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Design, Analysis, and Evaluation of a Remotely Actuated MRI-Compatible Neurosurgical Robot

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Abstract

The paper presents an MRI-compatible neurosurgical robotic system that is designed to operate the head-mounted meso-scale 6-degree-of-freedom (DoF) spring-based MINIR-II. The robotic system consists of an actuation module, a transmission module, and the robot module. The transmission module consist of a switching mechanism for reducing the required number of motors by half, an innovative linkage mechanism to insert and retract the robot with minimal tendon displacement and friction loss, and a quick-connect mechanism for easy attachment of the disposable MINIR-II. Design, analysis, and development of each module are described in detail. Most of the critical components such as the robot, the quick-connect, the linkage mechanism, and various gear-pulley combinations in our design are 3-D printed. Preliminary mechanical properties characterization of the system and the capability of the underactuated system to replicate the critical functions of the 6-DoF robot are presented. The robot motion capability in a brain phantom model and its MRI compatibility in a 7-Tesla magnet were verified.

Index Terms

Medical Robots and Systems; Mechanism Design; Tendon/Wire Mechanism; Flexible Robots

I. Introduction

Brain tumors are the most common cancer and the primary cause of cancer deaths in young children under 14 years old [1]. Brain surgery, which remains one of the most effective treatment methods for operable brain tumors requires better visualization, reduced invasiveness, and improved ability for complete tumor removal. Magnetic resonance image (MRI)-guided robotic neurosurgery can achieve these needs.

Different from neuroArm and ROSA[®] Brain, meso-scale robots have been explored to perform surgery with more dexterity such as the 7-degree-of-freedom (DoF) articulated robot for minimally invasive surgery [2], neurosurgical intracerebral hemorrhage evacuation robot (NICHE) [3], and the 3-segment flexible MINIR-II robot [4]. Many MRI-guided meso-scale robots [5], [6] have been developed for prostate intervention and needle targeting

procedure. Li *et al.* [7] designed a stereotactic neurosurgical robot for deep brain stimulation under MRI guidance. Some commercial systems such as the NeuroBlate[®] and Visualase[®] systems offer MRI-guided laser ablation to treat deep-seated lesion in the brain. There are two important issues with these dexterous small surgical robots. First, most of these robots use actuators that are not MRI compatible. Second, most of them are attached to a standalone robotic setup that needs to be registered with the incision site. In recent decades, researchers have tried to integrate MR imaging as part of the surgical robotics procedure by developing compact manipulation systems to fit inside the MRI bore [8], [9]. Pneumatic and hydraulic actuators are MRI-compatible but are limited by the time delay, complex control, potential cavitation, and leakage [10]. Ultrasonic and piezoelectric motors are the most common actuators in MRI-compatible robotic systems. However, when placed near the imaging region, they are shown to create artifacts [11].

Transmission is needed if the actuation system is to be placed far from the MRI isocenter. Chinzei *et al.* [12] used two long rigid arms as transmission in the transperineal intraprostatic intervention procedure. A versatile robot [13] has its four DoFs controlled from outside the MRI gantry via timing-belts. Tsekos *et al.* [14] used telescopic acrylic shafts to connect the ultrasonic motors with their robotic positioning setup. Recently, a multiplexed power transmission [15] was integrated in a prostate intervention robotic assistive system to actuate a 4-DoF needle manipulator sequentially. Previously, our group developed an MRI-compatible Bowden cable setup [16] with a skull-mounted head frame. Based on the preliminary evaluation and the drawbacks observed such as backlash and excessive friction in the flexible tube, we have now developed a more robust transmission using the combination of timing belts, kevlar wires, and gear-pulley combinations. We have integrated a switching mechanism to reduce the number of motors required and a novel quick-connect mechanism. The twelve linear electric motors are replaced with three ultrasonic motors. Only the skull-mounted head frame is preserved from our previous design.

The major contribution of our work includes the design of an MRI-compatible remotely-actuated system for a multi-DoF robot used to remove deep brain tumor. There has not been any MRI-compatible meso-scale surgical robotic system for multi-DoF robot other than the concentric tube robotic system [9]. Compared to commercial laser ablation systems, our robot is expected to gain access to a deep-seated tumor through the natural folds of the brain without cutting through the white matter. Our device having the multi-DoF bending ability to sweep over a large volumetric area will also potentially aspirate the tumor more completely using cautery and suction. The paper is divided into several sections: In section II, we provide the motivation and overview of the entire robotic system design. Section III discusses the design of the transmission system. Section IV presents the experimental setups and preliminary results to evaluate the performance of the robotic system. Lastly, we make some concluding remarks and discuss future works in section VI.

