedom. The Galil has its own language and program to move the motors and tune the control loop. However, it also comes with a C/C++ wrapper. Previously, within the CIIS lab, a wrapper that makes the Galil compatible with the CISST libraries were written allowing it to be used in the CISST Multitask structure.

SOFTWARE

Our software utilizes the CISST libraries, in particular the CISST MultiTask library and its component structure. The main files within our software currently include the Main, RobotTask, qtRobotGui, SpaceNavigatorTask and devGalilController.



The main program creates a TaskManager, from the CISST Multitask library. For each main component of our system, we create a task and add it to the Task Manager. The Task Manager makes the tasks thread-safe. We have 3 main tasks: the GUI, Robot and Space Mouse. These tasks are all periodic meaning they run and update periodically based on the period we set when creating the tasks.

The GUI task continually checks the various states (RobotState, ActuatorState) and updates the correct values on screen. It also can be used to change variables and manipulate the robot. The user interface was created using QT 4. The main file containing the interface is called ThroatGui. This file functions as a normal QT application. However, the guiTask acts as an interface between QT and the CISST system by creating a periodic task with the GUI object.

The main robot task has most of the functionality of the system. Its run method checks the various safety features to make sure no error has occurred. If there are no errors then the laptop will take the SpaceMouse input and move using incremental position control.

RESULTS

Using the passive degrees of freedom, we easily positioned the Robo-ELF through the Steiner laryngoscope. All three active degrees of freedom performed reliably, with smooth, consistent, reproducible motion. The velocity of the movement was reliably transmitted through motion of the 3D mouse, with no erratic artifacts and virtually no learning curve. The Robo-ELF provided a higher resolution image with superior field of view compared to the three rigid endoscopes. In addition, we were able to navigate the flexible tip around the arytenoids into the piriform sinuses, and through the vocal cords into the subglottis, overcoming the line of site lmitations of rigid scopes. Though we were able to visualize the intended biopsy sites in both cadavers, the first cadaver's Larynx was anteriorly positioned, so despite obtaining a clear view of the subglottis and anterior commissure with the Robo-ELF in a flexed position, the straight laryngoscopic forceps were unable to reach. Finally, after positioning the Robo-ELF above the vocal cords there was still ample room to use two instruments to perform bimanual endolaryngeal surgery.

DISCUSSION

We have shown that a relatively small, inexpensive 3 degree of freedom robot can be used to precisely control an unmodified clinical endoscope with virtually no learning curve. The Robo-ELF has demonstrated significant advantages over existing robotic surgery systems, and un-actuated rigid and flexible endoscopes in the field of laryngeal surgery. The flexible endoscope also has a working channel through which a therapeutic laser could be introduced, further taking advantage of standard clinical equipment.

The technologic advantages of this approach are substantial. This robot is inexpensive compared with other microscopic and robotic techniques, at approximately $30,000. On top of this platform, we also plan to integrate more sophisticated software features, including automated scope stabilization, 3D reconstruction from multiple monoscopic scope images, automated point-and-click navigation, video registration with pre-operative imaging data, and virtual fixtures. It could also be utilized with other technology, such as image-overlay, ultrasound, optical coherence tomography, and be manufactured with two chips for 3-D vision. Furthermore, it could be adapted to a variety of procedures including bronchoscopy, upper and lower gastrointestinal endoscopy and sinus surgery. Eventually there is potential for microvascular surgery at the base of the skull, as well as single port gastrointestinal and thoracic access surgery.

MANAGEMENT SUMMARY

The biggest lesson learned was that writing software is much easier than testing, debugging and documenting it. While most of the software was written, much of it still requires testing and extensive debugging before a final system can be in place. The goal of this project was to move forward the software in terms of motion (switching to position control, further separating the axes of motion, implementing control loop, etc), set up the user environment and document/test the robot for future clinical studies and work.

Future work is need to extensively test each of the safety features, the software components and each hardware component. While rough documentation is done for the system that currently exists, much will probably change as the software evolves.

The input device was found to be non-ideal since there is always a noticeable amount of movement in the other unintended axes. An alternative input device was considered. Although it was unable to be implemented, joysticks which use the Microsoft Direct X software show promise. However, to use such a device, would require a wrapped to be written to interface the device with the CISST libraries. An added benefit of this switch is the compatibly of many joysticks as several are compatible with the Direct X software.

A long term future goal of the project is to use the system in a clinical setting with live human subjects to test its improvement over simple mechanical movement of the flexible endoscope. This is planned to be done before the end of the year.

A long term technical goal would be the integration of computer vision algorithms in order to implement a point and click movement of the scope. This would allow the user to simply click on screen where he or she wishes the endoscope tip to move to without having to drive each axis individually. This would fully automate the system and allow for easier control for the surgeon.

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