

Prostate Targeting: Compact Robot with Harmonic Stepper Motors for MRI-Guided Needle Therapy

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Abstract – The superior image quality and excellent contrast offered by Magnetic Resonance Imaging (MRI) make it an ideal tool for guiding interventional procedures, particularly in targeting tumors within soft tissues. This paper presents an innovative robotic system, tailored for Magnetic Resonance (MR) environments, leveraging the benefits of MRI's high-resolution imaging capabilities for precise tumor targeting. The robot, designed with four degrees of freedom (DOFs), is driven by four novel Harmonic Pneumatic Motors, ensuring Magnetic Resonance (MR) compatibility. This motor utilizes a harmonic gearbox mechanism, incorporating a pair of flex and circular splines, with torque generated through the deformation of the flex spline. It achieves a step size of 0.9° and delivers a maximum measured output torque of $825 \text{ mN}\cdot\text{m}$. The robot's design includes a dual-stage needle guide, each stage is supported by two arms, enhancing its targeting accuracy. Experimental tests have demonstrated the robot's high positioning accuracy of 1.56 mm . Furthermore, MR testing confirms that the robot's presence results in a negligible signal-to-noise ratio (SNR) reduction, well within acceptable limits. The introduction of the Harmonic Pneumatic Motor-Driven Robot presents an improvement of compact MRI robots in the field, providing a potent combination of precision, safety, and compatibility in MRI-guided interventional procedures.

Keywords — Medical robotics, Pneumatic motor, MR, Prostate interventions.

I. INTRODUCTION

Ultrasonide-guided therapy has been widely used for prostate diagnosis and treatment because it provides the

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image of soft tissues, allowing surgeons to guide the needle to target tissue for biopsy or treatment in real time [1]. However, the provided images suffer from low quality and lack sufficient detail, making it challenging to discern suspicious areas accurately. Consequently, this limitation contributes to a high failure rate in cancer detection [2]. In response, a protocol known as sextant biopsy is implemented, involving the selection of 10-12 systematic biopsies from the peripheral zone, which aims to enhance the detection rate [3]. However, this systematic biopsy carries limitations including extended procedure time, additional patient morbidity, and overdiagnosis of indolent tumors. It fails to detect approximately 30% of cancers, with a false negative rate ranging from 17% to 21% [4].

In contrast, Magnetic Resonance Imaging (MRI) offers the ability to produce high-contrast images of soft tissues, making suspicious lesions visible [5]. Hence, MRI has been widely adopted for various minimally invasive interventions, such as breast biopsy [6], [7] prostate intervention [8], [9], and liver cancer [10], assisting accurate image-guided therapy. During these procedures, the lesion area is targeted using MRI, and a needle is inserted for biopsy or treatment. Compared with manual operations, robotic systems can position and orient the needle guide and assist doctors to conduct needle insertion, offering great benefits in terms of precision, operating time, and reliability, reducing redundant biopsies, minimizing procedure time and increasing the cancer detection rate [11], [12].

Recent studies, such as the PRECISION trial, and updated European Association of Urology (EAU) guidelines suggest that in centers with high-quality multiparametric MRI (mpMRI) and expert readers, targeted-only biopsy can achieve comparable or superior detection of clinically significant cancers, while reducing unnecessary sampling [13]. Nevertheless, systematic biopsy may still detect a minority of clinically significant cancers in MRI-negative regions, and current consensus continues to favor a combined strategy in many institutions. The robotic system is designed to support both paradigms, while emphasizing precision and efficiency in MRI-targeted biopsy. This dual capability ensures that the system is compatible with present clinical consensus and adaptable to the ongoing shift toward MRI-driven diagnostic strategies.

Another approach for prostate biopsy is fusion, a technique that integrates pre-acquired MR images with real-time ultrasound through image registration. This approach leverages the strengths of both imaging methodologies and demonstrates a higher cancer detection rate compared to ultrasound guidance alone [14]. Furthermore, it reduces the imaging time compared to in-bore MRI biopsy, providing a potentially faster and more flexible clinical workflow.

However, its accuracy depends on two image modalities. The real-time ultrasound is imperfect and can introduce errors. Additionally, unlike in-bore MRI biopsy, the clinician cannot directly visualize the lesion they are targeting, and they rely on the pre-operative MRI and the fusion map. In contrast, the direct MRI-guided biopsy eliminates registration-related errors and gains the direct visualization of the lesion to confirm that the needle is definitively within the lesion.

