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Body-Mounted Robot for Image-Guided Percutaneous Interventions: Mechanical Design and Preliminary Accuracy Evaluation*

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Abstract

This paper presents a body-mounted, four degree-of-freedom (4-DOF) parallel mechanism robot for image-guided percutaneous interventions. The design of the robot is optimized to be light weight and compact such that it could be mounted to the patient body. It has a modular design that can be adopted for assisting various image-guided, needle-based percutaneous interventions such as arthrography, biopsy and brachytherapy seed placement. The robot mechanism and the control system are designed and manufactured with components compatible with imaging modalities including Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). The current version of the robot presented in this paper is optimized for shoulder arthrography under MRI guidance; a Z-shaped fiducial frame is attached to the robot, providing accurate and repeatable robot registration with the MR scanner coordinate system. Here we present the mechanical design of the manipulator, robot kinematics, robot calibration procedure, and preliminary bench-top accuracy assessment. The bench-top accuracy evaluation of the robotic manipulator shows average translational error of 1.01 mm and 0.96 mm in X and Z axes, respectively, and average rotational error of 3.06 degrees and 2.07 degrees about the X and Z axes, respectively.

I. Introduction

Image-guided, robot-assisted percutaneous interventions such as biopsy and brachytherapy has been studied extensively over the last decade. Robotic systems for such interventions could be classified based on imaging modality (MRI, CT or US (Ultrasound)), robot actuation mechanism (passive or active) and robot mounting mechanism (table-mounted or body-mounted). In recent years, MRI/CT guided robotic systems for biopsy [1], [2], [3], [4], brachytherapy [5], stereotactic neurosurgery [6], [7] and needle steering [8], [9], [10] have been explored. However, such systems are table-mounted and are difficult to translate to

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clinical practice as they are optimized for a particular surgical procedure and scanner system. On the other hand, body-mounted systems can be easily adopted for any operating environment as they do not need scanner dependent mounting mechanisms. Hungr *et al.* developed a body-mounted, CT- and MRI-guided robotic system for percutaneous needle procedures [11]; however, it is suitable only for procedures in abdominal region. Song *et al.* presented an MRI-guided, body-mounted 2-DOF robotic assistant for liver interventions [12]; an MRI coil-mounted robotic device for cryoablation was developed by Wu *et al.* [13]. Also, our research group developed two generations of body-mounted robots for MRI-guided shoulder arthrography [14], [15].

The system presented in this paper is optimized for a shoulder arthrography procedure. Arthrography is a needle-based percutaneous procedure for enhanced visualization of anatomical structure of the joint to be examined for an injury. By injecting a contrast agent and acquiring high resolution anatomical images of the joint capsule, a trained radiologist can better examine the joint condition. In a typical arthrography procedure, fluoroscopy-guided needle insertion is performed to inject the contrast agent in the joint capsule under investigation. After injecting the contrast agent, high resolution CT or MR images are acquired for 3D visualization of the bone anatomy. While X-Ray/CT can visualize the bone structures with high image quality, MR images outperform them in soft tissue contrast which is essential for examining the injuries to ligaments or muscles. However, with existing Fluoroscopy/MRI clinical workflow, the patient is required to be transferred from one imaging room (fluoroscopy) to another (MRI) and results in an increased procedure time. Also, as MRI is an ionizing radiation free imaging modality and the contrast agent (gadolinium) used for MR imaging does not have any known allergic reactions, performing the entire procedure in an interventional MRI operating room can potentially reduce the procedure time and improve the procedure outcome. However, typical MRI bore size (60-70 cm) hinders the clinician's access to patient for in-bore procedure. To overcome this issue, we developed a body-mounted robotic assistant that can assist the clinician in performing needle-based percutaneous interventions within the scanner bore.

In this paper we present the design of a novel robotic manipulator optimized for MRI-guided shoulder arthrography. In our previous serial mechanism robot [15], the cables move during the operation of the robot, resulting in less optimized robot mounting and clinical usage. To overcome this challenge, the robot presented in this paper is designed with parallel linkage mechanisms for which during the normal operation of the manipulator the cables remain static, which is desired for body-mounted systems as to avoid any possible collision with the patient body. Also, it provides a larger workspace with a smaller footprint and is lightweight for targeted body-mounted robotic procedure. Here we present the mechanism design, robot calibration procedure and preliminary accuracy assessment in a bench-top setting.

II. Electromechanical System Design

The presented body-mounted robotic system provides four degrees of freedom for assisting image-guided, needle-based percutaneous interventions. The robot manipulator is designed and manufactured to be compatible with the MR environment, however it can also be used in the CT environment.

