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Robotically assisted ureteroscopy for kidney exploration

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Abstract

Ureteroscopy is a minimally invasive procedure for diagnosis and treatment of a wide range of urinary tract pathologies. It is most commonly performed in the diagnostic work-up of hematuria and the diagnosis and treatment of upper urinary tract malignancies and calculi. Ergonomic and visualization challenges as well as radiation exposure are limitations to conventional ureteroscopy. For example, for diagnostic tumor inspection, the urologist has to maneuver the ureteroscope through each of the 6 to 12 calyces in the kidney under fluoroscopy to ensure complete surveillance. Therefore, we have been developing a robotic system to “power drive” a flexible fiber-optic ureteroscope with 3D tip tracking and pre-operative image overlay. Our goal is to provide the urologist precise control of the ureteroscope tip with less radiation exposure. Our prototype system allows control of the three degrees of freedom of the ureteroscope via brushless motors and a joystick interface. The robot provides a steady platform for controlling the ureteroscope. Furthermore, the robot design facilitates a quick “snap-in” of the ureteroscope, thus allowing the ureteroscope to be mounted midway through the procedure. We have completed the mechanical system and the controlling software and begun evaluation using a kidney phantom. We put MRI-compatible fiducials on the phantom and obtained MR images. We registered these images with the robot using an electromagnetic tracking system and paired-point registration. The system is described and initial evaluation results are given in this paper.

Keywords

Uretersocopy; robotics; image guidance; electromagnetic tracking; evaluation

1. INTRODUCTION

Ureteroscopy is a minimally invasive procedure for the treatment and diagnostic evaluation of a wide range of upper urinary tract pathology (Figure 1). Ureteroscopy is a common urologic procedure with approximately 70,000 cases annually in the US. Ergonomic and visualization challenges as well as radiation exposure are limitations to conventional

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ureteroscopy. For example, for diagnostic tumor inspection, the urologist has to maneuver the ureteroscope through each of the 6 to 12 calyces in the kidney under fluoroscopy to ensure complete surveillance. This involves estimating the 3D position of the ureteroscope using the 2D images obtained from video and fluoroscopy. Moreover, ureteroscope control commonly requires use of both hands, one hand to move the ureteroscope in and out of the patient and the other hand to rotate and flex the ureteroscope, limiting the urologist's ability to simultaneously manipulate working instruments. Therefore, we have developed a robotic system to "power drive" a flexible fiber-optic ureteroscope with 3D tip tracking and pre-operative image overlay. Our goal is to provide the urologist precise control of the ureteroscope tip with less radiation exposure and image guidance to assist during the procedure.

A typical ureteroscopy procedure proceeds as follows [1], [2]: the surgery begins with cystoscopy (surveillance of the bladder with a larger cystoscope) and retrograde passage of a guide wire from the ureteral orifice up the ureter and into the renal pelvis. Usually a second "safety wire" is also passed. Wire passage is performed under fluoroscopic guidance. Commonly, the urologist will use one of the wires to provide access to inject a contrast agent into the renal pelvis, which opacifies the collecting system under fluoroscopy for identification of anatomy and pathology as well as safe navigation. Using additional fluoroscopy, a flexible ureteroscope is passed over one of the guide wires into the renal pelvis, the guide wire is then removed and a camera is connected to the scope lens, providing the urologist navigational access to the renal collecting system (note that some urologists will connect the camera before passage up the ureter to watch for obstructions or abnormalities). The urologist then maneuvers the ureteroscope to carry out the appropriate procedure, utilizing additional contrast agents and fluoroscopy as needed to confirm positioning within the collecting system and complete the surgery.

There are limitations to the typical ureteroscopy procedure. Significant radiation exposure to patient, urologist, and operating room staff is required for conventional ureteroscopy [3]. Additionally, bleeding within the collecting system (whether due to the pathology itself, or as a result of ureteroscopic access) as well as contrast agents used to aid fluoroscopic navigation, can hinder visualization.

