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Design of an MR-Compatible Biopsy Needle Manipulator using Pull-Pull Cable Transmission

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Magnetic resonance (MR) compatible needle manipulators can assist physicians with the insertion of biopsy needles and needle-like therapeutic instruments directly into millimeter-size tumors, using MR images as feedback. However, magnetic resonance imaging (MRI) systems present a challenging operational environment with high magnetic fields and limited space, making the development of MR-compatible robots difficult. In this paper, we present design requirement analysis and a novel prototype design for an MRI-guided biopsy needle manipulator and an MR-compatible transmission that provides sufficient driving forces for needle manipulation inside an MR scanner. The actuators of the manipulator are placed outside the MR room, which are several meters away from the scanner. A combination of a pull-pull cable-sheath and a cable-pulley transmission is used to transmit the actuator force to the manipulator. This configuration can be used to achieve MR-compatibility and leads to the ability to use conventional actuators such as DC motors, which have sufficiently high power to perform needle biopsy. We also studied the feasibility of the proposed transmission and actuation with the proposed manipulator. The accuracy and precision of the needle tip are evaluated and MR-compatibility is verified.

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NOMENCLATURE

θ_1 = rolling angle of the manipulator
θ_2 = pitching angle of the manipulator
d = sliding displacement of the manipulator
$s\theta_i = \sin\theta_i$, $c\theta_i = \cos\theta_i$
J_i = i^{th} joint axis (J_1: roll, J_2: pitch, J_3: slide)
x, y, z = x, y and z-directional position of the needle tip with respect to base coordinate system, respectively

1. Introduction

In recent years, there has been much advancement in the field of minimally invasive surgery, especially in the field of image-guided surgery.[1,2] Magnetic resonance imaging (MRI) is the most preferred imaging modality due to its high sensitivity, excellent soft tissue contrast, high spatial resolution and multi-planar volumetric imaging capabilities.[3] The combination of MRI and surgery robotics can offer many advantages, including higher precision and correctness of surgery, less pain and scarring, lower risk of complication and faster recovery periods. However, magnetic resonance (MR) images can only be obtained through the use of strong and precise magnetic fields; no ferromagnetic materials are allowed inside the MRI bore because these materials cause noise and thus make it difficult to obtain highly precise MR images.[4]

Several actuator types have been applied to MR-compatible robots. Most of these systems use piezoelectric, ultrasonic, and pneumatic actuators.[5] Piezoelectric/ultrasonic actuators for which energy is carried into the MR room over electric cables require high voltages and low currents. These actuators do not include any ferromagnetic components or permanent magnets and require cable shielding, and filtering of the power and the signal. Piezoelectric actuators can generate MR noise when they are not properly shielded or placed at a safe distance from the MR bore. Although ultrasonic motors are not affected by the magnetic field, their casings involve conductive material which results in substantial image artifacts when such motors are placed near an MR magnet.[6,7] The principle of hydrostatic transmission is based on a tele-

manipulator system, with mechanical transmission between the master and the slave. But, leakage and contamination of liquids is not preferable for surgical robot applications.[5] Pneumatic actuators are MR-compatible, with negligible signal-to-noise ratio reduction, but, under continuous control, they are subject to control instabilities due to the compressibility of air and delay due to long transmission. A ratchet-like pneumatic system with pistons as actuators for intra-MRI abdominal interventions has also been reported.[8] The PneuStep[9,10] is a clever pneumatic step motor that solves issues both of motor MR-compatibility and pneumatic actuator controllability. But, the PneuStep is made of numerous parts, making for a complex and expensive system; it also has a low torque/volume ratio. There are several researches using cable-driven mechanism for force control in haptic device. D. Chapuis et al. proposed a cable transmission composed of the slave module with position encoder and torque sensor, the berglass proles, PTFE tube or pulley and the master actuator with position encoder.[11] This transmission is not synchronous, as some slipping can occur. Therefore, a position sensor is required at the output. Encoder at the output shaft has risk of noise effect on MR images. It is not suitable for precise position control in MR environment. S. Menon et al. and B. Vigaru et al. proposed haptic devices using cable transmission.[12,13] In these devices, actuators and control devices are placed inside the MR room. The cable transmission used in the researches has limitation on long distance transmission and there exists electro-magnetic shielding problem.