II. Motivation and Overview of the Robotic System

A. Design criteria

The ultimate goal of this work is to develop a robust remotely-actuated neurosurgical system to advance and actuate the tendon-driven six-DoF MINIR-II robot [4]. To reliably actuate the robot, which will be head mounted on a patient's skull, in the closed-bore MRI using ultrasonic motors, a transmission and actuation system have to be designed for it. The design criteria can be classified into five aspects: force transmission efficiency, mobility, convenience, MRI-compatibility and complexity of the overall system.

1. Force transmission efficiency: The relative motion between the tendons and the movable section of the Bowden cable transmission structure in our previous design [16] led to significant loss in force transmission efficiency. A transmission mechanism that is movable during robot insertion and retraction and remains rigid during robot actuation has to be designed. **2. Mobility:** The placement of the robot at the predetermined incision site on the patient's skull requires the development of a positioning mechanism that has high mobility. Additionally, we have to pass twelve tendons through the positioning mechanism to reach and actuate the 6-DoF robot at the distal end. Thoughtful design is needed in the transmission to reduce the coupling between the routing path of the tendons and the highly mobile positioning mechanism. **3. MRI-compatibility:** Only non-magnetic materials are used to construct the robotic system to prevent any safety hazard in the MRI room. Electronic devices can result in artifacts in MR images and need to be isolated electromagnetically. Previous research [17] also shows that placing actuators at least 1 m from the MRI isocenter is an effective solution. **4. Convenience:** To improve the process flow during setting up of the robotic system, the actuation module should be easily decoupled from the positioning/transmission mechanism. A quick-connect mechanism is needed to allow easy disassembly and replacement of the disposable and patient specific robot so that the robotic system can be reused. With the use of a skull-mounted head frame to which the robot is attached to, the robot's initial trajectory is already aligned with the incision direction, thus skipping the pre-operative step that would register a standalone robot trajectory to the surgical site. **5. Complexity:** High complexity, due to the large number of actuators to operate the six-DoF robot and position the robot in 3D space, reduces robustness and increase size and cost. Thus, some DoFs in positioning the robot are manually operated and a switching mechanism is designed to reduce the number of actuators required.

B. Overview of the robotic system

The robotic system consists of three modules: the *actuation module*, the *transmission module*, and the *robot module*, as shown in Fig. 1. The major component of the actuation module is a Faraday cage that stores three ultrasonic motors (USR60-E3NT, Shinsei Corporation, Japan), four drivers (D6060S), and a 24 V battery, as shown in Fig. 2(a). It is designed to be placed in the MRI room and around 1 meters away from the robot. The only connection to outside the MRI room are the signal cables that connect the computer in the MRI control room to the Faraday box. The motion from the motors are transmitted to the transmission module by long-span timing belts. The actuation module also features a bridge, as shown in Fig. 1, that physically connects the Faraday cage and the rest of the robotic

system. The bridge, which can be extended to 1.5 meters, consists of two square cross section bars of different diameters with dense through holes along the longitudinal axis on their sides. The bridge is extended and fixed when the timing belts are in a reasonable amount of tension that prevents tooth jumping in the pulleys. It can be removed from both the Faraday cage and the transmission module during transportation of the robotic system.

The transmission module has five main functions: bridging the actuation module and the robot module, positioning the robot module in 3-D space around the incision site, selecting the robot segment to be actuated, enabling efficient force transmission, and enabling quick connection and disconnection of the disposable part of the robot module. To implement all these functionalities, the transmission module consists of four important mechanisms/parts: the positioning structure, the switching mechanism, the linkage mechanism, and the quick-connect mechanism, as shown in Fig. 2(b). The positioning structure caters to the different incision locations around the skull. It holds a plate on which the switching mechanism is placed. Through manual adjustment, the switching mechanism, together with the rest of the transmission and robot module, can be moved in y- and z-axis independently (refer to Fig. 1). There is also a rotation joint at the base of the linkage mechanism to adjust the motion plane of the linkage mechanism, as shown in Fig. 2(b). The detailed design of the other three components of the transmission module will be discussed in Section III.

