Development of a synchronous motion-tracking and video capture tool for flexible ureteroscopy

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ABSTRACT

Introduction: Hand/instrument motion-tracking in surgical simulation provides valuable data to improve psychomotor skills and can serve as a formative evaluation tool. Motion analysis has been well-studied in laparoscopic surgery; however, there are essentially no studies looking at motion-tracking for flexible ureteroscopy (fURS), a common surgical procedure requiring hand dexterity and 3D spatial awareness. We aimed to design a synchronized motion-tracking and video capture system for fURS capable of collecting objective metrics for use in surgical skills training.
Methods: Motion tracking of the ureteroscope was performed using a motion-tracking platform, inertial measurement units (IMUs), and an optical sensor. Position (x, y, z) and

KEY MESSAGES

- Hand/instrument motion-tracking in surgical simulation can provide valuable data to trainees to develop psychomotor skills.
- Our study outlines the development and validation of a motion-tracking and video-capture system for flexible ureteroscopy with unique metrics including lever deflection and scope translation at the insertion point.
- The collected metrics from our system has strong associations with categories used in validated evaluation checklists, such as the ureteroscopic global rating scale.

orientation (roll, pitch, yaw) of the ureteroscope handle, lever deflection, and translation of the scope insertion point were collected. Video capture of the operator’s hands was collected with a Raspberry Pi camera. All peripherals were controlled on a Raspberry Pi 4 and synchronized to its system clock.
Results: Our system demonstrated good accuracy in detecting translation of the ureteroscope in the x- and y-axes, and yaw, pitch and roll of the ureteroscope at discrete orientations of 0, ±30, ±60, and ±90 degrees. Unique to fURS, deflection of the lever was captured by the difference in IMU static accelerations with good accuracy. The optical sensor detected translation of the ureteroscope at the insertion point with good precision and an average error of 5.51%.
Conclusions: We successfully developed a motion-tracking and video-capture system capable of collecting motion-analysis parameters unique to fURS. Future studies will focus on establishing the construct validity of this tool.

INTRODUCTION

Flexible ureteroscopy (fURS) is a common surgical procedure for the management of upper urinary tract pathologies.1 Maneuvering a flexible ureteroscope efficiently and effectively is initially not intuitive to a junior learner, as this requires both hand dexterity and 3D (3-dimensional) spatial awareness. Performing fURS requires coordination of psychomotor skills, and, at times, fine rotational and translational movement of the ureteroscope in multiple degrees of freedom (DOF). Studies have shown that a trainee must complete around 60 cases to achieve a good level of competence, and 100 cases for complication rates to plateau.2 Numerous URS surgical simulation platforms have been developed to allow surgical trainees to tune their skills outside of the operating room.3-5 However, there remains a lack of objective constructive feedback to the trainee during simulation study, particularly with respect to how they can improve their specific hand/instrument motions.

It is well established that hand and instrument motion-tracking in surgical simulation can provide valuable educational information to the operator.6,7 Motion-tracking of psychomotor skills in laparoscopic surgery is well studied. Technologies implemented for motion-tracking include electromagnetic tracking systems, infrared cameras, accelerometers and optical sensors.7-10 Motion-analysis parameters (MAPs) such as operative time, path length, velocity, acceleration and jerk of the instrument have been reported to be able to distinguish between novice and expert laparoscopic operators.7,8,10-12 Heiliger et al. implemented instrument motion-tracking for a laparoscopic training course with inertial measurement units (IMUs) and demonstrated an ability to examine the learning progress of medical students in an ex-vivo environment.13 Hardon et al. delivered a laparoscopy training course with the integration of motion-tracking in its training goals paired with instant, objective feedback after each trial and reported an improvement in instrument-handling skills over time.14 Motion-tracking systems have the potential to serve as a formative evaluation tool by providing operators with feedback on how their psychomotor skills compare to operators of varying expertise and tracking learning progress over time.