Conventional electromagnetic actuators such as DC motors, due to their relatively simple transmission, ease of use and maintenance, and cost-effectiveness, have been widely used in the development of surgical robots. But, their ferromagnetic components or permanent magnets inhibit their application to MR-compatible robots. For use of conventional electromagnetic actuators in an MR room, the actuators must be anchored at a safe distance from the scanner and be well shielded; they must also utilize transmit force and motion over a long transmission line. Previous study of the use of an electromagnetic actuator in an MR room have shown that such an actuator can be used within the MR room if the actuator is well shielded and placed at a distance of about 2.5 m from the isocenter of the magnet.[5]

In this study, the research objective is to develop a long-distance MR-compatible actuation method and to apply this method to a prostate intervention robot for MRI-guided needle insertion. MRI-guided needle placement using the proposed method will guarantee accurate targeting of prostate cancer without MRI-oriented specific actuators or MR-compatible encoders. In order to achieve the research goal, a new, MR-compatible transmission and actuation method is proposed. A biopsy needle manipulator is designed and manufactured to verify the MR-compatibility and evaluate the performance of the proposed actuation method. In this manner, conventional actuators and encoders can be used while satisfying the MR-compatibility requirement. This paper is organized as follows. Chapter 2 proposes an overall concept for the MR-compatible actuation system. In Chapter 3, a new MR-compatible biopsy needle manipulator is proposed and design requirements, mechanical design and kinematic analysis of the proposed robot are described. In Chapter 4, experimental results of the prototype of the proposed robot are presented. The motion control in free space and MR-compatibility tests in the MR room are performed to assess the feasibility of the proposed actuation method and to identify the position accuracy of the needle tip and the SNR of the MR images. In Chapter 5, we draw our conclusions.

2. MR-Compatible Transmission and Actuation

2.1 Overall concept

The MR scanner is placed within an electromagnetically shielded room to allow its correct functioning and to protect sensitive equipment located around the facility. There is a waveguide (a metal tube with length about 10 times larger than its diameter) in the penetration panel between the MR room and the control room.

The key idea is to use a novel MR-compatible transmission and electromagnetic (EM) shielding in the MR room to ensure the spatial separation of the MR-compatible components and the MR-incompatible components. MR-compatible components, which are involved in the transmission and in the biopsy needle manipulator, are placed only inside the room; the other non-compatible components, including the electromagnetic motor, motor driver, power supply, and personal computer with ADC board, are placed outside the room. Motion and force can be transmitted from outside the electromagnetic shielding of the MR room through a waveguide.

In this way, while placing the MR-incompatible actuators outside the MR room, if the transmission part can be made of only MR-compatible materials, the proposed method will have the following advantages: a) It can satisfy the MR-compatibility requirement; b) It allows conventional electro-magnetic actuators to be used in the control room and prevents the intrusion of sources of electromagnetic interference; c) It allows all interfering components (such as motor drivers, controller, encoders, wires, etc.) to be placed outside the MR room; d) It allows the control of the biopsy needle manipulator without MR-compatible sensors. Fig. 1 provides a schematic of the MR-compatible transmission and actuation system.

2.2 Design of MR-compatible transmission and actuation

Considering the MRI environment, the specifications of the transmission need to be determined carefully. The distance between the center of the MR scanner and the control room is 3.48~4.17 m.[14,15] We used a pull-pull cable transmission with 5 m length. There are several waveguides with diameters of 50 mm. The proposed MR-compatible transmission needs to be designed to transmit power through the waveguide from an electromagnetic actuator placed outside the MR room.

Mechanical transmissions are commonly used to transfer power over certain distances into constrained workspaces. We chose a cable-driven transmission, which enables remote actuation using small components. Cables have a good weight-to-length ratio, especially over long distances. A cable-driven transmission does not suffer from backlash or ripples, which problems are common for chain or belt-driven transmissions. There are two types of cable-driven transmissions, the pull-pull cable-sheath type and the pull-pull cable-pulley type (Fig. 2). A pull-pull cable-sheath transmission exhibits hysteresis behavior due to friction; this results in position errors, especially for long-distance transmission.[16] In contrast, a pull-pull