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Robotic System with Multiplex Power Transmission for MRI-guided Percutaneous Interventions

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Abstract

In minimally invasive prostate percutaneous interventions, Magnetic Resonance Imaging (MRI) compatible robotic assistive systems developed over the years tend to have multiple degrees of freedom (DOF) to accomplish complex surgical tasks. This paper presents a novel design of an MRI-compatible transmission that allows one driving motor to control a multiplexed DOF robot system. The transmission could reduce the number of motors in the system, while maintaining the functionality of the system, by controlling each motion sequentially rather than simultaneously. A series of preliminary experiments as well as a targeting accuracy test are conducted to evaluate the accuracy of the system.

I. Introduction

Prostate cancer is one of the most common cancers in American males based on data compiled by the American Cancer Society. It is estimated that there will be 180,890 new cases of prostate cancer and about 26,120 deaths resulted from it in 2016[1]. Most prostate cancers are first detected during a prostate-specific antigen (PSA) screening and/or a digital rectal exam (DRE). If the results suggest that the subject might have prostate cancer, a biopsy is performed manually, often guided by TransRectal UltraSound (TRUS). If the result of the biopsy is positive, a common treatment would be TRUS-guided brachytherapy [2].

Unfortunately, the TRUS provides low resolution images and inferior soft tissue contrast [3], where doctors can neither see the malignant tissue nor the radioactive seeds clearly on the images, which undermines the performance of the biopsy or brachytherapy. Magnetic resonance imaging (MRI) can be considered a promising alternative because it provides high volume resolution and superior soft tissue contrast [4]. In addition, researchers are also trying to apply robotic systems to solve the problem that manually executed percutaneous interventions lack precision and repeatability [5].

In spite of the advantages of MRI-guidance and robot assistance, respectively, the combination of both methods is still challenging in this field [6]. The working environment of the robot is a close-bore space with a high magnetic field. The limited space that could be accessed requires the system to be compact while maintaining a sizable workspace. To be safe, only nonferromagnetic materials, such as polymer composite materials, can be allowed in the high density magnetic field, although the mechanical properties of these types of materials impair the performance of the system. In addition, because the robotic system itself is a mechatronics system that will introduce noise in the imaging process, reducing the interference during robot operation is also an important factor to develop MRI-guidance robotic systems.

Given all the challenges mentioned above, many MRI-guided surgical robots were designed, built, and evaluated to help us better understand the design procedure of the system and how the imaging system and robot interact with each other. Fischer et al. presented a 2-DOF pneumatically actuated needle manipulator for transperineal prostate interventions where the insertion of the needle was done manually [6]. Song et al. enhanced the system into a 4-DOF parallel robot so that the robot could fully access the entire volume of the prostate, which the predecessor could not do automatically [7]. Eslami et al. took it a step further by replacing the triangle-shape stages with trapezoid-shape ones to improve the accuracy and reliability of the manipulator [8]. The actuators for the robot were also switched from pneumatic ones to piezo motors to benefit from the high torque/weight ratio the motors provide and to reduce the overall size of the robot. Another 6-DOF robotic assistive system fully actuated by nonharmonic piezoelectric motors was presented by Li et al [9]. With a different setup, Goldenberg et al. also achieved a 6-DOF robot actuated by ultrasonic motors [10]. Stoianovici et al. reported a 3-DOF MR-safe robot with custom-made pneumatic step motors [11] and Patriciu et al. designed a 5-DOF robot for prostate brachytherapy using the same type of motor [12]. A dielectric elastomer actuator was used by Tadakuma et al. to create a parallel bistable system for MRI cancer therapy [13].

In order to complete complex surgical procedures, most systems listed above tend to have several DOFs; thus, the same number of motors as DOFs are needed in order to fully actuate the whole system. It would be efficacious to develop a generalized design of a transmission system that could control this kind of robot using fewer motors than traditionally needed. In that way, the cost, weight, and size of the system can be reduced while also reducing the interference due to the noise of the motors in the imaging procedure. However, the motion time will possibly be longer moving each DOF in series.

In this paper, we present the design of a novel transmission whose concept is to control a general multiplex DOF MRI-compatible robot with a single driving motor. The implementation of the whole system will be presented in section II. To gain a better understanding of the performance of the transmission, a series of preliminary assessment tests are quantitatively established and described in section III and the results of the experiments are discussed in section IV.

II. System Implementation

A. 4-DOF Surgical Needle Manipulator

The system presented in this paper is designed upon a 4-DOF surgical needle manipulator that our lab has developed over the years for minimally invasive transperineal percutaneous prostate interventions [8]. The main function of the manipulator is to set the position and angulation of a surgical needle according to preplanned target information; the insertion is performed manually to alleviate patient safety concerns which often arise for robotic-controlled insertion. As shown in Fig. 1, the manipulator is composed of a front and a rear stage. To make use of the space between and under the patient's legs, the stages are designed as trapezoidal shapes. Each stage comprises a U-shape frame and two sliders, connected by two parallelogram mechanisms that convert the lateral motion of the slider into vertical motion of the U-shape frame, while enhancing the stiffness and stability of the stage. The displacement of the slider along the X axis is achieved by driving an anti-backlash nut inside the slider with a leadscrew. Each of the 4 sliders can stop independently at any desired position along their own leadscrew and they are driven by 4 motors. Each stage provides two translation DOFs in the XY plane and, by connecting the two stages with ball joints and rigid bars, the system also obtains the rotational DOFs about the X and Y axes for the needle.

