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A 4-DOF Robot for Positioning Ultrasound Imaging Catheters

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Abstract

In this paper we present the design, fabrication, and testing of a robot for automatically positioning ultrasound imaging catheters. Our system will point ultrasound (US) catheters to provide real-time imaging of anatomical structures and working instruments during minimally invasive surgeries. Manually navigating US catheters is difficult and requires extensive training in order to aim the US imager at desired targets. Therefore, a four DOF robotic system was developed to automatically navigate US imaging catheters for enhanced imaging. A rotational transmission enables three DOF for pitch, yaw, and roll of the imager. This transmission is translated by the fourth DOF. An accuracy analysis was conducted to calculate the maximum allowable joint motion error. Rotational joints must be accurate to within 1.5° and the translational joint must be accurate within 1.4 mm. Motion tests were then conducted to validate the accuracy of the robot. The average resulting errors in positioning of the rotational joints were measured to be 0.28°-0.38° with average measured backlash error 0.44°. Average translational positioning and backlash errors were measured to be significantly lower than the reported accuracy of the position sensor. The resulting joint motion errors were well within the required specifications for accurate robot motion. Such effective navigation of US imaging catheters will enable better visualization in various procedures ranging from cardiac arrhythmia treatment to tumor removal in urological cases.

Introduction

Long, thin flexible instruments such as catheters are used to perform an ever-increasing range of minimally invasive procedures. Catheters are useful because it is possible to gain surgical access to difficult-to-reach anatomical regions with significantly less trauma to the patient when compared with conventional surgical techniques. However, catheters are difficult to manipulate precisely, and navigational imaging options are limited by expense and clinical feasibility. Therefore, these instruments are limited in functionality to performing mostly simple tasks that do not require high positioning accuracy. Stent placement and balloon angioplasty [1] are examples of tasks which require careful placement in 1D, but do not involve accurate 3D navigation or dexterous manipulation of tissue.

Ultrasound (US) imaging catheters, which contain an US transducer at the distal tip of the catheter, are useful for acquiring images from within the patient. These instruments, used routinely for over a decade in clinical practice [2], are advantageous in comparison with external probes because targets can be visualized with higher acoustic frequencies in the near-field. Signals from external probes provide lower quality imaging due to attenuation by intervening layers of muscle, fat, and other tissue. However, the difficulty in manually controlling these US catheters is a disadvantage compared with external probes. Clinicians maneuver US catheters by adjusting control knobs and advancing/rotating the catheter handle (Fig. 1). Steering the US imager and aligning the plane with a target to obtain adequate views is a challenging and time-consuming process. Therefore, many clinicians prefer to only use US catheters while performing critical tasks. An example of a critical task is septal puncture [1], in which the risk of atrial perforation and subsequent morbidity is high.

To increase the utility of these high-quality imaging devices, we developed a robotic system for automatically guiding US imaging catheters within the heart [3-5]. The system was used to demonstrate millimeter-level positioning accuracy and sub-degree-level angular steering accuracy in bench-top experiments. These techniques enabled complex control of the US catheter to be performed with simple commands. For example, the system was used to rotate the US imager about its own axis without displacing the catheter (Fig. 2 (*left*)). This is useful for collecting a series of 2D images and reconstructing high-quality 3D and 4D volumes (3D + time) for procedure guidance or diagnosis while keeping the US catheter fixed in a safe location. The system is also able to align the US plane with working instruments inside the heart. As instruments are navigated throughout the workspace, the system maintains imager alignment, enabling constant visualization of instrument-tissue interactions (Fig. 2 (*right*)).

In our previous work, the physical implementation of the system was designed for initial prototyping of the robotic system and demonstrating the imager-steering functionality. As the US catheter steering system is made ready for testing in animal models it was necessary to design, fabricate, and test a new method for mating actuators to the catheter handle. The new robot is smaller, lighter, more portable, and more robust. US catheters can be inserted, clamped into the robot, and removed within 10 seconds. The fast installation time is necessary in order for the robot system to be clinically feasible. The following sections of this paper begin with an overview of the robotic system. The transmission of the catheter steering robot is presented and the motion of each joint is characterized to verify positioning accuracy. The new four degree of freedom (4-DOF) robot for positioning US imaging catheters is robust, easily integrates with existing clinical practices, and will enable safe US imaging in a range of surgical procedures.