During the procedure, a flexible ureteroscope (Figure 2) must be maneuvered through a complex 3D environment. However, the urologist is not always sure of the positioning of the ureteroscope tip in the anatomy. Hence, these procedures are always accompanied by fluoroscopy to verify ureteroscope tip position. This leads to increased radiation exposure for the patient and the medical staff. Furthermore, the urologist has to keep track of the ureteroscope in the 3D environment using the 2D projection image from the fluoroscope with limited spatial information as to the relationship of the ureteroscope within the kidney. Also, conventional ureteroscope control is effected through the use of two hands, one to move the ureteroscope in and out, and the other to rotate and flex the tip of the ureteroscope.

This control mechanism makes it particularly difficult to maneuver the ureteroscope in the lower pole of the kidney where the instrument must be tightly flexed and then rotated and pulled back to move into the lower calyces. As the physician is forced to constantly hold the

ureteroscope during the entire procedure, it can lead to arm fatigue and subsequent arm tremors and loss of long-term productivity for the urologist due to chronic motion injury. Approximately one-third of urologists reported hand and wrist problems, of which 85% needed medical or surgical interventions [4]. Moreover, the control mechanism requires an assistant to hold the ureteroscope steady when the operating urologist carries out manipulations through the working channel.

Medical robotics has the potential to address the ergonomic challenges associated with conventional ureteroscopy. In the domain of minimally invasive endoscopic procedures, several research groups have developed robotically assisted prototypes. Ruiter et al. presented a robotic drive system for colonoscopy using a joystick and a touch controller [5]. Fang et al. presented a prototype hand held manipulator to motorize a flexible rhinoscope during ENT procedures [6]. Another robotic system is the Hansen catheter system (Sensei) that drives a passive catheter element and relies on visual feedback for navigation. This system was used to perform ureteroscopy in swine [7] and also for laser lithotripsy of renal calculi in 18 human patients [8].

However, the Sensei is a standalone system with a dedicated operator interface and monitor. It uses a 4.67 mm (15 French) diameter catheter and costs several hundred thousand dollars. Researchers from Turkey have also developed a robot named “Arienna” for robotically assisted ureteroscopy [9]. This robot was clinically tested for treatment of kidney stones in 21 patients. However, this robot has a large footprint and occupies a large space in the procedure suite which could be disruptive for the clinical workflow. In this proposal, we present a robotic framework designed as an add-on module that can work with existing commercial ureteroscopes. Our robotic framework is much smaller, far less expensive, and does not disrupt the existing clinical workflow.

2. METHODS

In our robotically assisted scenario, once the urologist has obtained access to the kidney as described above, the ureteroscope would be placed in our robotic device, which would be positioned between the patient’s legs. The urologist could then manipulate the ureteroscope using a joystick control as described below. This workflow is shown in Figure 3 on the previous page and consists of the seven steps listed. The workflow follows the standard workflow except for the part between the pink boxes, where robotic assistance would be employed.

Our prototype system is shown in Figure 4. This robotic prototype allows independent control of the three degrees of freedom of the ureteroscope via brushless motors. Each degree of freedom of the robot is limited by electronic as well as mechanical limits. The robot provides a sterile interface for mounting the ureteroscope. Furthermore, the robot design facilitates a quick “snap-in” of the ureteroscope, thus allowing the ureteroscope to be mounted midway through the procedure.

To register the MR images to the kidney phantom, MR visible fiducials were placed on the phantom, and an electromagnetic tracker (Aurora, Northern Digital) is applied to track the

tip position relative to the image space. To determine the tip position, the paired-point registration method is applied as follows.

The kidney phantom with the fiducials attached was placed in the MRI machine and a series of axial images were obtained. The location of four fiducials was determined in MRI space. The same four fiducials were localized with the electromagnetically tracked ureteroscopy tip and paired-point registration was completed. Following this, the position of the ureteroscopy tip could be overlaid on the MRI images as the tip was moved.