The robot module consists of the MINIR-II robot and a skull-mounted head frame with a rail and carriage. The maximum height that the linkage mechanism and the head frame can reach is 25 cm, which is enough to fit in the room above a person's skull in a standard wide-bore MRI. The detailed information about the MINIR-II robot can be found in [4]. As a summary, it is a tendon driven flexible robot, whose backbone comprised of three interconnected spring segments. Each spring has two actuation DoFs controlled by two pairs of orthogonally oriented fish wires (referred to as "tendons" in the rest of the paper), respectively. The robot is designed to meet several criteria, including a workspace to cover brain tumors of up to 40 mm diameter, a bending angle of at least 90° in each segment, an outer diameter that can fit inside a trans-sulcal endoport such as the NICO BrainPath[®], and a lumen that can incorporate multiple instruments including bipolar cautery probes, suction tube, and irrigation tube. In the MINIR-II robot, tendons for a distal segment are passed along the central axis of the proximal segments to minimize segment coupling [4]. The coupling effect is further minimized through the addition of sheath (Teflon tubing) for each tendon inside the robot to prevent tendon tangling. The robot module is placed on a rail attached to the skull-mounted head frame [16] and will be inserted and retracted by an ultrasonic motor at the base of the linkage mechanism. The rail is designed to allow insertion and retraction of the robot along its motion trajectory for about 65 mm.

III. Design of the Transmission Module

A. Quick-connect mechanism

In the quick-connect mechanism, twelve tendons from the robot and twelve Kevlar strings (referred to as "cables" in the rest of the paper) from the transmission module need to be connected simultaneously and be free to move individually once connected to drive the

robot. This quick-connect can be described as a two-level structure: a single connector at the low level and the chassis to integrate twelve connectors at the high level.

1) Design and principle of a single connector—Each connector consists of a male part and a female part, and is responsible for one segment motion direction in one DoF. The cable from the transmission is attached to the male part while the tendon from the robot is attached to the female part. The male part is a rod with a conical cap and a tunnel along its long axis, as shown in Fig. 3(a). The female part has a conical tail with a tunnel that allows the passage of the tendon from the robot which then terminates with a knot, as shown in Fig. 3(b). The cantilevers, facing each other, have their fixed ends attached to the front wall. Their free ends have overhangs that form a circular entrance. Stoppers are built on the side walls just underneath the cantilever beams to stop the inward deformation caused by the pulling force, as shown in Fig. 3(d). The connection principle of the male and female parts is similar to the snap fit connection. Once inserted, the back of the male part pushes against the retaining sides of the overhangs when it is being pulled by the transmission to actuate a robot segment. To disassemble the connector, a rigid sleeve is inserted into the female part until it pushes the overhangs and keeps the cantilever beams open. Together with the sleeve, the male part is removed from the female part when the cable is pulled, as shown in Fig. 3(c).

2) Housing of the quick-connect mechanism and the connection/

disconnection procedure—The quick-connect chassis consists of a proximal housing and a distal housing. The twelve cables and twelve tendons are arranged into a 4 columns $\times$ 3 rows matrix in the proximal housing and distal housing, respectively. The 4 columns represents the two DoFs of each segment while the 3 rows represent the 3 different robot segments. The proximal housing has a base plate, a connection plate, and a disconnection plate, arranged in the descending order of their proximity to the male connectors, as shown in Fig. 4. The initial configuration of the twelve connectors in both proximal and distal housings are shown in Fig. 4(a). The plate stoppers are used to hold the disconnection plate and the position plate in place. When making the quick connection, the distal housing is aligned with the proximal housing to allow the male parts (and the twelve sleeves) to be inserted into the female parts smoothly without deforming the cantilever beams. The plate stoppers are removed, after which the connection plate and the position plate are pressed together to insert the male parts through the overhangs (Fig. 4(b)). The quick connection of twelve connectors is then simultaneously formed. The proximal and distal housings are then clamped together using a clip on the top side of the housings, thus providing an initial slack in the cables/tendons.

The disconnection starts by pressing together the disconnection plate and the position plate, allowing the sleeves to deform the cantilevers in the female part (Fig. 4(d)). While the distal housing is being pulled away from the proximal housing, the disconnection plate in the proximal housing continues to be pressed against the male parts to provide a tension force that simultaneously disconnect twelve male parts out from their corresponding female parts.

B. Linkage mechanism

1) Design of the linkage mechanism—The linkage mechanism is a movable mechanism to insert and retract the robot along a slider without displacing the cables that pass through it. Once the robot is inserted, it has to maintain its structural shape to prevent unnecessary loss in force transmission. Thus, a rigid crank-slider mechanism with one DoF actuated by an ultrasonic motor (USR30-E3NT, Shinsei Corporation, Japan) is used.