Despite being well-established in laparoscopic training, there are limited studies that investigate motion-tracking in endoscopic procedures.15-17 Salvadó et al. utilized an electromagnetic tracking system to collect motion-tracking data in semi-rigid ureteroscopy and reported correlations between an operator's MAPs (time taken, path length, numbers of movements) and assessment scores from validated checklists: the Global Rating Scale (GRS) and urethral checklist (UC).18 There are numerous simulators developed for fURS, such as URO MentorTM (Simbionix Ltd., Israel) and Scope Trainer (Mediskills Ltd., United Kingdom); however, no URS simulators to date implement motion-tracking analysis feedback specifically for fURS.3, 4, 19-23 Learner performance with fURS simulators have been traditionally assessed with validated checklists, such as the procedural-specific GRS adapted by Matsumoto et al. for the endourological environment.24, 25 Checklist assessments rely on subjective expert observation and expert evaluator availability.7, 8, 26 Thus, designing a system which can provide objective data collection and feedback on an operator's instrument handling technique is valuable. Such a system would allow novice fURS operators to develop their psychomotor skills in a safe, monitored, and controlled setting prior to exposure to real patients. The primary objective of our study is to design and validate a synchronized motion-tracking and video-capture system for fURS.

METHODS

The tool was designed for a single-use flexible ureterorenoscope, EU-ScopeTM (Innovex Medical Co., Ltd., Shanghai, China). The tip deflection range is 275°. Institutional review board approval and written consent were not required as no human subjects participated in the study.

The hardware components of the tool include: 1) a Raspberry Pi (Raspberry Pi, United Kingdom), 2) the Patriot motion-tracking system (PolhemusTM Vermont, USA)27 3) two IMUs (SparkFun Electronics, Colorado, USA), 4) an optical sensor (JACK Enterprises, Tennessee, USA), 5) an Arduino Uno (Arduino Uno, Ivrea, Italy), 6) a Raspberry Pi camera, 7) an analog-to-usb video converter (Hauppauge, Pennsylvania, USA), and 8) 3D printed housing. The software components include: 1) the Patriot firmware, and 2) the user interface with control scripts.

Hardware

Raspberry pi

The Raspberry Pi 4 interfaces with the motion-tracking and video-capture peripherals (Fig. 1). It is a widely available platform at a lost cost ($40 CAD) with many interfaces for sensors and cameras.

Inertial measurement unit

Two IMUs were used to capture ureteroscope lever deflection. The tool implemented the MPU9250 IMU Breakout Board which consists of a 3D accelerometer, 3D gyroscope, and 3D magnetometer which measure static acceleration, angular rotation, and magnetic field strength. The IMUs are attached onto the side of the lever and on the handle inferior to the lever to measure deflection through the difference in static acceleration (Fig. 2A-B). The outputs are processed by 16-bit analog-to-digital converters (ADC). The sensitivity of the accelerometer can be set between 2 g-force (g) to 16 g. When operating at the range from -1 g to +1 g, it has a sensitivity of 0.005°/LSB (least significant bit). An alternative sensor for capturing deflection of the ureteroscope is a potentiometer, which captures rotational movement such as in a volume knob.

Optical sensor
The PMW3360 motion sensor board implements a PMW3360DM-T2QU (PixArt Imaging, Taiwan) navigation gaming sensor. Movement in the x- and y-axes is detected by acquiring images and performing digital image correlation. The sensor is placed above the insertion point to measure ureteroscope translation along its longitudinal axis (Fig. 2C, Fig. 3). A 16-bit output represents movement in counts per inch (CPI). The resolution can be programmed from a range of 100 to 12000 CPI (4 to 472 counts per mm). The frame rate is up to 12000 frames per second (fps). Optical sensors are commonly used in applications which require collection of translation. For example, they are utilized under gaming mouses to translate movement of the mouse on the desk to move the computer cursor with high accuracy.

Microcontroller
The Arduino Uno interfaces the optical sensor with the Pi. The Arduino Serial Peripheral Interface (SPI) library was used to communicate with the optical sensor. The Arduino is versatile, cost-effective, and has open-source software is available here: https://www.arduino.cc/en/software.28

Patriot system
The Patriot motion-tracking system uses electromagnetic technology. Our tool employs one standard RX2 sensor on the ureteroscope handle (Fig. 2A-B) which tracks six DOF to capture translational (forward-back, side-side, up-down) and rotational (roll, pitch, yaw) movements of the handle. Roll, pitch and yaw is the rotation about the ureteroscope's longitudinal, vertical and lateral axes, respectively (Fig. 3). The Patriot system samples at a rate of 60 Hz. The field source defines the x, y and z axes of the sensor outputs. Its optimal working range is 90 cm (Fig. 2D).