Background

This paper focuses on the design, fabrication, and testing of the actuation module which manipulates the catheter. However, the actuation module is one component of a larger robotic system (Fig. 3) for steering US catheters to provide enhanced US imaging for clinicians. The system consists of the following parts:

1. Actuation module
2. Sensing
3. Steering control
4. Ultrasound machine
5. Image processing
6. User interface

The position and orientation of the catheter tip are controlled by sensing the catheter pose and adjusting the motor outputs in an iterative loop until the desired pose is reached. The pose is sensed by electromagnetic (EM) trackers attached to the tip of the catheter. The steering control module (described in previous work [3, 4]) directs the motion of the US catheter tip. EM sensor values and inverse kinematics based calculations are used to determine motor outputs. The kinematic model describes the relationships between the imaging plane orientation, tip location, and catheter controls. The US machine, which displays US images to the clinician, is also connected to the computer through a frame grabber. The computer contains an image processing module for recording 2D images and reconstructing useful panoramas of anatomical regions. Through the user interface, the clinician can designate what regions of the anatomy to image, begin instrument tracking, or detach the catheter from the robot to manually navigate the catheter if desired.

Our system provides functionality that is different from commercially available catheter robots. Existing systems such as the Amigo (Catheter Robotics, USA) and CorPath (Corindus, USA) simply replicate manual joint space control knobs and allow clinicians to remotely teleoperate the catheter from a shielded room [6, 7]. This improves operator comfort and reduces radiation exposure from fluoroscopic imaging, but does not reduce the difficulty in understanding the necessary knob adjustments needed to navigate catheters. The Artisan (Hansen Medical, USA) and EPOCH/V-Drive (Stereotaxis, USA) systems feature limited Cartesian control, but they do not control the orientation of the catheter, which is necessary for aiming the US imager [8-11]. By fully articulating the four DOFs of US catheters, our system is able to control the position of the catheter and one DOF of its orientation.

Methods

The clinician-friendly robot (Figs. 4-6) was designed to position 4-DOF US imaging catheters in an animal operating room setting. It was designed to mate with the handle of any size AcuNav intracardiac echocardiography catheter (Biosense Webster, USA), and the mating profile could easily be adjusted to fit other types of catheter handles. The first DOF translates the catheter along its axial direction (Fig. 1). This motion is necessary for advancing or retracting the catheter further into or out of the patient. The second DOF twists the L/R (pitch) knob to create a catheter bending motion and pitch the US imager. The third DOF twists the P/A (yaw) knob to create a catheter bending motion which causes the imager to experience yaw. The fourth DOF rotates the handle of the catheter to produce a roll motion about the axis of the catheter. Hard stops inside the catheter limit pitch and yaw axis rotations to ±90° relative to the catheter handle. The translation stage was designed to allow 15 cm of travel. These limits are enforced in software with a factor of safety to prevent collisions with hard stops. The roll axis was designed to enable continuous rotation.

The translation stage travels along a linear slide and is actuated by a fast-motion lead screw with 1.27 cm of travel per rotation. This joint motion can be actuated independently of the other joints. Ball bearings are attached at both ends of the lead screw to ensure smoother operation.

The rotational transmission consists of multiple helical gears that are attached to concentrically rotating parts and constrained by ball bearings. The transmission for the pitch and yaw DOFs consists of multiple components (Fig. 4): Part (A), which is fitted to the P/A knob, Part (B), a bearing ring which positions eight ball bearings equidistantly around the grooved circumference of the knob, and Part (C), a cover to constrain the ball bearings in the axial direction. Each of these three parts can rotate independently of each other. Part (D) of the pitch DOF, which is fitted to the L/R knob, is fully coupled to Part (C) of the pitch DOF. Part (E) is a second bearing ring which positions eight balls in place. Part F is a second cover which constrains the ball bearings on the pitch driver. The roll DOF consists of Part (G), which is a round knob mated directly to the catheter handle by a set screw clamp, and is fully coupled to Part (F). Components related to yaw motion are colored pink, components related to pitch motion are colored green, and components related to roll motion are colored blue. The catheter handle is shown in teal. The fully constructed robot is pictured in Fig. 7.