The mechanism consists of a base, two links and a slider, as shown in Fig. 5(a). The motion line of the slider is fixed by the head frame that is mounted on the skull at the incision opening. At the base, there is a house for the first revolute joint, a platform to hold the motor and a pair of worm and worm gear to act as the transmission of the motor. The motor and worm gear combination prevents the linkage mechanism from changing shape once the robot is inserted to its target depth, allowing efficient force transmission in the tendons. Another toothed pulley is fixed to the joint between the two links and connected to the first pulley through a timing belt. Thus, the second link is rotated directly by the motor and the motion of the motor translate into forward and backward motion of the slider. The proximity of this particular ultrasonic motor to the MRI isocenter may require it to not be turned on during live MRI imaging.

The cables go through twelve channels in the center of the joint shafts of the linkage mechanism, as shown in Fig. 5(b) to make sure the tendon displacement is minimal during insertion and retraction of the robot.

2) Kinematic analysis of the linkage mechanism—The kinematic analysis is performed to determine the joint that should be actuated in the linkage mechanism to minimize the constrained reaction force on the head frame that is fixed on the skull. In the schematic shown in Fig. 6(a), joints for the first link, the second link and the slider are denoted by O , A and B , respectively. The length of either link is l . The red dashed line is the motion line and the solid line segment on joint B represents the slider. The angle between the motion line and the horizontal base is denoted as θ . Angles of joints O , A and B are denoted by γ , α and β , respectively, and the angle between the slider and the motion line is denoted by δ . In reality, δ is zero since the slider always moves along the motion line. From Fig. 6(b), the angle between the motion line and the second link, $\phi_1 = \alpha + \gamma + \theta$. Assuming a frame with the origin at O and the x -axis along the motion line, the coordinates of the slider are $x = l\cos(\gamma + \theta) - l\cos(\phi_1)$ and $y = l\sin(\gamma + \theta) - l\sin(\phi_1)$. Based on the principle of virtual work, the input forces on joints O , A and B , τ_γ , τ_α and τ_β can be related to the output forces on the slider, f_1 (x-direction) and f_2 (y-direction), and T , as follows:

$$\begin{bmatrix} \tau_\alpha \\ \tau_\gamma \\ \tau_\beta \end{bmatrix} = \begin{bmatrix} l \sin(\phi_1) & -l \cos(\phi_1) & -1 \\ l \sin(\phi_1) - l \sin(\gamma + \theta) & -l \cos(\phi_1) + l \cos(\gamma + \theta) & -1 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ T \end{bmatrix} \quad (1)$$

Note that we want to choose an actuation joint from O , A and B to minimize f_2 and T . From Eq. (1), $T=0$ requires $\tau_\beta=0$, meaning the joint B cannot be actuated. In this case, using the sum-to-product identities of trigonometric functions, Eq. (1) can be simplified as:

$$\begin{pmatrix} \tau_\alpha \\ \tau_\gamma \end{pmatrix} = \begin{pmatrix} l \sin(\alpha + \gamma + \theta) & -l \cos(\alpha + \gamma + \theta) \\ 2l \cos(\frac{\alpha}{2} + \gamma + \theta) \sin(\frac{\alpha}{2}) & -2l \sin(\frac{\alpha}{2} + \gamma + \theta) \sin(\frac{\alpha}{2}) \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$$

If joint O is actuated ($\tau_\alpha=0$), $\frac{f_1}{f_2} = \frac{\cos(\phi_1)}{\sin(\phi_1)}$. f_2 is only small when ϕ_1 is close to zero or π .

However, this requirement limits the motion range of the slider. If the joint A is actuated ($\tau_\gamma=0$), $\frac{f_1}{f_2} = \frac{\sin(\phi_2)}{\cos(\phi_2)}$, where $\phi_2 = \frac{\alpha}{2} + \gamma + \theta$. ϕ_2 is $\angle AGB$, as shown in Fig. 6(b) and thus equal to $\frac{\pi}{2} + \beta'$. When the motion line passes joint O , $\beta' = \angle OBG = 0$ and f_2 can always be zero. Therefore, joint A is actuated in this design to minimize f_2 .