Raspberry pi camera module
The Raspberry Pi v2 camera module is powered by a IMX219 (Sony, Japan) 8-megapixel sensor. It records the operator's hand movements (Fig. 2D). It attaches to the Pi camera port via ribbon cable. The maximum resolution is 1920 x 1080 pixels at 30 fps.

Analog-to-USB video grabber
We used an analog to digital video converter, USB-Live 2, to capture endoscopic video. The analog (s-video) output from the video tower is collected, digitized and transmitted to the Pi at a resolution up to 1280 x 720 at 30 fps.

Housing for all peripherals

Housings for peripheral sensors were designed using a computer-aided design software, SolidWorks 2021 (Dassault Systèmes, San Diego, USA), and a 3D-printer, Ender 3 Pro (Creality, Shenzhen, China). The IMU housing consists of: 1) a press fit attachment to the lever and 2) a circular attachment to the handle inferior to the lever (Fig. 4). The Patriot sensor housing was attached to the inferior aspect of the ureteroscope's handle with a circular attachment. The optical sensor housing was positioned superior to the instrument port, with an opening for the sensor to acquire images over the tunnel for the ureteroscope. Except for the Patriot sensor, which was already self-contained, all housings were designed with a cover for water protection.

Software

Python user application
A user application was developed using the Python Tkinter package (Python Software Foundation, Wilmington, USA) which coordinates synchronous data collection (Fig. 5).

Motion-tracking data collection
The optical sensor is polled by the Arduino at a rate of 66Hz. The data is sent to the Pi via serial communication. The PyUSB package was used to read from and write to the Patriot system, available here: https://github.com/pyusb/pyusb. IMU data was collected using the open-source mpu9250-jmdev Python package, developed by Jeferson Menegazzo.[29] All data from the sensors were sampled at an average rate of 25 Hz by the Pi and saved with the Pi system's timestamps to a ".csv" file for post-processing.

Video-capture collection
The video images captured by the camera module were displayed on the graphical user interface (Fig. 4). The video captured by the analog to USB video converter was sent to the Pi via the USB 2.0 port. The Fast Forward Motion Picture Experts Group (FFmpeg) library, available here: https://ffmpeg.org/ffmpeg.html, was used to record the captured video at a frame rate of 25 fps. The video was encoded using H264 compression and saved as an ".avi" file.

Testing

Optical sensor
Translation of the ureteroscope was measured by the optical sensor at the insertion point. A series of 10 trials were conducted for distances of 25, 50, and 100 mm along the longitudinal axis of the ureteroscope. The actual translation was measured by an electronic caliper.

IMU and Patriot
The translation and orientation of the ureteroscope handle was measured by the Patriot system. The deflection of the ureteroscope lever was measured by the IMUs on the lever and handle. The Patriot and IMUs are well validated. Therefore, tests were conducted to demonstrate that the sensors were capturing movement as expected.

Translation of the ureteroscope was tested by moving 300 mm along the x and y-axes of the working space. The Patriot source which defines the reference axes was placed approximately 300 mm away from the simulator box, such that the working space included the area in front of the simulator box (Fig. 2). Roll, pitch and yaw of the ureteroscope handle were tested within the -90 to +90° range by orienting the ureteroscope at 0, ±30, ±60 and ±90° with reference to a 30-60-90 triangle. The deflection of the lever was tested within its full range.

RESULTS

Rotation of the ureteroscope is depicted in Fig. 6A-C as discrete orientation changes at 0, ±30, ±60 and ±90° along the yaw, pitch and roll axes. Negative orientation data was shifted to be in the positive range (0-360°). Translation of the ureteroscope 300 mm in the x and y axes is depicted in Fig. 6D as discrete positional changes. The deflection of the lever up, down and back to neutral is depicted in Fig. 7. The data was post-processed with a Butterworth filter with a normalized cut-off frequency of 0.2.

The optical sensor demonstrated an average error of 5.51% across all three distances. The percent error corresponds to a discrepancy between the actual distance measured and the distance detected by the sensor, which was between 1.37 to 5.37 mm. The highest standard deviation across all trials was 2.02 mm (Table 1).

