Body-Mounted MRI-Conditional Parallel Robot for Percutaneous Interventions

Structural Improvement, Calibration, and Accuracy Analysis*

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Abstract—To assist in percutaneous interventions in the lower back under magnetic resonance imaging guidance, a 4 degree-of-freedom body-mounted parallel robot is developed. The robot structure is improved comparatively to a previously developed robot, to increase the stability, enhance accuracy, and streamline the assembly and calibration process. The optimized assembly and calibration workflows are carried out, and the system accuracy is evaluated. The results demonstrate that the system positioning and angular accuracy are 2.28 ± 1.1 mm and 1.94 ± 1.01 degrees respectively. The results show that the new system has a promising and consistent behavior.

I. INTRODUCTION

Adult and pediatric patients often suffer from nerve injury and pain [1]. Magnetic resonance imaging (MRI) is the preferred imaging modality for soft tissue and musculoskeletal interventions [2]. For clinical diagnosis, percutaneous interventions with contrast injections are often performed [3]. The injections can be carried out under the guidance of other medical imaging modalities or manually in the MRI room. Fluoroscopy, computed tomography (CT), or ultrasound imaging are used to guide such insertions [4, 5]. However, the former two expose the patients to ionizing radiation, while ultrasound imaging does not provide good resolution and adequate results, especially for deep nerve inspection. Also, the patient needs to be transferred to the MRI room after contrast injection, hence increasing the procedure time and causing patient discomfort. When manually injected in MRI room, a trial and error process is carried out based on the MR imaging [6]. To shorten the procedure, avoid radiation exposure, and take advantages of the high-resolution imaging ability of MRI, a possible solution is to employ robotic technology. An MRI-conditional robot that is able to manipulate the needle guide to desired pose automatically is needed. The assistant device could reduce the high dependence on operator's experience during the MRI-guided injection process.

MRI-guided robots for percutaneous interventions have been studied before [7]. The development of MRI-conditional robots is challenging because of two major reasons: (1) the high magnetic field in MRI room requires that ferrous materials must be avoided, and conductive parts should be reduced in order to minimize image distortion. Consequently, the robot rigidity should be of concern; (2) the robot and the

patient need to fit inside the limited space in the MRI scanner bore, so that a compact robot is highly desired.

Our project is aimed at developing an MRI-conditional robot that could be used for lower back percutaneous interventions. Compared with table/bed mounted methods that result in large supporting base size [8], we use body-mounted design to directly attach robot onto the patient body. The latter is usually smaller and can decrease the effect caused by relative motion between patient and robot [9, 10]. A previous generation of parallel robot was described in [11]. Preliminary accuracy evaluation of this robot showed an average needle guide positioning and angular error of 1.04 mm and 3.06 degrees respectively. It was a promising result for arthrography procedure. To use the robot for lower back injections, it needs to be further improved to increase the rigidity and targeting accuracy.

The robot described herein is designed to be attached on the patient's lower back (Fig. 1). It can automatically orient and position the needle guide to a desired pose based on the clinical plan so that the physician could manually insert the needle. The structure design is optimized to increase stability and accuracy. We streamline the assembly and calibration process, and carry out accuracy analysis.

II. ROBOT STRUCTURE

The 4 degree-of-freedom (DOF) MRI-conditional parallel robot is mounted on the patient's lower back using straps (Fig. 1). The strap fixation was proved to be a reliable method [12]. Compared to the serial robot [13], the parallel structure reduces the number of moving parts, and thus avoids the potential collision between robot and patient or MRI scanner bore.

The robot consists of two similar 2-DOF stages (top and bottom, see Fig. 2), and the dimensions are $215 \times 187 \times 84$ mm. Each stage has a scissor mechanism, and the scissor end effectors support a needle guide. Top and bottom stages are connected using dovetail slot parts. In the top stage case, there

Figure 1. Body-mounted MRI-conditional robot on the lower back of the patient inside MRI scanner

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Figure 2. 4-DOF Robot structure

Figure 3. Component parts arrangement in the top stage

are nine embedded MRI fiducials (MR-SPOT 122, Beekley Medical, US) for the robot registration.