The transmission for the three rotational DOFs was designed such that pitch, yaw, and roll actuators are mechanically attached to the translation stage. This results in a smaller footprint, which is advantageous in the clinical setting. The alternate method is for the pitch and yaw actuators to be mechanically grounded to the catheter handle, which decouples all four DOFs and simplifies the control, but increases the inertial loads on the roll axis. Pitch and yaw can be actuated independently of other joint motions. Lubricant was applied to the rotational joints to reduce friction. Roll motion causes the entire catheter to rotate, which causes the relative positions of the pitch and yaw knobs on the catheter to change, thereby bending the catheter in unwanted motion. All roll motion must therefore be accompanied by complementary pitch and yaw rotations in order to maintain the desired knob positions on the catheter handle. This necessary compensation of pitch and yaw for roll motion is calculated in the robot software. The effectiveness of pitch and yaw compensation, as well as the accuracy of motion for each joint, is examined in the next section.

Each DOF is actuated by a servo-controlled DC motor (Maxon Motors, Switzerland). Motor signals (generated by the steering controller) are sent to four EPOS2 controllers, which perform fast low-level control cycles on the motor positions of each individual actuator. The translation motor has an 84:1 gear reduction and is coupled to the fast-motion lead screw by a shaft coupling. Each of the three rotational joint motors has a 53:1 gear reduction, and is connected to a smaller helical gear on the output shaft. These helical gears are mated with helical gear teeth on the Part (A-D-G) components of the yaw, pitch, and roll knobs. The gear ratio for each of the three rotational joints is 2.54. The motor mounts were designed such that the distance from the motor to the catheter is adjustable. A screw (not shown) on each of the three motor mounts is tightened to bring the helical gears together. A tighter connection will decrease backlash at the expense of increasing forces in the transmission. The screws were adjusted to decrease the backlash as much as possible without compromising the structure of the robot.

The knobs that engage with the catheter handle and the helical gears that connect the motors to the knobs were 3D printed using VeroBlue material (Objet, USA). The catheter cage, which grounds the catheter and the knobs to the translation stage, was constructed from 6.5 mm thick acrylic.

In a typical operating workflow the clinician connects the US catheter to the transducer adapter for the US machine, manually introduces the US catheter to the vasculature, and then manually navigates the tip of the catheter to the general region of interest. At this point the clinician may unclip the transducer adapter, insert the catheter handle into the robot, squeeze the handle clamp, secure the catheter in place using a wing screw, and reattach the transducer adapter. This process is easily reversed to remove the catheter and resume manual control. The connections between the catheter handle and the robot enable clinicians to be able to remove the catheter and reinsert the catheter in less than 10 seconds.

The steering controller relies on two types of measurements in order to accurately position the catheter tip and point at desired targets. First, readings from the encoders on the actuators serve as measurements for the controller to assume precisely where the joints are positioned. Second, measurements from the EM tracker at the tip of the catheter enable the controller to know the full pose of US imager. The accuracy of the US imager pose is limited by the accuracy of the EM tracking system (trakSTAR, Northern Digital Inc., Canada), which is rated at 1.4 mm in position and 0.5° in orientation. The relationship between the joint inputs and the catheter tip bending output is sensitive such that 1.5° of the pitch or yaw joints produces average 1.4 mm motion at the tip. Therefore, it is important to prove that the physical implementation of the robot is able to position the rotational joint inputs by the desired angular adjustment within 1.5° and to adjust the translational joint to the desired position within 1.4 mm. This level of accuracy is sufficient for navigating the US imager to the desired location and pointing in the desired direction.

Experiments and Results

The robotic US catheter steering system depends on accurate positioning and orientation steering in order to visualize the desired anatomical features and track the clinician's working instruments. In this section we identify potential error sources resulting from mechanical design and implementation, and then we test the motion of the robot to experimentally determine the accuracy. A high-resolution optical tracking system (Claron Technology Inc., Canada) with root mean square (RMS) accuracy 0.25 mm was used to collect position measurements at roughly 20 Hz.

The linear motion of the translation axis was first examined in order to verify that the axial deviation of the nut travelling on the lead screw is as small as possible. An optical tracking marker was placed on the lead screw nut and its displacement was measured by the tracker while the translation axis was made to traverse its full 15 cm range of motion 10 times. The position measurements of the linear stage were compared with the desired straight path. The distance from each measured point to the desired straight line was calculated for each of the 4460 data points (Fig. 8). The average deviation from the centerline was calculated to be 0.0738 mm, which is less than the specified resolution of the position sensor.

Next, the backlash in the translation stage was examined. The rated backlash in the actuator gearhead is 1.6°. This amount of gearhead backlash is expected to cause up to 0.226 mm backlash when switching the direction of linear motion. Additionally, errors and misalignments in the mounting of the lead screw and motor shaft coupling may also contribute to the translation motion error.