DISCUSSION

We developed a novel motion-tracking and video-capture tool for fURS. We demonstrated good accuracy in capturing the movement and rotation of the ureteroscope handle. We also captured the operator's manipulation of the ureteroscope's lever, which is associated with the deflection of the ureteroscope tip. The tool's ability to capture translation of the ureteroscope at the insertion point was tested and demonstrated good accuracy and precision. The tool was able to simultaneously video-capture the operator's hand movements. System synchronization was confirmed visually between the video playback and the motion-tracking output system timestamps.

The testing demonstrates the ability of the tool to capture MAPs similar to those reported in previous studies for laparoscopy and semi-rigid ureteroscopy. Salvadó et al. collected hand-motion data for semi-rigid ureteroscopy and reported MAPs such as time to task completion and number of hand movements as discriminatory between expert and novice operators.18 Similarly, our tool records the time taken to complete a task, and goes well beyond a simple count of hand movements. Van Empel et al. utilized motion-tracking to analyze a knot square-tying task in laparoscopy and reported that the 3D space (volume, mm3) used by the operator's hand was significantly smaller in expert operators.11 Similarly, our tool can extrapolate total working space through positional changes of the handle. Our tool also had a similar average error in detecting translation of a laparoscopic simulator which used an optical sensor at the insertion point of the instrument (5.51% in our study vs. 6.75% and 5.4% for right and left-handed laparoscopic instruments).30

Our system is designed specifically for fURS training; and, therefore, there were additional MAPs we sought to capture. First, movement of the ureteroscope handle is dictated by the dominant hand. However, the non-dominant hand is often responsible for guiding the ureteroscope tip into the access sheath. Operators can manipulate the instrument at this point independent of the ureteroscope handle. Our tool can accurately and precisely report translation of the ureteroscope at the insertion point by placement of the optical sensor above it. Second, compared to laparoscopy, the manipulation of the ureteroscope lever plays a crucial role in visualization of anatomy and the ability to complete a task. Our tool captures the extent of lever manipulation through the difference in static acceleration of the IMUs attached to the lever and handle. The rotation of the ureteroscope handle also factors into visualization of structures. Koo et al. reported preliminary findings where roll of the ureteroscope handle was less pronounced in experts compared to novices using the Patriot system.5 Our tool reports handle rotation to a good level of accuracy about all three axes. With these metrics, we have developed a tool capable of robustly capturing clinically relevant movements in fURS.

Virtual reality (VR) simulators are becoming increasingly popular in the surgical simulation space. Uro Mentor is an example of a simulator for both rigid and flexible ureteroscopy which incorporates motion-tracking analysis. However, VR systems can cost upwards to $70,000 CAD.31 In addition, the simulator requires space in an operating room and various equipment including a mannequin, and requires the operator to wear a bulky headpiece.32 There is a high level of simulation achieved with VR but at additional costs and resources, which may only be accessible to large endourological centres.

A strength of our system is that its motion-tracking and video-capture data has strong associations with categories used in validated evaluation checklists, such as the ureteroscopic GRS.24 For example, the "Time and Motion" category assesses optimization of time and number of movements made, which can be identified from time to task completion and number of unnecessary movements identified on video-capture. Two categories, "Instrument Handling" and "Handling of Endoscope," assess for smooth movements and a well-centered ureteroscope. We can assess the smoothness of the operator's movements by calculating the number of directional changes made with respect to the ureteroscope's position. We can determine how often the ureteroscope's center changes by calculating the number of orientation changes in each DOF. We anticipate that our tool will eventually be able to go beyond the current validated checklists in assessing learner skill acquisition because it is able to accurately and objectively capture all relevant DOF associated with fURS. In a simulation setting, this tool has the potential to inform the learner of which exact movements are unnecessary. By providing this feedback immediately and objectively without an expert instructor watching, we are hopeful that our tool will shorten the fURS learning curve.

There are several limitations to our system. The system integrates Patriot, a commercial system which has accurate motion-tracking capabilities, but adds a substantial cost. However, Koo et al. demonstrate that the Patriot has capability to distinguish between expert and novice operators in fURS when looking at differences in roll of the ureteroscope.5 The novel metrics gathered in the system (i.e. insertion point translation, lever deflection) utilizes off-the-shelf components (i.e. IMU, optical sensors) making it more accessible for interested researchers to replicate these components. Due to our focus on motion analysis, the system does not yet integrate force measurements, which is important when learning how to properly handle tissue in endoscopic procedures.33 However, haptic feedback is more relevant for semi-rigid URS rather than flexible URS which has limited tactile feedback.31 The system also cannot assess non-technical skills such as leadership and situational awareness. Goldenberg et al. and Brunckhorst et al. both mention this limitation in most methods of assessment for surgical skills.22, 23

Our system will be the subject of future studies. The next step would be to implement a study which assesses the system's construct validity. Specifically, it would be important to determine which MAPs specific to fURS can discriminate between expert and novice operators. Ultimately, would the tool have potential to serve as an objective measure of performance and provide trainees with insight into areas for improvement?