The components arrangement for the top stage is shown in Fig. 3. Each stage consists of two coaxial rotating discs (top and bottom), supported by 4 roller sets. Each disc is actuated by a motor module (piezo-electric motor, encoder, and pulley) through timing belts. This arrangement keeps the motor module away from the needle guide to reduce MR imaging distortion, and also reduces the backlash and cable movement. The long arms of scissor mechanism are attached to the rotating discs using two hinges, such that they could be driven separately. When discs rotate, the scissor extends and retracts, and the needle guide pose is adjusted. For homing the robot, each disc has a flag that can trigger a limit switch attached on the base frame. The motors (Piezo LEGS series, LR5012-00B10, MICROMO, Clearwater, Florida, US), encoders (E4T Miniature Optical Kit Encoder, US Digital, WA, US) and roller bearings (xiros ball bearings, B623B1G, igus, Germany) are standard parts made of non-ferrous materials. Brass pins, screws, and self-lubricated bushings are used to keep the structure stable and reduce the friction. The customized parts are mainly made of 3D-printed acrylonitrile butadiene styrene (ABS) and laser-cut acrylic plates. All parts are non-ferrous to ensure the robot is MRI-conditional. We tested the compatibility of our previously developed robot in MRI environment, and the results showed that the robot did not induce any undesired movement or imaging distortion [14]. Our new robot uses the same standard parts and similar

Figure 4. Supporting board design based on robot forward kinematics

Figure 5. Fixtures for robot assembly and calibration

customized parts to maintain the compatibility. The reason for employing less precise rapid prototyping technology is to reduce the design iteration time and produce low-cost preclinical prototypes.

Compared to our previously developed parallel robot [11], we introduce modifications for improving robot rigidity and accuracy, and simplifying the assembly and calibration process:

A. Rigidity Improvement.

The needle guide is directly supported by the scissor mechanism end effectors. To improve the needle guide rigidity, the cantilever beam structure of the scissor mechanism needs to be supported in vertical direction. For this goal, a supporting board is employed as shown in Fig. 3. Similar to [15], the supporting board has a groove (Fig. 4) that is designed to support and guide the scissor mechanism end effector. The shape of the groove follows the end effector trajectory calculated by forward kinematics [11]. This supporting board prevents the scissor mechanism from bending and increases the end effector accuracy. To reduce the friction between supporting board and mechanism end effector, plastic thrust bearings and brass bushing are employed.

B. Accuracy Improvement

For each stage, the rotating discs are coaxially aligned with four movable roller sets, and locking screws are employed to preserve the relative positions. To increase the system accuracy and rigidity in vertical direction, a thrust ball bearing is installed between the top and bottom rotating discs on each stage. Ball bearing between discs can fix the gap height and increase the disc system rigidity. Moreover, the relative position accuracy between stages is improved by using dovetail slot structures, to realize better alignment and reduce assembly difficulty.

C. Assembly and Calibration Simplification.

To help assemble rotating disc and base frame, a long fixture (Fig. 5) is employed. Three press-fit pins are used to align the rotating discs relative to the other one. According to the robot kinematics, when pins are inserted, the scissor mechanism end effector is coaxial with the rotating disc centers. The assembly and calibration workflow are presented in Section III.

(a) Experiment platform

(b) Optical markers and coordinate systems distribution

Figure 6. Experimental setup with optical tracking system

III. ROBOT ASSEMBLY AND CALIBRATION

The two stages are assembled separately. The press-fit pins and long fixtures (Fig. 5) are used to implement a consistent and convenient assembly. The assembly process is: (1) Connect the rotating discs by using press-fit pins (Fig. 5), and install the thrust ball bearing to keep the distance between discs fixed; (2) Fix the discs to base frame by using the long fixture (Fig. 5), to constrain the discs to correct position and depth; (3) Push all four movable roller sets against the discs. Tighten the locking screws after the adjustment; (4) Adjust the motor module positions to tension the timing belts, and use screws to lock in place; (5) Assemble scissor mechanism and supporting board; and (6) Remove assistant fixtures (press-fit pins and long fixture).

After the two stages are assembled separately, they are connected using dovetail slot parts, to constrain both relative translation and rotating freedoms. Finally, the needle guide is installed to pass through the scissor mechanism end effectors.

By applying the robot calibration process, the robot home position is defined. The calibration process is performed with the Polaris optical tracker (Northern Digital Inc., Waterloo, ON, the root-mean-square accuracy is 0.25 mm.), as shown in Fig. 6(a). The robot base is fixed on a base board, and is connected to the control and power boxes through MRI compatible cables. As shown in Fig. 6(b), optical markers are attached to base board, robot, and rigid body, to define coordinate systems. The optical tracker is used to track position and orientation of each coordinate system. On the base board, there are four red markers defining the base frame O_{base} that is used as the reference system during the whole experiment. Three yellow markers are attached to robot top rotating disc to form the robot frame O_{rot} , to determine the disc center motion. A 3D-printed rigid body is inserted in the needle guide along its axis. Three blue markers are attached to the rigid body to form a top frame O_{top} that represents the pose of needle guide. O_{base} and O_{rot} are used during the calibration process.