The motor was actuated to drive forwards and cause the lead screw to engage with the lead screw nut in the positive direction. Then the position of the linear stage was measured while the stage was driven forwards and backwards by a constant distance of 2.4 mm. During direction changes, a small amount of distance was lost as the lead screw rotated to engage with the threads in the opposite direction. This test was conducted 10 times with different constant distances (2.4 mm, 5.9 mm, and 11.8 mm). The average measured backlash was 0.011 mm, which is less than the specified resolution of the position sensor. Therefore, despite the backlash error in the translation axis, the ability of the system to linearly translate the robot is more accurate than the EM tracker positioning error 1.4 mm.

The rotational transmission consists of three separate actuators to rotate pitch, yaw, and roll. Friction exists between the ball bearings separating the three joints, causing each joint to exert a small rotation on neighboring joints when actuated. These small joint motions are allowed by the backlash between helical gears. This effect was studied by attaching optical tracking markers to each of the three knobs and measuring the rotation of all three knobs continuously during actuation of one knob.

First, the pitch joint was repeatedly actuated in increments of 1.70°. Fig. 9 (*top*) shows the resulting effect on the yaw and roll joints. The yaw and roll joints experienced average unwanted rotation of 0.28° and 0.38°, respectively. Second, the yaw joint was repeatedly actuated in increments of 1.77°. Fig. 9 (*middle*) shows the resulting effect on the pitch and roll joints. The pitch and roll joints experienced average unwanted rotation of 0.38° and 0.28°, respectively. Third, the roll joint was repeatedly actuated in increments of 1.82°. The pitch and yaw joints were also actuated in increments of 1.82° to ensure that the relative rotations of the knobs with respect to the catheter handle remained constant during roll actuation. Fig. 9 (*bottom*) shows the resulting rotations of all three joints. At each point during rotation the average angle error between pitch and roll was 0.028°. The average angle error between yaw and roll was 0.031°.

The total backlash in each rotational joint of the robot is a combination of the backlash in the gearhead (rated at 1.6°) and the helical gears, with fasteners and material strain contributing a negligible amount of backlash. The total backlash was measured by rotating each joint by 8.21° and changing directions repeatedly. Hysteresis curves are shown in Fig. 10. The yaw, pitch, and roll joints experience average 0.44° of backlash when changing directions. This error due to backlash is approximately 70% less than the allowable joint position error, 1.5°. Therefore, the joint motions are sufficiently accurate to manipulate the US catheter knobs.

Conclusion and Future Work

An accurate actuation module is necessary for providing a clinically relevant robotic system for steering US catheters. In our study, we have demonstrated that our new robotic system satisfies the desired accuracy specifications. The level of accuracy required was determined by the relationships between joint inputs and catheter tip outputs. Measurements of the robot motion with the high-resolution optical tracker demonstrated that the robot is capable of positioning its joints with sub-millimeter and sub-degree level accuracy. These errors are the results of friction in custom designed ball bearing joints, small inaccuracies in the fabrication and assembly stages of the robot, limited resolution of encoders measuring motor positions, limited resolution of the optical tracker, and noise in the experimental setting. Based on the analysis presented in the Methods section, we have demonstrated that the errors in the physical implementation of the robot are small enough to be assumed as negligible. Many of the joint motion errors were measured to be less than the specified accuracy of the optical tracker. A more accurate sensor would be necessary in order to more accurately measure the joint-level positioning ability of the robot.

The robotic system presented here offers a smaller footprint than our previous system, which is crucial for a clinical robot. The attachment and detachment procedure for the US catheter has been entirely redesigned, greatly reducing catheter reattachment time from 50 minutes to less than 10 seconds.

Future work will involve installing the new actuation module into the robotic system. The robot will perform US imaging during surgical procedures in an animal model. During the procedure the image processing module will create panoramas showing specific regions of the patient's anatomy in 4D (3D plus time). Additionally, the robot system will be configured to track a target (such as another catheter) during a surgical procedure. The system will steer the US catheter to direct the imager at the target, thereby visualization instrument-tissue interactions during the procedure. Experimental validation of the actuation module has demonstrated that the US catheter can be manipulated with sufficient accuracy to achieve enhanced visualizations during catheter-based procedures.