CONCLUSIONS

We have designed a motion-tracking and video-capture system for fURS. It is capable of collecting novel MAPs deemed important in fURS. The next step will be establishing the construct validity of the system for a particular ureteroscopy task, such as visualization of calyces.

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FIGURES AND TABLES

Figure 1. Diagram of connections between Raspberry Pi 4 and all system peripherals. The Pi has USB 2.0 and 3.0 ports, inter-Integrated Circuit (I2C) communication protocols, and a Camera Serial Interface (CSI) camera port. The Pi is controlled by the user remotely through a personal computer with Secure Shell Protocol (SSH).

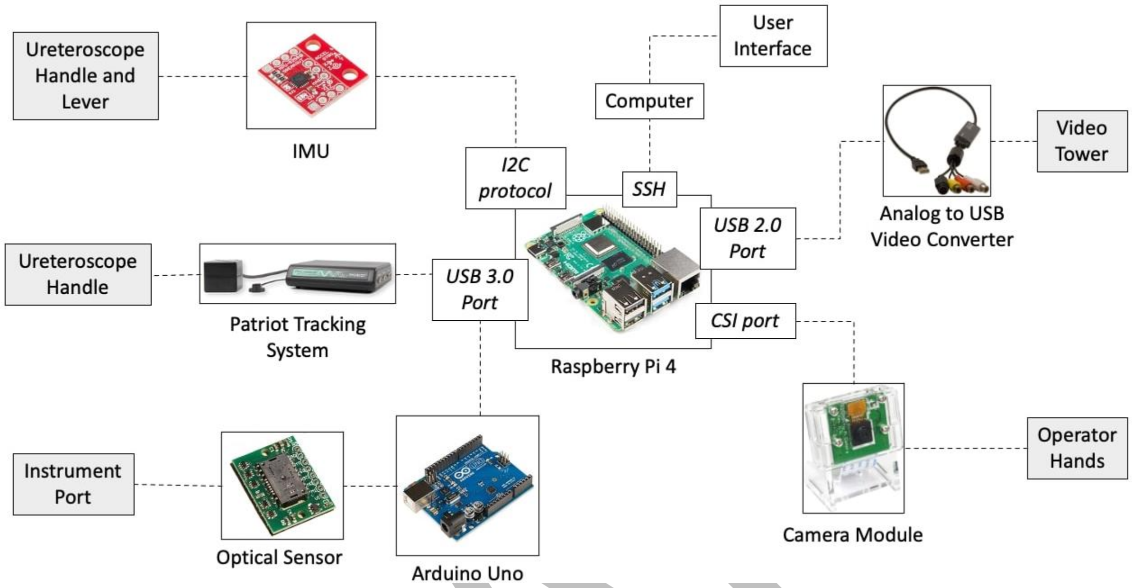

Figure 2. Complete motion-tracking and video-capture tool. A) B) Inertial measurement unit and Patriot standard sensor fitted onto the single-use flexible ureterorenoscope. C) Optical sensor fitted to project above the insertion point of the ureteroscope onto a simulator box. D) Complete view of tool with Patriot source (i.e., reference coordinates for x, y and z axes) and Raspberry Pi camera module pointing toward operator's hands.