A. Manipulator Design

The 4-DOF robotic manipulator is a combination of two identical stages, each providing 2-DOF motion; Fig. 2 shows the fully assembled robot and its components. Each stage has a scissor mechanism actuated by two rotary joint assemblies. As shown in Fig. 3, each joint is rotated by an actuation unit via a timing belt.

Each stage provides 2-DOF motion in the plane of the scissor mechanism. Two arms of the scissor mechanism are actuated independently by the rotary joint assembly. As shown in Fig. 3, each rotary joint is made of 3 separate plates, two 3D printed rings on top and bottom and a large acrylic pulley (116 mm diameter) sandwiched between them. The large acrylic pulley is actuated via a timing belt driven by an actuation unit. As shown in Fig. 3, each actuation unit contains a piezoelectric motor (Piezo LEGS series, LR5012-00B10, MICROMO, Clearwater, Florida, US), an optical encoder (E4T Miniature Optical Kit Encoder, US Digital, WA, US) and a pulley mounted on the motor shaft. Piezoelectric motors are chosen to make the manipulator compatible with both MR and CT environments. Each motor has a diameter of 23 mm, and can provide 50 mNm torque which results in compact assembly while satisfying the desired torque requirements. The optical encoder has a base resolution of 500 counts per revolution, however, operating it in quadrature mode provides 2000 counts per revolution, resulting in resolution of 0.18 degrees per count. The pulley mounted on the motor shaft has 21 teeth, while the large acrylic pulley actuating the arms of the scissor mechanism has 176 teeth, resulting in a resolution of 0.021 degrees at the rotary joints. Optimized placement of the motors, encoders and cables keeps the overall dimensions of the robot within 160 mm $\times$ 200 mm $\times$ 84 mm and total weight of less than 700 grams.

The rotary joints are supported by three roller assemblies, out of which two are fixed sets and the third allows adjustment to achieve wiggle-free motion. The timing belt is tensioned by adjusting the movable actuation unit assembly positions. At the distal end of the scissor mechanisms, a pinned ball-joint provides a needle guide insertion point. Each ball joint positions the needle in their plane of motion. When two stages are combined, the needle guide passing through the two ball joints produces the desired position and orientation. To realize a simpler homing procedure, optical limit switches (RPI-0226, ROHM Semiconductor, Kyoto, Japan) are provided for each of the rotary joint assemblies. These limit switches in conjunction with the calibration procedure described in section III are used to produce an accurate and repeatable homing procedure.

To achieve compatibility with the MR environment, the structural materials, including all the screws, nuts, and pins, are chosen to be either brass or plastics. The bearings used both in the roller assemblies and the actuation units are made of plastic and glass (Xiros ball bearings, B623B1G, Igus, Germany). The top and bottom mounting plates are made of laser cut acrylic to provide necessary mounting features for the actuation unit assembly and rotary joints. The rotary joints and the scissor mechanisms are 3D printed with ABS plastic using Fused Deposition Modeling (FDM) process.

Robot registration is essential for image-guided, robot-assisted percutaneous interventions. As the presented system is optimized for MRI-guided shoulder arthrography, a robot registration frame consisting of nine MR visible fiducial markers organized in three planar

Z-shapes is rigidly attached to the robot structure. Using the line marker registration algorithm [16], this frame provides precise transformation between the scanner and robot coordinate systems.

B. Robot Kinematics

Forward and inverse kinematics are essential for taskspace control of the robot. We reported analytical formulation of robot kinematics in our previous work [17]; the kinematics has been adopted for the current version of the robot. Figure 4 shows the coordinate system and kinematic parameters for the current robot. As with any parallel linkage mechanism, the kinematics of this system also has a mechanical limitation and requires careful consideration for implementing the control method.

1) Forward kinematics: Given the joint positions of the top stage θ_{t1} , θ_{t2} and the kinematic parameters described in Fig. 4, the position of the end effector (ball joint) of the scissor mechanism is given by:

$$\mathbf{P}_t = \begin{pmatrix} X_t \\ Z_t \end{pmatrix} = \frac{1}{2} \begin{pmatrix} r \cos \theta_{t1} + r \cos \theta_{t2} \\ r \sin \theta_{t1} + r \sin \theta_{t2} \end{pmatrix} + hn \quad \text{where,}$$

$$h = (d_1 + 2d_2) \cos \left(\frac{\cos^{-1} \left(1 - \frac{r^2}{d_1^2} (1 - \cos(\theta_{t2} - \theta_{t1})) \right)}{2} \right) \quad \text{and}$$

$$n = \frac{1}{\sqrt{2(1 - \cos(\theta_{t2} - \theta_{t1}))}} \begin{pmatrix} \sin \theta_{t1} - \sin \theta_{t2} \\ \cos \theta_{t2} - \cos \theta_{t1} \end{pmatrix}$$

Similarly, given the joint positions of the bottom stage θ_{b1} and θ_{b2} , the position of the end effector (ball joint) of the scissor mechanism can be computed as $\mathbf{P}_b$.