Acknowledgments

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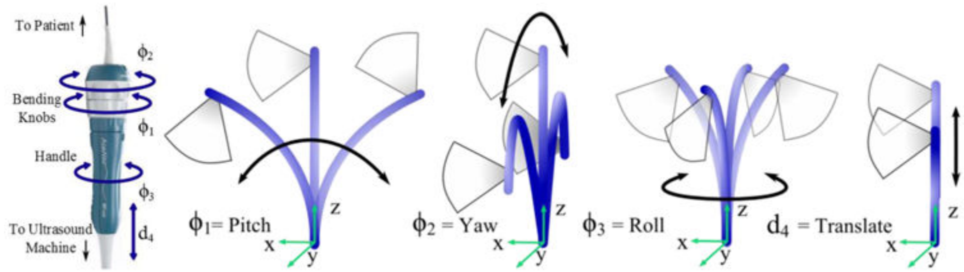

Figure 1. Catheter handle degrees of freedom and resulting Catheter tip motions

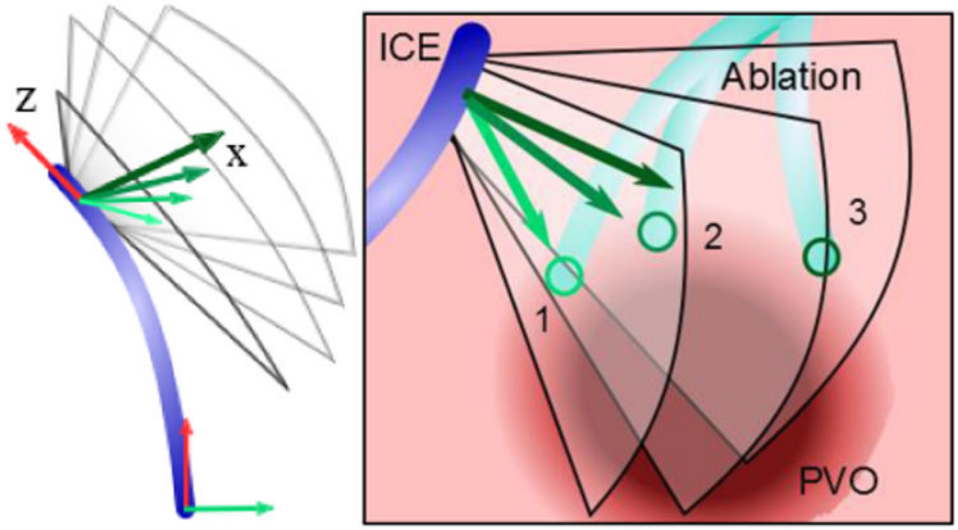

Figure 2. (*left*) Diagram of Catheter motion during Panorama image collection, (*right*) Diagram of Instrument Tracking