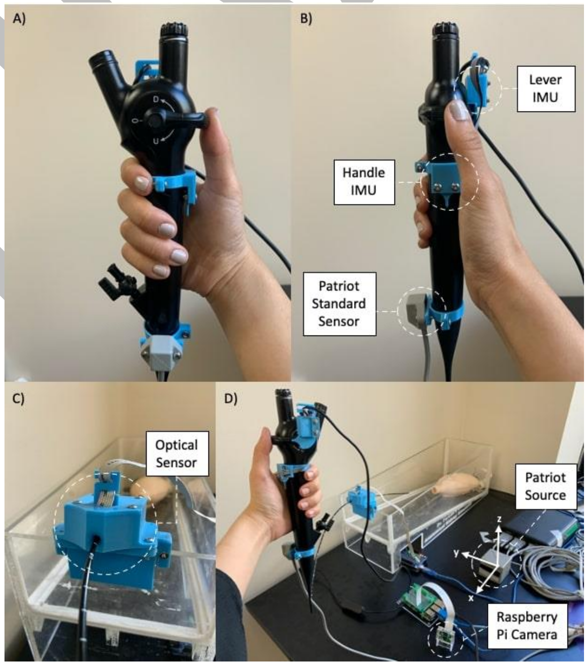

Figure 3. Illustration of the measurement of roll, pitch and yaw in relation to the rotational movement of the ureteroscope, and translation at the insertion point.

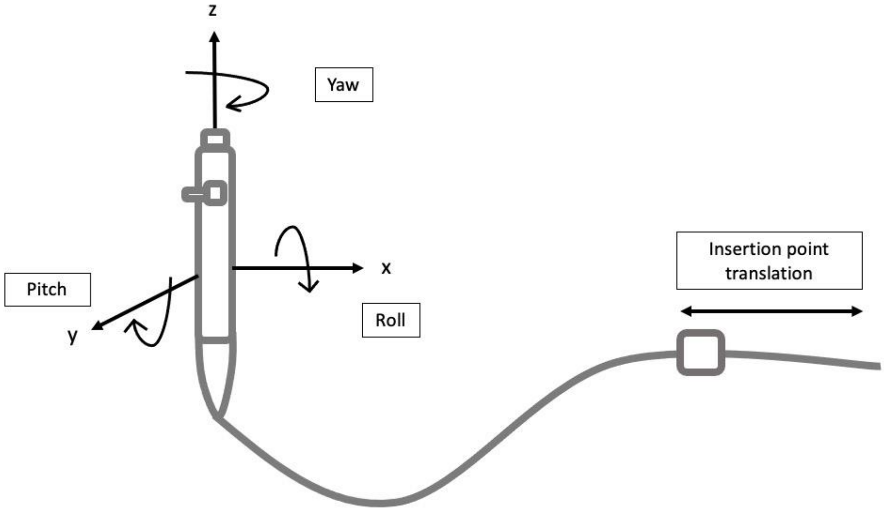

Figure 4. Diagrams of sensor mounts and components used in the motion-tracking system. (A) Mounts for two internal measurement units and Patriot sensor used on the ureteroscope. (B) Attachment clip (bottom) and the housing (center) for the optical sensor.

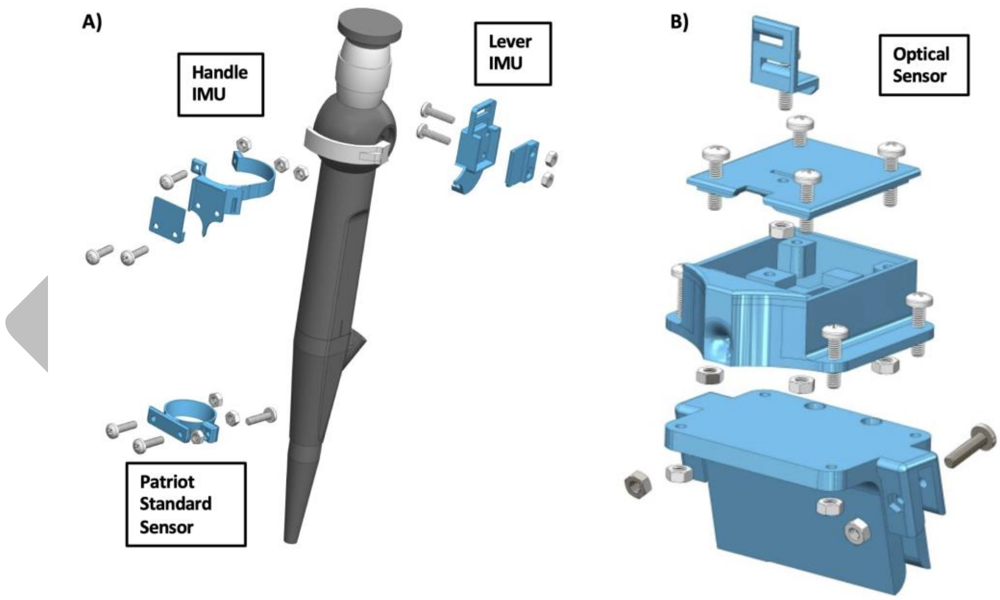

Figure 5. Graphical user interface to control the system with buttons to connect all peripherals and start and stop data collection with the Raspberry Pi. The user interface refreshes every 100th data frame to indicate ongoing data collection and video capture of the operator hands.