To better visualize the tip in the image space, the volume rendering ray casting technique is applied based on the intensity and gradient values. Intensity values are determined from the dataset. By applying threshold to the intensity values, blank spaces could be removed to improve visualization. Gradient values are computed by the central difference gradient estimator method. The central difference method returns a normal vector for each voxel. The length of the normal vector is used as the gradient value. Higher gradient values indicate edge area with the higher intensity change. By applying a threshold to the gradient values, a better visualization could be acquired with the highlighted edges.

3. RESULTS

Our prototype system is shown in Figure 4. This robotic prototype allows independent control of the three degrees of freedom of the ureteroscope via brushless motors. Each degree of freedom of the robot is limited by electronic as well as mechanical limits. The robot provides a sterile interface for mounting the ureteroscope. Furthermore, the robot design facilitates a quick “snap-in” of the ureteroscope, thus allowing the ureteroscope to be mounted midway through the procedure.

The experimental setup is shown in Figure 5. The ureteroscope is attached to the robotic motion system (left side). The right side of the picture shows a ureter/kidney phantom (Ideal Anatomic, no longer in business). The electromagnetic tracking field generator was placed under the phantom and a catheter-based electromagnetically tracked sensor was introduced into the working channel of the ureteroscope and placed at the ureteroscope tip. A day before the test, fiducials were placed on the kidney phantom and a set of MRI images were obtained. These images were used to register the phantom to the electromagnetic tracking system as described in the previous section.

The software application is shown in Figure 6. The left side of the screen shows the intra-renal pelvis view from the ureteroscope (black dots indicate bad pixels on the laboratory scope used). A urology fellow used the robotic device and joystick to manipulate the scope to a red target wire placed in an upper pole renal calyx. The right side of images shows a four quadrant view from the reconstructed MR images after access to an upper pole calyx. In the four quadrant view, the top left is an axial view, the top right is a coronal view, the bottom left is a sagittal view, and the bottom right is a volume rendered view. The urology fellow found the interface intuitive to use and the views provided useful information about the position of the ureteroscope tip without having to use fluoroscopy.

It should be noted that the current work is based on pre-operative images and does not address the issue of respiratory motion. Respiratory motion is not typically a problem in diagnostic ureteroscopy, but can be an issue in procedures such as lasering of stones. One potential solution would be to add another tracked sensor to measure respiratory motion and implement a respiratory compensation method.

4. CONCLUSIONS

Robotically assisted ureteroscopy may improve the precision of minimally invasive kidney procedures while reducing radiation exposure for both the urologist and the patient. We have designed a “snap-in” robotic device to enable the urologist to power-drive the ureteroscope through the kidney. Preliminary experiments show the potential of the device. In future work, the system might be used in clinical practice to provide tip positioning guidance while minimizing the use of fluoroscopy. This could be done using a technique similar to “roadmapping” in Interventional Radiology. Fluoroscopy units typically have two monitors, one for a live image and one for a reference image. The urologist will often fill the renal pelvis and calyces with contrast and take a single fluoroscopic reference image. Then, as the scope is moved into different calyces, the urologist will take additional fluoroscopic images and compare the new live image with the reference image. If instead electromagnetic tracking could be used to track the ureteroscope tip, the tip could be tracked as it moves and the image updated in real-time without the need for additional fluoroscopy.

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Figure 1.

Dr. Craig Peters manipulating the ureteroscope during kidney exploration in the operating room. Dr. Peters is looking at the video image from the ureteroscope.

Figure 2. Conventional ureteroscope control mechanism allows three degrees of freedom – translation, rotation, and flexion.

Figure 3.
Clinical workflow for robotically assisted ureteroscopy

Figure 4. Left side shows 3D CAD model and right side shows working prototype of robotically assisted ureteroscopy device designed and built in our laboratory.

Figure 5. Experimental setup in lab showing ureterscope and robotic driver on left and phantom in water dish on right. Underneath phantom is the electromagnetic tracker field generator. Electromagnetic control box is in the middle.

Figure 6. User interface. Left side shows ureteroscopy live camera. Right shows different MR images and the ureteroscope tip EM-tracker (red square) in space: top-left shows axial slice, top-right shows coronal slice, bottom-left shows sagittal slice and bottom-right shows volume rendering