The robot home position can be defined at any known position. For convenience, we define the home position as the scissor mechanism end effectors at the disc center, and the x_{rot} axis coincides with the x_{base} axis. At this position, the needle guide is perpendicular to the base board. The two stages are

Figure 7. Target positions selected, and positioning and angular error definition in accuracy experiment

calibrated separately, and the process is: (1) Use the optical tracker to define coordinate systems O_{rot} and O_{base} ; (2) Rotate the two discs together until both homing flags trigger the limit switches, and record the positions as limit switch positions; (3) Rotate the discs together again, until the x_{rot} axis coincides with x_{base} ; (4) Rotate and adjust the bottom disc until the press-fit pins (Fig. 5) can be inserted through all three holes, record both disc positions as homing positions; and (5) Calculate the differences between the limit switches positions and the homing positions for both discs, and acquire the relative offsets.

The steps are repeated for each stage, then two stages are calibrated. Stages are assembled together, and all discs can find their home positions according to limit switch positions. Every time the robot is powered on, the discs rotate together from random places, until all the limit switches are triggered; then the offsets calculated during the calibration process are applied to respective discs, so discs are able to rotate to pre-defined home positions with this relative position information.

IV. ACCURACY EVALUATION

An accuracy experiment is carried out to evaluate the positioning and angular errors, with the same experimental platform in Fig. 6. O_{base} is used as the reference frame, and O_{top} is used to determine the needle guide pose.

The scissor mechanism end effector workspace is a circle [4, 5]. Twelve points along end effector trajectory and one point at the home position are chosen as the target points (Fig. 7). The end effector is moved to these thirteen points by rotating the discs from each stage, and the optical tracker records the O_{top} pose data 200 times at each configuration. Positioning and orientation errors are calculated between actual pose and desired pose. The actual pose is acquired by the collected data of O_{top} from tracking system, and the desired pose is calculated based on the forward kinematics. The distance between the desired bottom end and actual pose is defined as the positioning error, and the angle between desired orientation and actual needle guide orientation is defined as angular error.

The experiment is firstly carried out with needle guide in vertical pose. Same point positions are selected on both

Figure 8. Error of vertical needle pose experiment

TABLE I THE ERROR OF ANGULATED TARGETING EXPERIMENT

Bottom position	Average value		STD	
	Angular error (degree)	Positioning error (mm)	Angular error (degree)	Positioning Error (mm)
1	2.08	1.98	1.07	0.84
2	2.25	2.26	1.10	1.02
3	0.76	2.38	0.49	0.88
4	2.02	1.64	0.79	0.46
5	1.09	1.39	0.48	0.33
6	2.17	2.29	1.03	1.11
7	1.87	2.98	0.47	0.77
8	2.07	1.85	0.93	0.97
9	1.28	1.99	0.50	0.37
10	2.01	2.95	1.26	1.61
11	1.60	4.37	0.43	0.76
12	2.40	2.98	0.97	0.79
13	1.59	3.25	0.47	0.88
Total	1.94	2.28	1.01	1.10

stages, and repeated 3 times. The results are shown in Fig. 8. The average positioning and orientation errors for all vertical poses are 2.58 mm and 1.57 degrees respectively. The results demonstrate that the two mechanisms behave similar, and they have the same error distribution characteristics.

For angulated targeting experiment, different points are selected from each stage. Under each selection of bottom points, nearby points from the top stage are selected. The orientation and positioning errors are defined as shown in Fig. 7. Every set of points are repeated 3 times. The results are summarized in TABLE I, and are classified according to the bottom position number.

The results show that the errors vary in the workspace. The average orientation and positioning errors are 1.94 degrees and 2.28 mm respectively, and STDs are 1.01 degrees and 1.10 mm respectively.

V. CONCLUSION

The new developed robot solved many problems discovered during experiments of the previous generation. Compared to the prior robot, the alignment accuracy and calibration process are taken into account during the structural design, to reduce the friction and assembly difficulty, as well as increase the structure rigidity, accuracy, and stability. The assembly and calibration process are carried out, showing an improved process to set up the robot as well as defining the home position based on the calibration. To assess the robot

accuracy, thirteen points are selected from both stages, and the orientation and positioning errors are measured at each pair of points. The results show that the error is consistent, and the orientation errors are more promising than the prior system. Increased positioning error comes from enlarged scissor mechanism with heavier needle guide, deformation of plastic material and low manufacturing accuracy. These result in backlash and control error, and could be improved by using higher stiffness material machined with higher accuracy. In the future, the accuracy experiment will cover bigger motion range and orientation angle. The errors will be characterized and compensated by applying control method.

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