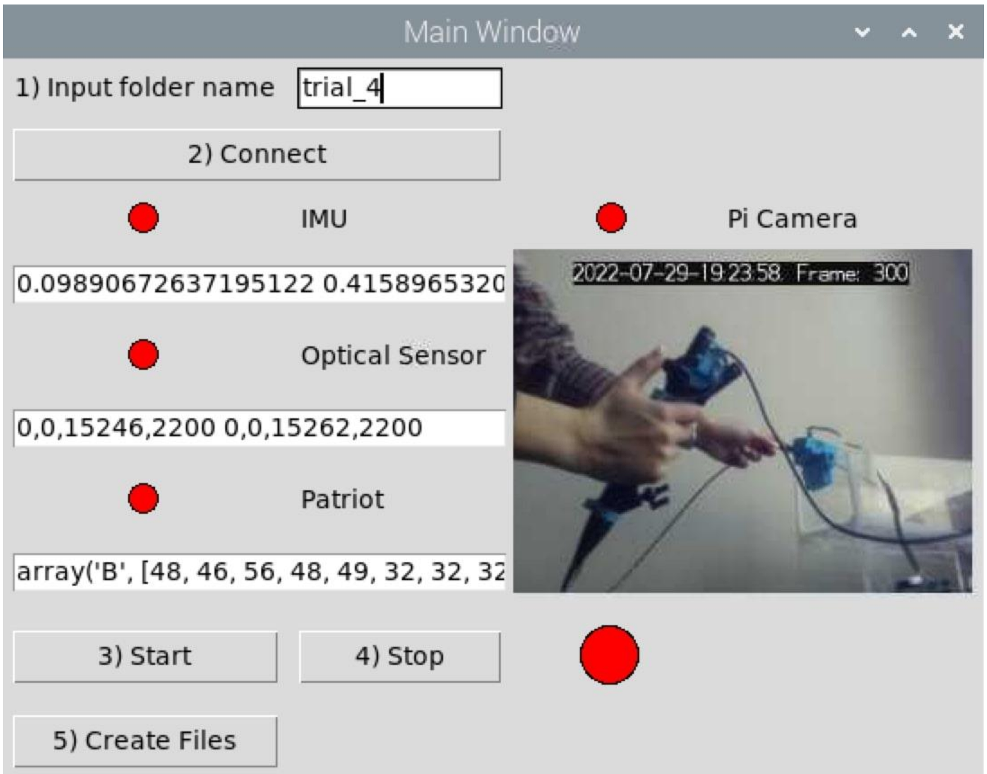

Figure 6. Position and absolute orientation data collected from the Polhemus Patriot sensor attached to the ureteroscope handle. Orientation data when rotating ureteroscope (A) in the z-axis (roll); (B) in the y-axis (pitch) from 5 to 365 degrees; (C) in the x-axis (yaw). (D) Position data when translating scope 300 mm along the x-axis (+), y-axis (+), x-axis (-), and y-axis (-) every 10 seconds.