Now given the $\mathbf{P}_b$, $\mathbf{P}_t$, the distance between the planes of top and bottom scissor mechanisms L , and the needle length s , the direction vector and the tip position can be determined as,

$$u = \frac{\hat{\mathbf{P}}_b - \hat{\mathbf{P}}_t}{\|\hat{\mathbf{P}}_b - \hat{\mathbf{P}}_t\|} \quad \text{and} \quad \mathbf{P}_{tip} = \hat{\mathbf{P}}_t + su$$

where, $\hat{\mathbf{P}}_b = [\mathbf{P}_b(1), 0, \mathbf{P}_b(2)]$ and $\hat{\mathbf{P}}_t = [\mathbf{P}_t(1), L, \mathbf{P}_t(2)]$

2) Inverse kinematics: Given the needle tip position $\mathbf{P}_{tip}$ and the direction vector u , the intersection of the needle path and planes of the scissor mechanisms of the top and bottom stages could be computed as $\mathbf{P}_t$ and $\mathbf{P}_b$. Given the desired position ($\mathbf{P}_d$) of the scissor

mechanism for the top stage, the desired joint angles θ_{t1} and θ_{t2} can be computed as follows: Let $[V_x, V_z]^T = \mathbf{P}_t/p_b$ where $p_t = \|\mathbf{P}_t\|$ then,

$$\phi = \text{atan2}(V_z, V_x) - \pi \quad \text{and}$$

$$\gamma = \cos^{-1} \left(\frac{d_1^2 p_t \pm d_1 \sqrt{d_1^2 (d_1^2 + p_t^2 - r^2) + d^2 (r^2 - d_1^2)}}{r(d^2 - d_1^2)} \right)$$

where, $d = d_1 + 2d_2$

now given the values of ϕ and γ , the desired angles of the rotary joints are:

$$\theta_{t2} = \phi + \gamma \quad \text{and} \quad \theta_{t1} = \phi - \gamma$$

Similarly, given the desired position ($\mathbf{P}_b$) of the scissor mechanism for the bottom stage, the desired joint angles θ_{b1} and θ_{b2} can be computed.

III. Calibration Procedure

The presented robot has a novel and unique mechanical design. A new calibration procedure is developed to initialize the robot and define the home position for each joint. The encoders mounted in the actuation unit provide relative position, and the optical limit switches mounted on each joint provide a repeatable homing procedure. Figure 5 shows the calibration setup and steps performed to define the robot coordinate system and home position.

By design, all the robot joints can have continuous 360 degree motion, provided the difference between two joints on each stage does not exceed the mechanical limit of the scissor mechanism. Having such unrestricted motion is desirable, however, it introduces challenges of defining the home position and reference coordinate frame of the system. To define the coordinate system, a reference plate is designed to be rigidly connected to the robot base with known orientation from the robot and reference plate CAD models. The reference plate provides relative orientation of the top mounting plate of the robot, but as none of the actuated rotary joints are mechanically attached to the mounting plate, their home position or reference point can not be established by CAD design.

As shown in Fig. 5a, five optical tracking markers (surrounded by yellow circle) are mounted on the reference plate, where two markers are used to define X_R axis (green line) and the midpoint of the two markers is set as the origin. The direction of the Z_R axis is defined as shown in the Fig. 5a (blue line) and all the five markers form the X_R - Z_R plane, resulting in Y_R axis pointing upward. The defined coordinate system (O_R, X_R, Y_R, Z_R) is used as a reference frame. To simplify the problem, first the bottom stage is mounted on the reference plate alone, which includes one scissor mechanism and two rotary joints. As shown in Fig. 5a, to define the reference (zero) position of each of the rotary joints, three

optical tracking markers A, B and C (surrounded by red circles) are mounted on the top rotary joint. A rigid body is defined based on A, B and C, such that the two markers (A and B) define the X_J axis, where A points toward the +Ve X_J axis direction. The midpoint of A and B is set as the origin O_J , which coincides with the reference frame origin O_R and the center of the rotary joints. The Z_J axis is defined to be in the ABC plane, resulting in Y_J axis pointing upwards. By design, the angle between the lines AB and O_JC is 60 degrees.