B. Multiplexed Power Transmission

To replace the motors from the old system with the new transmission, an interface is developed. Instead of being connected directly to motors, the leadscrews are now individually connected to four intermediate shafts using a timing belt (Fig. 2). Then the other side of each intermediate shaft is connected to a pulley-gear pair that could operate independently on a fixed shaft. The pulley-gear pair is comprised of a timing belt pulley and a secondary gear that are fixed together to achieve the same angular velocity (see Fig. 3c). By turning the selected gear, the desired slider will move accordingly.

The idea of this transmission (Fig. 3c) is to build a generalized robotic drive system for multiplexed DOF control while reducing the number of motors so that it is less than the number of DOF needed to fully control the system. That is to say, the number of motions controllable at one time is less than the overall number of motions of the whole system. The motions that can be controlled directly in this system are the motions of the 4 sliders. In this proposed transmission design, only one driving motor is used so that the motions can only be actuated sequentially rather than simultaneously. Therefore, two mechanisms are required for this transmission, a mechanism to enable the driving motor to drive the desired motion

and another to lock down all the other uncontrollable motions while the desired one is actuated.

Borrowed from the basic ideas of an automobile transmission, three motions are defined for the driving gear to control the desired slider motion. One is the driving motion whereby the driving motor turns a hexagonal shaft to output power through a driving gear (Fig. 3c). The hexagonal shaft is used to transmit the torque while enabling the driving gear to slide to different positions along the shaft. The second is a shifting motion provided by the shifting motor and a screw-nut mechanism. It aligns the driving gear with a secondary gear that drives the desired slider. The third is the engaging motion also provided by the same mechanism. This motion brings the gears in and out of contact. When the gears are engaged, the power transmits from the driving motor to the secondary gear, through two sets of timing belts, to the screw-nut mechanism, moving the slider. When the gears are disengaged, the driving gear is in neutral position, where the driving motor is cut off from the transmission line, and free to align with another gear to actuate a desired slider.

The motors are non-magnetic ultrasonic double shaft motors (USR30-S4N, Shinsei Corp., Tokyo, Japan) with an optical incremental encoder (E5 series, US Digital, Vancouver, USA) mounted directly on its back. Note that the difference between the driving motor and the other two is that the two take on little load and they can be replaced by other MRI-compatible actuators that provide linear motion. The control system (mainly DMC-2143, Galil Motion Control, California, USA) is based on a control unit developed in [2].

As shown in Fig. 3a, the clutching mechanism consists of a pedal, a spring, and a rack. The goal is to stop the secondary gears from unintentional turning. To achieve compact design, the pulley-gear pairs are touching each other. Turning one pair could cause unintentional turning for other pairs. Moreover, locking the whole system in place is also crucial when the driving gear is at the neutral position.

C. System Functioning

To position the needle, the motions introduced above have to work in an orderly fashion. The driving gear always starts in the neutral position and it will only stop at the 4 positions along the hexagonal shaft that are aligned with the 4 secondary gears (see Fig. 3c). At first, the driving gear shifts itself to align with the secondary gear that drives the desired slider, and then the engaging motion brings the two gears in contact with each other. Meanwhile, the pedal of the clutching mechanism is pushed, compressing the spring because this is coupled with the engaging motion. All the dimensions are carefully designed so that when that happens, the rack unlocks the secondary gear. After then, the power transmission line between the driving motor and the slider is connected and the driving motor moves the slider to a desired position. Finally, the (dis)engaging motion brings the driving gear back to the neutral position and gets it ready for the next motion cycle. The secondary gear, though released by the driving gear, is once again locked by the rack. In all, it is a “shift, engage (unlock), drive, and disengage (lock)” cycle and it will be repeated until the robot arrives at the desired target position.

To ensure that the clutching mechanism works properly without losing any teeth in the process, the secondary gears can only stop at a limited number of angular positions. A full revolution is 80 teeth for each gear and 5000 counts for the encoder. As one angular pitch for the gears yields 62.5 counts and the reading must be an integer, the smallest step is two angular pitch. Thus, the smallest displacement one slider can travel is 0.05 mm because the pitch for the leadscrew is 2 mm. In an early stage of the robot development, a fourth encoder (Fig. 3c) has been installed on an intermediate shaft to check whether encoder counts are lost between the driving motor shaft and the intermediate shaft. Measurements show that no counts are lost between the two encoders.

III. Experiments

The purpose of the experiments is to assess the performance of the robot after adopting the transmission. Therefore, the following experiments are performed to obtain useful data:

- Preliminary experiments on backlash and position accuracy of each slider;
- Accuracy tests on needle translation targeting (no angulation).