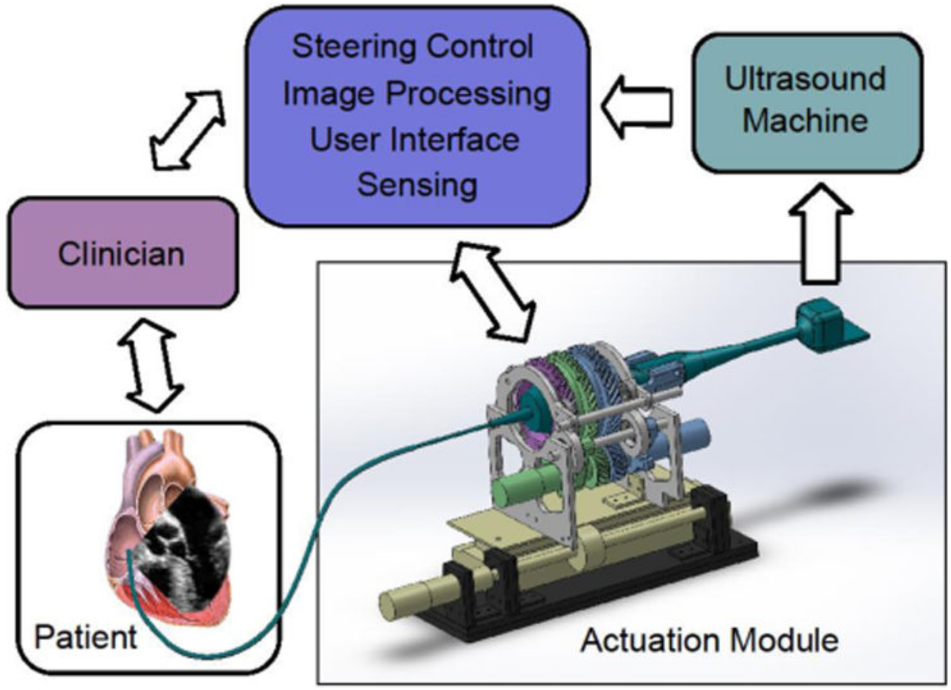

Figure 3. System Diagram

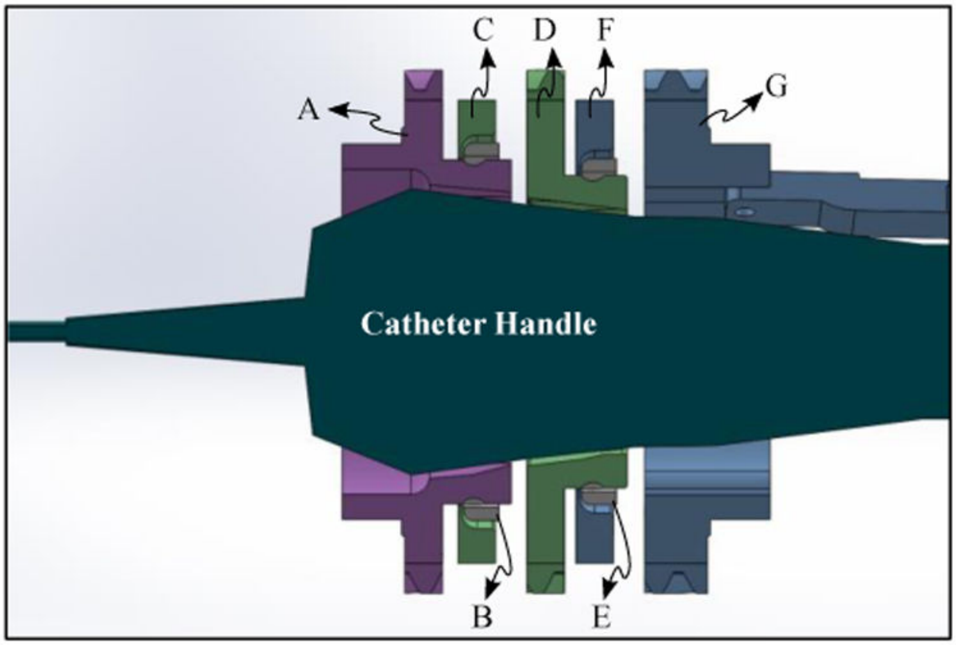

Figure 4.

Cross-Sectional view showing knob interactions with the Catheter. Parts (A,B) enable yaw, parts (B,C,D,E) enable pitch, parts (E,F,G) enable roll.