3) Wrapping angle expression and its change throughout robot insertion—For tendons that pass through the center of each joint in the linkage mechanism, friction of the tendon is proportional to the exponential of the total wrapping angle. Friction can thus be minimized if the wrapping angle is minimized. As shown in Fig. 6(c), the slider and the motion line is always colinear in an actual procedure. θ is a constant throughout the robot insertion process for a predetermined insertion trajectory. Its range is $0 \leq \theta \leq 90^\circ$. The range of α is $0 \leq \alpha < 180^\circ$ and its value at the initial linkage configuration is defined as ψ , whose maximum value can be calculated from the desired insertion depth. γ is the angle measured from the first link to the horizontal line while β is measured from the motion line to the second link. The relationship for these angles can be expressed as: $\alpha + \beta + \gamma + \theta = \pi$. The total wrapping angle, w , is the sum of absolute values of all joint angles. $w = (\pi - \alpha) + |\beta| + |\gamma| = \theta + \beta + |\beta| + \gamma + |\gamma|$. During robot insertion, the slider moves from left to right in Fig. 6, which requires the first link to rotate in the clockwise direction and the second link in the counterclockwise direction. Therefore, both $\gamma + |\gamma|$ and $\beta + |\beta|$ are non-increasing terms and the maximum wrapping angle occurs at the initial linkage configuration.

4) Insertion depth determines ψ —Referring to Fig. 6(d), joint O is the center of two concentric circles, Ω_1 and Ω_2 . Ω_1 with a radius of $2l \sin \frac{\psi}{2}$ and Ω_2 with a radius of $2l$ are formed by all possible locations of the slider at the beginning and at the end of the insertion procedure, respectively. The motion line that passes center O intersects Ω_1 and Ω_2 at D and E_1 , respectively. The motion range in this case is the length of line $\overline{DE_1}$, which is the minimum possible insertion depth, $l_{min} = 2l(1 - \sin \frac{\psi}{2})$. Any other segment from D to Ω_2 that does not pass through center O is longer than l_{min} . Therefore, l_{min} has to be equal to or larger than the insertion depth. Knowing the insertion depth allows us to calculate the maximum value of ψ .

5) Determination of initial linkage configuration by choosing appropriate β and γ —With θ and ψ known, we can express the linkage angle relationship as $\kappa = \beta + \gamma = \pi -$

$\alpha - \psi$. Case 1: If $\kappa < 0$ (rare), we can make $\beta < 0$ and $\gamma < 0$, leading to wrapping angle, $w_1 = \theta$. Case 2: If $\kappa > 0$ (more common), we can make $\beta > 0$ and $\gamma > 0$, leading to wrapping angle, $w_2 = \theta + 2\kappa$. In either case, we have the additional option of making either β or $\gamma < 0$, leading to $w_3 = \theta + 2\kappa + 2|\tau|$, where τ is either one of β or γ that is negative. This resultant wrapping angle is larger than w_1 or w_2 , thus making this option inappropriate. We can further narrow down the linkage configuration in case 2 by ensuring the motion line pass through center O since it is compatible with the optimal configuration concluded from the kinematic analysis.

C. Switching mechanism

1) Overview and power flow of the switching mechanism—The switching mechanism reduces the required number of motors by allowing 2-DoF control of only one robot segment at one time. In most cases, only the end segment needs to be actuated to sweep across the entire brain tumor. Therefore, the critical function of the robot is preserved even when the reduced number of motors. There are two driving motors to control the two DoFs of each robot segment and another selector motor to choose the robot segment to control. The switching mechanism, as shown in Fig. 7(a), consists of the driving part (two receiving pulleys) and the selection part (one receiving pulley) with both receiving power from the motors via three timing belts. The two receiving pulleys for the driving part are connected to another two driving pulleys via short timing belts. To achieve satisfactory tension in these belts, we went through multiple trials and errors to finalize the distance between the centers of every pair of pulleys. In the driving part, there are six drive units, each of which controls one DoF of the robot. The pair of cables originating from one drive unit should be connected to the pair of tendons responsible for a particular degree-of-freedom (DoF) in a robot segment. The two pairs of Kevlar strings originating from the top and bottom drive units in the same column should be connected to the two DoFs of the same robot segment. The selection part consists of six cams that would engage a pair of drive units (in the same column of the switching framework) with their corresponding drive gears on the power train at one time, allowing 3-D motion of a particular robot segment. When a new pair of drive units are engaged, the previously engaged drive units are disengaged from the power train and their motion are locked to fix the bending position of the previously actuated robot segment. By engaging (unlocking) and disengaging (locking) the different pairs of drive units, all three robot segments can be controlled by three motors to approximate the performance with six motors. In this way, the number of ultrasonic motors required is halved without making compromise on the critical functionalities of the robotic system.

2) Drive part of the switching mechanism—As shown in Fig. 7(b), each drive unit is composed of a square cross-section aluminum slider, a gear-pulley combination and a recovery compression spring. A Kevlar string is wound on the pulley, resulting in two antagonistic cables being passed towards the robot. The recovery spring is installed between a plate (cam follower) at the tail of the slider and a stopper that is fixed on the switching framework. During contact between the cam and its cam follower, the gear-pulley combination moves away from a rack fixed on the framework to mesh with a drive gear located on the drive shaft. When the cam moves away from its cam follower, the recovery

spring pulls the slider back, allowing the gear-pulley combination to mesh with the rack, thus locking the position of a robot segment.