The calibration process starts from an unknown configuration of the robot. To define the home position of the top rotary joint on which the markers are mounted, as shown in Fig. 5b, both top and bottom joints are rotated concurrently until the angle between the X_J axis and negative X_R axis is 52.14 degrees, resulting in the position of the top joint relative to negative X_R axis to be 37.86 degrees. At this point, the scissor mechanism end-effector coincides with the center of the rotary joints and the top rotary joint is defined to be at the home position. To identify the angle between the top and bottom joints, as shown in Fig. 5c, two markers (S1 and S2) are placed on the scissor mechanism. The second joint is moved until the distance between the markers S1 and S2 is approximately 58.77 mm; at this distance between the markers S1 and S2, and given the robot kinematics parameters (Fig. 4), the resulting relative angle between the joints is 37.86 deg, which results in center of the ball joint being coincident with the center of the rotary joints.

After both joints are at the home position their encoder position is reset to zero and both are moved towards the limit switches. Their positions upon triggering the limit are recorded, giving the absolute home position offset for each joint from the limit switch positions. These offsets are then programmed as part of homing procedure to repeatably initialize the robot from any unknown configuration. The top stage is then mounted on the bottom stage, and the above described calibration procedure is repeated. This calibration procedure results in the robot initialized to the home position. Once, the robot is calibrated, the homing procedure could be repeated using only the limit switches and the optical marker are not required.

IV. Experiments and Results

Experiments are performed in bench-top environment to evaluate the taskspace accuracy and repeatability of the system. As shown in Fig. 6, the robotic manipulator, control system and optical tracking system (NDI Polaris Spectra, Northern Digital Corp, RMS error 0.25 mm) are setup to accurately measure the needle guide position and orientation. A base plate with five optical markers is defined as a reference frame and a rigid body with four optical markers is attached to the needle guide for measuring its 6-DOF pose. As the needle guide is attached to the bottom spherical joint, it is necessary to perform a pivot calibration to define the tip offset from the rigid body to the distal end of the needle guide. To perform the pivot calibration, the bottom stage was kept at a fixed position and the top stage was moved to produce pivoted motion of the rigid body; using the tracking system application, necessary offsets for the tip of the rigid body are defined.

A. Accuracy Assessment

Accuracy and repeatability are evaluated for the home position and 10 joint-space targets (Fig. 7) spread across the robot workspace. Using robot forward kinematics, both the position of the needle guide tip (center of the bottom spherical joint) and the orientation were derived and compared with the position and orientation acquired from the optical tracking system; mean absolute error and standard deviation are reported. Experiments were repeated 20 times in the following sequence: Homing-T1-...-T10-H, where *Homing* is reinitialization of the robot home position using the limit switches, *T1 – T10* represents 10 taskspace targets and *H* represents *Home* position at the end of each repetition cycle. To reduce any effect of elastic deformation of 3D printed scissor mechanism and the acrylic pulleys, all targets were defined along a vertical axis, meaning that the needle guide should be perpendicular to the reference frame. Table I shows average position error and standard deviation for the needle guide tip; error along the Y (needle insertion) axis is not presented as it does not represent the robot mechanism error. Table II shows orientation errors and standard deviation; errors in rotation about Y axis (needle rotation) are not presented as the needle rotation is not controlled by the robot.

V. Discussion

We presented the design and preliminary accuracy evaluation of a novel body-mounted robotic assistant for image-guided percutaneous interventions. A fully integrated system with a prototype robotic manipulator, custom developed control system and robot control application are presented. Average needle positioning accuracy of 1.06 mm and orientation accuracy of 3.06 degrees shows promising results for a prototype device. One of the sources of error is the weight of the needle guide tracking frame causing elastic deformation of the scissor mechanism. However, in a realistic scenario, the needle guide would not be exerting such forces on the scissor mechanism as it would be a hollow tube providing the needle insertion path. In the future, this error could potentially be reduced by replacing the 3D printed scissor mechanism components with higher quality CNC machined materials, providing better rigidity. Other factors affecting the accuracy could be imperfect coaxial alignment of the rotary joints, elastic deformation of the acrylic pulleys, acrylic structure for the robot enclosure, offset between the top and bottom stages, and any manufacturing inaccuracies. Also, the results in Table I and Table II show that the mean error and standard deviation among the targets is different, which could be the result of varying elastic deformation and rotary joint alignment in different parts of the robot workspace. It could be seen that the error is higher for targets T5-T9 which are all on the -Ve X side of the Z axis; this could be due to larger misalignment between the top and bottom rotary joints in that region of the workspace. The higher orientation errors could be attributed to misalignment between the top and bottom stages which are assembled together with less precise, laser cut mounting holes on the acrylic plates. Some of these error sources could be eliminated by providing better mechanical references for the mounting mechanism and machined or precision cut components.