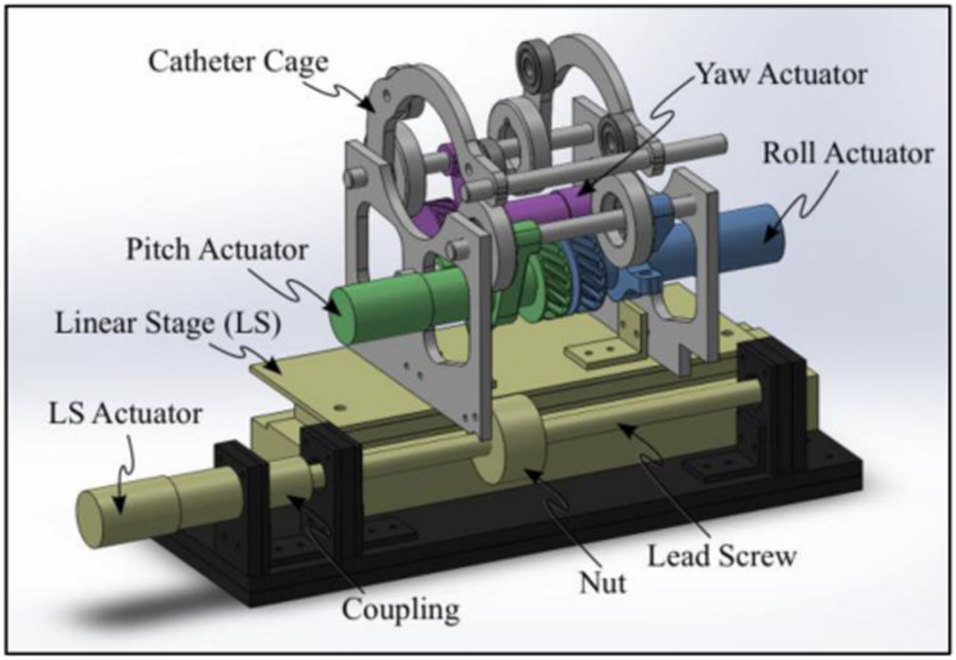

Figure 5. Cad model showing Actuator arrangement

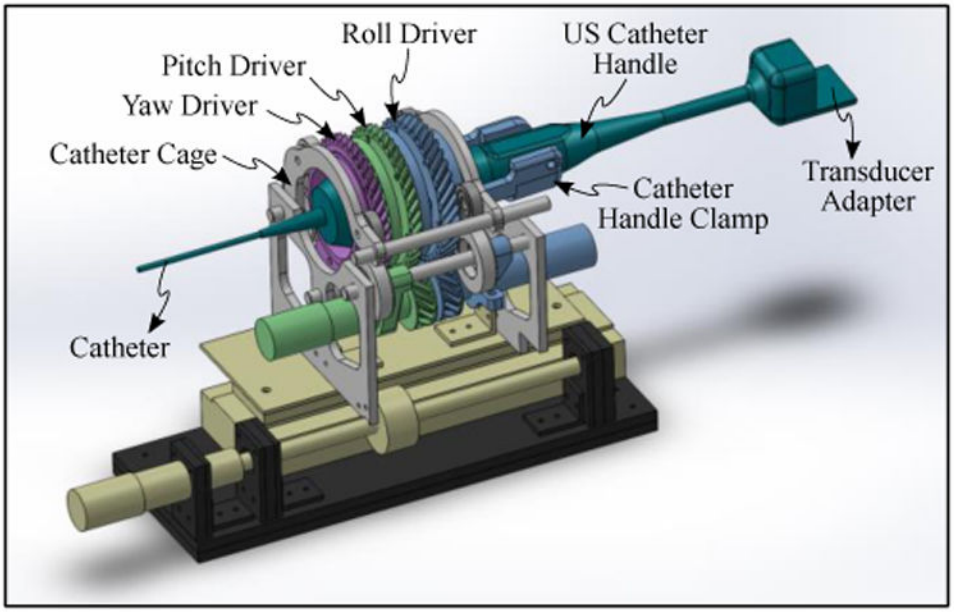

Figure 6. Cad model of the complete Robotic System

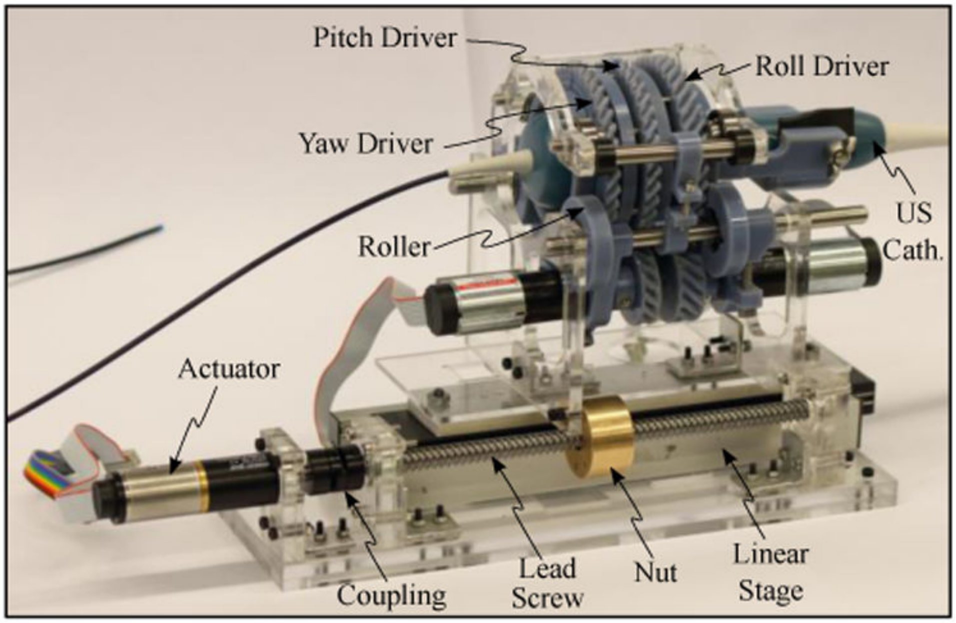

Figure 7. Fully assembled Robotic System