3) Selection part of the switching mechanism—Cams in the selection part are used to push drive units forward and guide them back with recovery force from the springs. Each gear-pulley combination of the drive unit should always be meshed with either the drive gear or the rack. In our design, the profile of a cam consists of two arcs. One arc makes up the majority of the cam profile while the other one creates the protrusion of the cam. The radial difference between the two arcs, as indicated by the length difference between the two tangent lines to the two arcs, is 1.5 times the tooth height of the gear, as shown in Fig. 8(b). The cam angle, ω , can be defined as the angle between the vector at which the cam nose is pointing at and the global horizontal line. The entire selection part consists of two rows of cams, arranged behind the cam follower of every drive unit, as shown in Fig. 8(a). Since only one selector motor is used to activate 2 DoFs of one robot segment, one motor operation needs to be able to activate two cams to push their respective drive units forwards. This is achieved by connecting the selector motor via a timing belt with the bottom cam shaft, which is in turn connected to the top cam shaft through a pair of meshed gears. The top and bottom cams in a particular column are made to have cam angles of the same magnitude but opposite signs, as shown in Fig. 8.

IV. Evaluation results

A. Preliminary mechanical properties characterization

Preliminary characterization experiments were performed to measure the mechanical properties of the robotic system. The extreme backlash for 6 DoFs was determined to be ± 1.66 mm, which mainly comes from the accumulated slack of belts and cables. We will reduce backlash by modifying the transmission design in our future work. There was a bilinear relationship between the output bending angle and input tendon displacement. The 1st linear stage, covering 0–10° of bending angles, is dominated by uncertainties such as coil compression, structural deformation, and tendon slack. The 2nd stage, covering all bending angles beyond 10°, is dominated by the bending stiffness of the spring segment, thus leading to a significantly larger bending angle per mm of tendon displacement, compared to the first stage. The experimental relationship between bending angle and tendon displacement in both stages are fit with linear functions. The first stage has a linear coefficient of 0.497 °/mm with a repeatability of 0.08 °/mm and the second stage has a linear coefficient of 6.065 °/mm with a repeatability of 0.03 °/mm. The linearity of the second stage is characterized by an R-squared value of 0.998. Comparison between the theoretical model for the MINIR-II robot [4] and the experimental data in the 2nd stage leads to an accuracy error of 1.33%. As we are planning to integrate Fiber Brag Grating (FBG) sensors along the robot body, we will also implement a robust feedback with feedforward controller, with the feedback component especially important to compensate for the uncertainties in the first stage of the robot motion.

B. Evaluation of motion range and switching mechanism effectiveness

Each robot segment was actuated independently and bent between its two extrema, as shown in Fig. 9. The work ranges of the actuated segments and motion coupling effects were determined through a vision-tracking experiment, in which vision markers attached to the robot segments were tracked by the MicronTracker (Claron Technology Inc., Canada). The results are summarized in Table II. All segments could move nearly from -90° to 90° . The results also show the effectiveness of the switching mechanism in decoupling actuated robot segment from the other segments, as shown in Fig. 9(d). The base segment was engaged and bent to the negative direction in the first stage before the middle segment was engaged and bent to the positive direction in the second stage. Then, the end segment was actuated through two cycles to simulate the tumor removal procedure. In the last stage, the end, middle and base segments were moved back to their home configuration in order. Throughout this robot segment switching process, the drive units of the two non-actuated robot segments were locked to the racks very effectively and not engaged with the drive shaft, as proven by the minimal changes in the positions of non-actuated robot segments. The slight motion of 10° in the base segment as the middle segment was actuated is attributed to the imperfect tendon routing in the flexible robot and not the ineffectiveness of the switching mechanism. During actuation of different robot segments, there was no shape change in the linkage mechanism which was being locked in place by the block force of the ultrasonic motor, suggesting no relative motion between the linkage mechanism and the tendons. This indicates an improvement in the force transmission efficiency compared to our previous flexible transmission system [16].

C. Motion capability evaluation

We inserted the MINIR-II robot into a brain-like phantom model made of 2% gelatin (Knox, USA), which has similar stiffness of around 1 kPa as that of the human brain. The phantom contains a tumor-like phantom in the center of it, as shown in Fig. 10(a). The middle and end segment of the robot were actuated independently from the home configuration, as shown in Fig. 10(b), to verify its motion capability. In a separate experiment, the middle segment was actuated and locked in place before the end segment was actuated back and forth, as shown in Figs. 10(c–d). The videos for these experiments are attached as supplementary files.