VI. Conclusions and Future Work

In this paper we presented the electromechanical design of a novel body-mounted robotic device and accuracy evaluation in a laboratory environment. The presented system is optimized for MRI-guided shoulder arthrography, however, it can be adopted for any image-guided percutaneous intervention. The results achieved from the accuracy assessment experiments indicate an average needle guide position error of 1.04 mm and an average orientation error of 3.06 degrees, which is sufficient for targeting the joint capsule in the arthrography procedure. In the future, to achieve better accuracy and repeatability, we will improve the system design and rigidity with machined scissor mechanisms, more precise rotary joint mountings and an optimized calibration procedure with mechanical references. Also, we will evaluate the taskspace accuracy for more complex needle insertion paths, MRI-comparability and system accuracy in the the MR environment. We are working on an innovative robot design with a similar mechanism, but with two separate mechanical units: (1) a detachable actuation units and (2) a disposable needle guide alignment unit. This approach could potentially address the sterilization requirements for mass production of the disposable units and a reusable actuation unit could lower the overall cost of the device.

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Fig. 1:
Mock setup showing robot mounted on the shoulder of a simulated patient laying on the MRI scanner table

Fig. 2:
CAD rendering of the robot showing both the top and bottom stages assembled together and robot registration fiducials (green circles).

Fig. 3:

Partial assembly rendering of an actuation unit with a piezoelectric motor, an optical encoder, a rotary joint assembly (two 3D printed plates and an acrylic pulley sandwiched between them) and a timing belt.

Fig. 4:
Top and side views of the robot, showing coordinate system and kinematic parameters.

Fig. 5:

Robot calibration steps: (a) Procedure starts from an unknown robot configuration, (b) both the rotary joints are rotated in clockwise direction until the top joint reaches the home position and (c) bottom joint is rotated until the angle between both the joints is 37.86 degrees, resulting in the scissor mechanism end-effector being coincident with the center of the rotary joints. Yellow and purple arrows indicate the positions of the top and bottom rotary joints respectively.

Fig. 6:

Experiment setup showing: robot, robot controller, a laptop running robot control application, optical tracking system, optical tracking reference frame (green circles) and needle guide pose tracking frame (red circles)

Fig. 7:
Overlay of desired (green circle) and twenty measured (red circles) target positions

TABLE I:

Robot positioning accuracy (Units: mm)

Target	Target		MeanError		STD	
	Tx	Tz	Tx	Tz	Tx	Tz
Homing	0.41	-0.14	0.42	0.17	0.25	0.13
1	15.13	-4.15	0.26	0.49	0.21	0.15
2	28.32	-5.18	0.64	1.13	0.33	0.19
3	0.72	-15.67	0.13	1.44	0.17	1.32
4	3.83	-28.53	0.28	0.54	0.14	0.40
5	-14.68	-5.53	2.02	0.56	0.25	0.14
6	-25.95	-12.46	1.50	0.16	0.11	0.10
7	-9.80	12.25	1.91	2.33	2.17	2.36
8	-19.87	20.83	1.11	2.81	2.75	0.97
9	8.63	13.10	2.14	1.54	1.27	2.73
10	13.67	25.34	1.47	0.21	0.18	0.17
Home	0.41	-0.14	0.30	0.14	0.28	0.08
All targets			1.01	0.96	1.29	1.42

TABLE II:Robot orientation accuracy (**Units: degrees**)

Target	MeanError		STD	
	Rx	Rz	Rx	Rz
Homing	0.38	0.17	0.26	0.10
1	5.29	2.07	0.80	0.24
2	2.73	1.68	0.50	0.33
3	3.06	0.93	0.20	0.75
4	6.69	2.41	0.44	0.61
5	2.32	3.64	0.95	0.51
6	4.72	5.24	0.64	0.51
7	1.27	1.20	1.62	1.96
8	1.16	1.08	1.58	1.52
9	3.28	3.66	1.37	1.90
10	3.86	2.12	1.26	0.85
Home	2.01	0.60	3.08	0.90
All targets	3.06	2.07	2.18	1.74