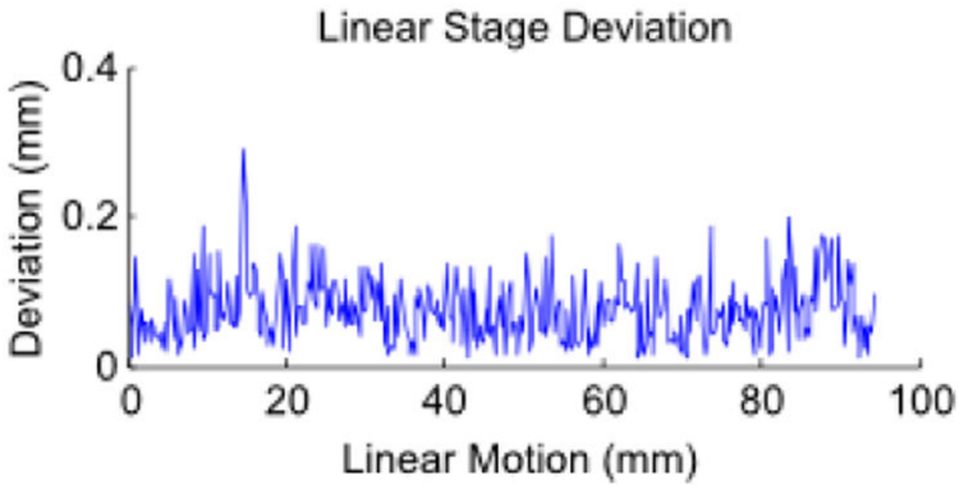

Figure 8. Deviation in translation axis

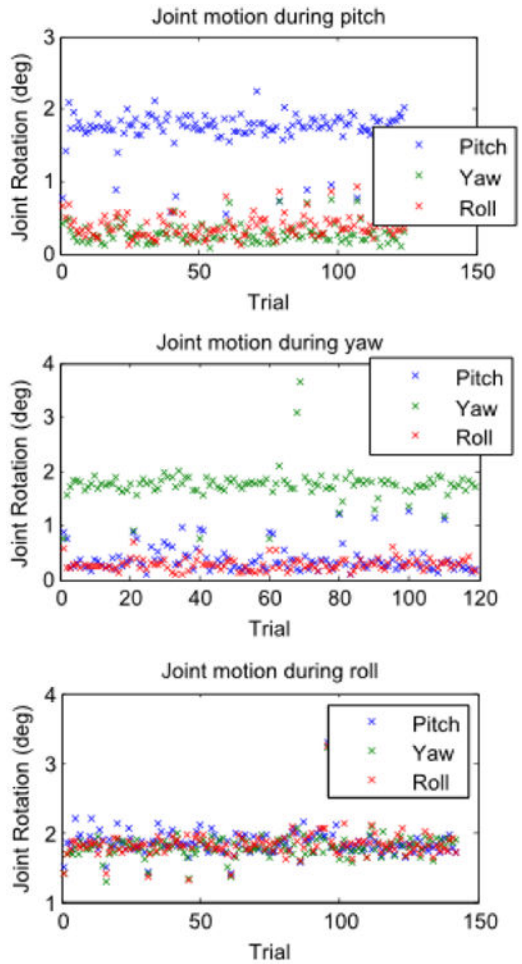

Figure 9. Joint motion during (*top*) yaw, (*middle*) pitch, and (*bottom*) roll

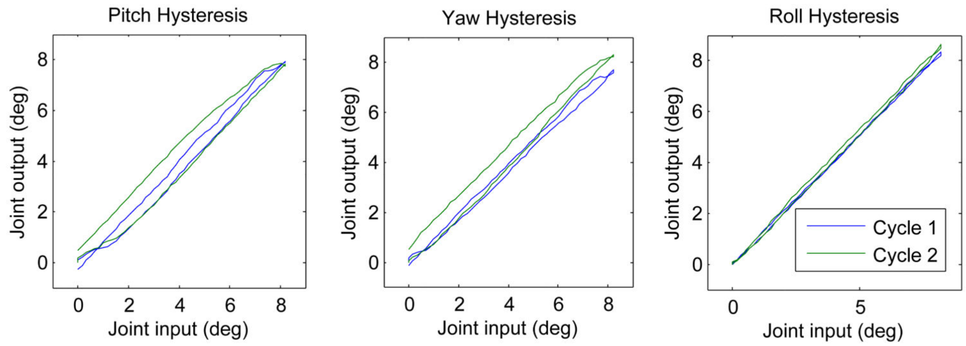

Figure 10. Hysteresis curves for rotational joints