D. MRI compatibility evaluation

The MRI compatibility of the robotic system was verified by setting it up in a 7-Tesla MRI, as shown in Fig. 11(a). Two static MR images of the robot were taken before and after the robotic system was powered on. The powering on of the robotic system led to an SNR drop of 3.56% from 39.9 to 38.47. The image quality is further qualitatively evaluated by comparing the images acquired during the robot actuation process when the motor drivers were sending out signals to the motors for both DoFs of the end segment. A T2-weighted dynamic brain imaging sequence was performed to take 64 images at 2 frames per second and the robot end segment was bent to different configurations (it was being bent out of plane in the MR images shown in Figs. 11(b–d)). The robot motion caused the displacement of gelatin phantom, resulting in the white space around the robot. There is no visible artifact or observable degradation throughout the dynamic MR scanning procedure.

V. Conclusion and Future Work

A remotely actuated robotic system, consisting of an actuation module, a transmission module, and the MINIR-II robot has been developed. The novelties include using a switching mechanism to reduce the number of actuators required to replicate the functionalities of a 6-DoF robot, a quick-connect mechanism for assembly and disassembly of twelve tendons, and a linkage mechanism that improves force transmission efficiency. Preliminary evaluation shows a system that has sufficient working range, capability to move in the brain environment, and is MRI-compatible. The second linear stage of the input-output relationship closely matches the theoretical model. However, the system has its weakness in backlash and unmodeled uncertainties for small bending angles. In our future work, we attempt to make design changes to the transmission to improve the open-loop control of the robot. We will investigate the effect of the location of ultrasonic motors and drivers on the MR image quality. We will also integrate position and orientation sensor such as the EndoScout® sensor to improve robot tracking during the procedure.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Brain tumor statistics. Available: <http://www.abta.org/aboutus/news/brain-tumor-statistics/>
2. Shang J, Noonan DP, Payne C, Clark J, Sodergren MH, Darzi A, Yang G-Z. Robotics and Automation (ICRA), 2011 IEEE International Conference on. IEEE; 2011. An articulated universal joint based flexible access robot for minimally invasive surgery; 1147–1152.
3. Sheng J, Gandhi D, Gullapalli R, Simard JM, Desai JP. Development of a meso-scale SMA-based torsion actuator for image-guided procedures. IEEE Transactions on Robotics. 2016
4. Kim Y, Cheng SS, Diakite M, Gullapalli RP, Simard JM, Desai JP. Toward the development of a flexible mesoscale MRI-compatible neurosurgical continuum robot. IEEE Transactions on Robotics. 2017
5. Krieger A, Iordachita I, Song S-E, Cho NB, Guion P, Fichtinger G, Whitcomb LL. Development and preliminary evaluation of an actuated MRI-compatible robotic device for MRI-guided prostate intervention; Robotics and Automation, 2010 IEEE International Conference on; 2010. 1066–1073.
6. Goldenberg AA, Trachtenberg J, Yi Y, Weersink R, Sussman MS, Haider M, Ma L, Kucharczyk W. Robot-assisted MRI-guided prostatic interventions. Robotica. 2010; 28(2):215–234.
7. Li G, Su H, Cole GA, Shang W, Harrington K, Camilo A, Pilitsis JG, Fischer GS. Robotic system for MRI-guided stereotactic neurosurgery. IEEE Transactions on Biomedical Engineering. 2015; 62(4):1077–1088. [PubMed: 25376035]
8. Elhawary H, Tse ZTH, Hamed A, Rea M, Davies BL, Lamperth MU. The case for MR-compatible robotics: a review of the state of the art. The international journal of medical robotics and computer assisted surgery. 2008; 4(2):105–113. [PubMed: 18481822]
9. Su H, Cardona DC, Shang W, Camilo A, Cole GA, Rucker DC, Webster RJ, Fischer GS. A MRI-guided concentric tube continuum robot with piezoelectric actuation: a feasibility study; Robotics and Automation (ICRA), 2012 IEEE International Conference on; 2012. 1939–1945.