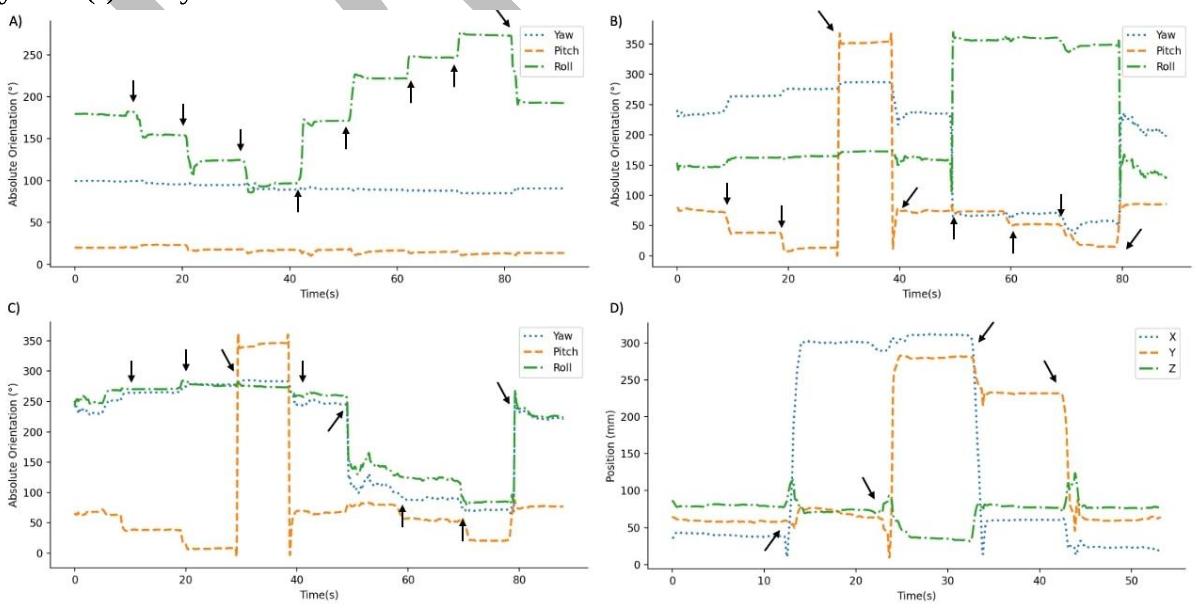

Figure 7. Difference in static acceleration of the IMU attached to the lever of the ureteroscope when moving the lever up, down to neutral, down and up to neutral (full range of motion) to the IMU attached to the handle. Lever motion is associated with 275° deflection of the ureteroscope tip.

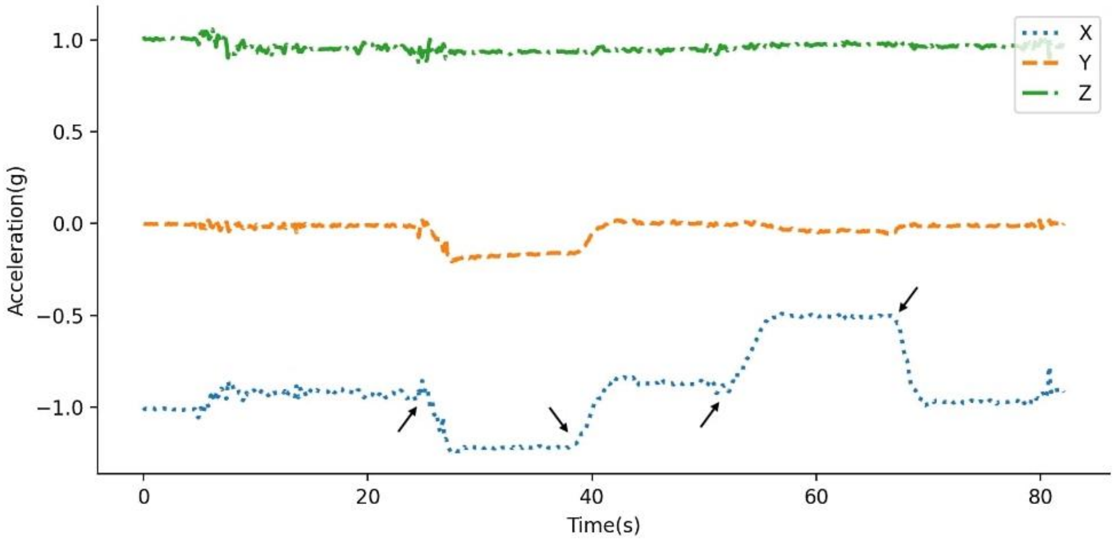

Table 1. Optical sensor accuracy testing for measurement of translation of ureteroscope along longitudinal axis			
	Electronic caliper distance (mm)	**Sensor reported mean distance ± SD (mm)**	**Error (%)**
Optical sensor	24.93	23.56 ± 1.30	1.37 (5.49)
	50.22	47.37 ± 0.80	2.85 (5.68)
	100.42	95.05 ± 2.02	5.37 (5.35)
Average error			3.20 (5.51)

SD: standard deviation.