Accuracy is evaluated by computing the error, which is defined as the Euclidean distance between the position that is reached and the commanded position. The motion time is another important aspect to assess the performance but the focus of this paper is mostly on accuracy.

A. Preliminary experiments

The purpose of these tests is to investigate general performance in basic tasks, such as moving the slider. This could also be a reference baseline for later targeting experiments. The experiment setup and workflow for these tests is similar to that described in [14].

B. Targeting experiment

The targeting experiment is conducted to see how well the system will do with high level tasks such as reaching target points.

To track the position of the surgical needle and collect data, a tracking system (fusionTrack 500, Atracsys, Puidoux, Switzerland) is employed as shown in Fig. 4, which has 0.09 mm RMS in 2 m distance. A trackable marker frame is fixed to the needle support and the position and the orientation of the marker frame with respect to tracker coordinates is collected at each desired position.

Before the experiment, reachable targets are picked and a motion plan is generated. The robot starts from the home position found by the homing procedure for the first time, goes through target 1 to 4 sequentially, and then goes back to the recorded home position. This simulates a surgical routine for multiple insertions and the experiment is repeated 13 times (the largest number of iterations without resetting or tuning the system). Note that there is no reset, meaning a separate homing procedure, between iterations to correct the home position. This is to test how the error accumulates after continuous iterations.

To filter the tracking data, 200 readings are recorded and averaged at every position. With the position and orientation information, to compare tracking data to the robot coordinates data, the transformation matrix between the tracker coordinates and the robot coordinates is computed. As the two coordinates are fixed during the experiments, the transformation matrix is constant. Then, we can recover the position and the orientation of the needle with respect to the robot coordinates using the transformation matrix. Because the first home is achieved by calling the homing procedure, it can be considered accurate and set as the origin of the robot coordinates. This comparison can reflect the repeatability of the system but it cannot fully present targeting accuracy because there might be error at the home position in each iteration and that will propagate. In the real surgical procedure, we can call the homing procedure before every targeting procedure to reduce the error.

IV. Results and Discussion

The results of the preliminary experiments show 0.055 mm maximal error in the slider position with a mean of 0.016 mm and less than 0.165 mm backlash for 4 sliders. Because the home position is a critical reference point for targeting, the accuracy of reaching it with a homing procedure is also tested and the position error is less than 0.1 mm. This is acceptable compared to the smallest step calculated in the previous section. The backlash can actually be further reduced with the risk of increasing the load. Prior to the targeting experiment, the overall backlash is set to be less than 0.1 mm for each slider.

For the targeting experiment, metrics (Table I) similar to [14] are computed to compare with that reported from the clinical version of the robot (described in Section II.A). The mean error is 1.34 mm in X and -0.76 mm in Y across all targets and the desired accuracy in air is ± 1 mm. We could see that the difference in 1-dimensional (1D) error (error in X or Y) between the two systems is less than 1 mm. During the experiment, the time traveling from one position to the next is also recorded for future reference; for example, the motion time from home position to target 1 is 1.95 minutes. One possible reason is that the motors are at a lower speed to avoid overheating. Also the trajectory planning is not yet optimized for this transmission.

The plots in Fig. 5 reveal more about how the data varies with respect to time. The lines for the targets have a similar trend with the line for the home position, suggesting that the home position error will be accumulated at target points. This shows why the accuracy of reaching the home position is vital. The variation of error at each target suggests that the error can be unequally distributed. Target 3 gets the largest error and looks almost like an outlier. This could be because the error propagates differently across the workspace. Future experiments will be designed to explore the distribution of the error and why it occurs.

V. Conclusion

In this paper, a generalized multiplex power transmission design that could control a 4 DOF MRI-compatible surgical needle manipulator with fewer motors is demonstrated. After adopting this transmission to the manipulator, the motion time and the targeting accuracy are examined to assess the performance. We focused on system accuracy and conducted related

experiments. Future work will involve further analysis of the position error and an optimization of the control scheme to shorten the motion time.

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Figure 1.
4-DOF robot: overall view of the old system [8]

Figure 2.
4-DOF robot: new design with multiplex power transmission

Figure 3. Multiplexed transmission: a) Clutching mechanism in locked position, b) Clutching mechanism in unlocked position, c) overview of the transmission

Figure 4.
Experimental setup with optical tracking system and marker frame

Figure 5. Plot of a) error in X coordinates, b) error in Y coordinates, c) error in the XY plane depicting the error variation with each iteration

TABLE I.

Targeting Accuracy Experiment
(all measurements are in mm)

Target	(X,Y)truth	mean(X,Y)	error(X,Y)	STDEV(X,Y)
1	(15,10)	(16.23,10.32)	(1.23,0.32)	(0.13,0.16)
2	(10,-15)	(10.93,-16.04)	(0.93,-1.04)	(0.14,0.23)
3	(-10,-10)	(-8.16,-11.53)	(1.84,-1.53)	(0.17,0.25)
4	(-15,15)	(-13.64,14.20)	(1.36,-0.80)	(0.14,0.17)