10. Yang B, Roys S, Tan U-X, Philip M, Richard H, Gullapalli RP, Desai JP. Design, development, and evaluation of a master–slave surgical system for breast biopsy under continuous MRI. *The International journal of robotics research*. 2014; 33(4):616–630. [PubMed: 25313266]
11. Fischer GS, Krieger A, Iordachita I, Csoma C, Whitcomb LL, Fichtinger G. *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer; 2008. MRI compatibility of robot actuation techniques– a comparative study; 509–517.
12. Chinzei K, Hata N, Jolesz FA, Kikinis R. Surgical assist robot for the active navigation in the intraoperative MRI: Hardware design issues; 2000.(IROS 2000). *Proceedings. 2000 IEEE/RSJ International Conference on*; 2000. 727–732.
13. Oura M, Kobayashi Y, Okamoto J, Fujie MG. *Biomedical Robotics and Biomechanics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on*. IEEE; 2006. Development of mri compatible versatile manipulator for minimally invasive surgery; 176–181.
14. Tsekos NV, Yacoub E, Tsekos PV, Koutlas IG. Design of an MRI-compatible robotic stereotactic device for minimally invasive interventions in the breast. *J. Biomechanical Eng*. 2004; 126(4):458–465.
15. Wang Y, Kim S, Burdette EC, Kazanzides P, Iordachita I. *Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of the. IEEE; 2016. Robotic system with multiplex power transmission for MRI-guided percutaneous interventions*; 5228–5232.
16. Cheng SS, Wang X, Desai JP. *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on*. IEEE; 2017. Design and analysis of a remotely-actuated neurosurgical robotic system. (Accepted)
17. North OJ. *Medical robotics for use in MRI guided endoscopy*. 2013

Fig. 1.

The complete neurosurgical robotic system consisting of actuation module, transmission module (switching, linkage, and quick-connect mechanism), and robot module (inside the skull model).

(a)

(b)

Fig. 2.

(a) Actuation module and (b) transmission module shown together with the positioning structure and the head frame.

Fig. 3.

The (a) male part and (b) female part of the single connector. (c) Schematics showing quick connection (top) and disconnection (bottom) of the single connector. (d) Detailed schematic of how the cantilever of the female part gets deformed during the disconnection.

(a)

(b)

(c)

(d)

Fig. 4.

(a) The proximal and distal quick-connect housing before connection. (b) Press the connection plate and the position plate together during connection. (c) The connected quick-connect mechanism. (3) Press the disconnection plate and the position plate together during disconnection.

Fig. 5.

(a) Schematic of the linkage mechanism with part of the quick-connect mechanism (slider) (Yellow line shows the actuation path to deform the linkage mechanism during insertion and retraction of the robot). (b) Schematics of the two links and the important channels in each joint that allow passage of cables.

Fig. 6.

(a) Schematic of the linkage mechanism for kinematic analysis. (b) Angle relationship in the linkage mechanism; the shadow linkage with $\beta' = 0$ indicates the configuration with $f_2 = 0$. (c) Definition of angle directions in wrapping angle analysis. (d) Motion range analysis and configurations for minimum wrapping angles (the shadow for case 1 and the solid for case 2).

Fig. 7.

(a) Schematic of the switching mechanism that receives timing belts from the motors (Yellow line shows the power flow) (b) Schematic of the single drive unit that contains mainly a slider and a gear-pulley combination

Fig. 8.

(a) Rear view of the switching mechanism showing the positions of the cams (Yellow line shows the power flow from the selector motor to the cams) (b) Schematic showing the cam and the three different orientations for engagement of each of the three robot segments

(a)

(b)

(c)

(d)

Fig. 9.

Angle change of all robot segments during actuation of the (a) base segment, (b) middle segment, and (c) end segment. (d) Angle change during sequential motion test of all robot segments.

(a)

(b)

(c)

(d)

Fig. 10.

(a) Experimental setup to test robot motion in brain phantom. Robot configuration (b) when it was not actuated, (c) when its end segment was actuated up, and (d) when its end segment was actuated down.

(a)

(b)

(c)

(d)

(e)

Fig. 11.

(a) The entire robotic setup in the MRI room. Dynamic MR images showing the robot end segment at the (b) 30th frame (c) 40th frame (d) 50th frame, and (e) 60th frame throughout the 32s actuation process.

TABLE I

Mechanical properties of the robotic system

Backlash (mm)	1st stage coefficient (°/mm)	2nd stage coefficient (°/mm)	Linearity (R ²)	Accuracy (%)
±1.66	0.497±0.08	6.065±0.03	0.998	1.33

TABLE II

Work ranges and coupling variations of three robot segments

Actuated segment	Range (°)	Base variations (°)	Mid variations (°)	End variations (°)
Base	−89.4–89.4	N/A	4.2	0.9
Middle	−89.6–87.9	2.5	N/A	0.5
End	−82.1–83.5	0.3	0.2	N/A