Despite its advantages, MRI generates a strong magnetic field, meaning that any ferromagnetic materials would pose a hazard to both devices and patients. Using paramagnetic materials can also generate magnetic flux, which interferes with the MRI's magnetic field and distorts the image produced. For these reasons, robot systems operating under MRI conditions are required to be non-metallic and non-conductive. According to the response of devices to the strong magnetic field of MRI, three classifications are defined: MR-safe, MR-conditional, and MR-unsafe [15]. MR-unsafe devices pose significant risks in the Magnetic Resonance (MR) environment; MR-conditional devices can be used in the MR environment under specific conditions. MR-safe is the most stringent term, meaning that devices pose no hazards to patients under any circumstances with minimal testing required [16].

The strong magnetic field in MRI presents extra challenges to the robot's operation inside. Commonly used electromagnetic motors contain magnetic material that can distort images, and the strong magnetic field generated by the MRI system can interfere with these electromagnetic motors [17], making them unsuitable for use in an MR environment. To address this, various MR-safe/conditional actuators have been developed, such as piezoelectric actuators [18], [19], hydraulic actuators [20], [21], and pneumatic actuators [22–24]. Piezoelectric actuators operate by changing the shape of the piezoelectric material when an electric field is applied, and they contain no ferromagnetic materials. However, the electricity they use can produce heat and generate electromagnetic interference (EMI), resulting in the SNR reduction of MR images. As a result, piezoelectric motors used in an MR environment must be shielded to minimize their EMI influence [25], which would add complexity to the entire system. Current piezoelectric actuators are not classified as MR-safe due to their conductive components and potential electromagnetic interactions; therefore, robots driven by these actuators require extensive validation testing to ensure safe and reliable operation across varying MRI field strengths. Hydraulic actuators, driven by pressured liquid, do not generate an electromagnetic field, and the incompressible nature of the liquid allows for power to be transferred through long hoses with minimal energy loss [16], [26]. But the potential liquid leakage limits its application in a clinical environment [27], [28].

In contrast, pneumatic motors can be fabricated using non-metallic and non-conductive material, their operation does not generate EMI and does not distort MR images [29], [30]. Additionally, air leakage poses no danger in clinical settings. Compressed air is accessible in most MR rooms, allowing for long distance power transfer via air hoses. One drawback is the compressibility of air in long hoses, leading to control uncertainties and nonlinearities of the motor [31]. This issue can be mitigated using feedback and control strategy or

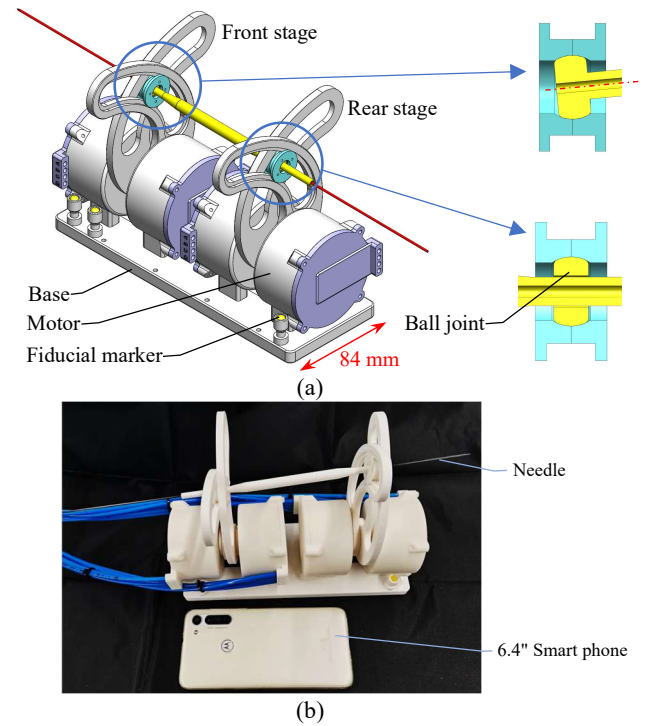


Fig. 1. (a) CAD model of the robot with the ball joints in two stages. (b) The robot compared with a 6.4-inch smartphone.

controlling the motors with air sequences [32]. The robot system proposed in this paper is powered by pneumatic stepper motors, leveraging the benefits of pneumatic actuators while addressing their inherent challenges.

First developed in the 1950s, harmonic drive mechanisms have been widely used in various applications [33], [34]. Stoianovici employed this mechanism to design a pneumatic actuator in 2005 [35], in which the flex spline is squeezed by the fluid energy. In this way, the motor can generate rotatory output with fluid energy from the cylinders. By this principle, this work introduces a harmonic motor design that utilizes compressed air to actuate pistons, which directly deform the flex spline to generate rotatory motion. The proposed pneumatic-driven approach achieves competitive operational longevity while maintaining mechanical simplicity.

Several robot systems have been proposed for use in the MR environment [36], [37], [38]. Li *et al.* introduced an MR-guided robot in 2015 for in-bore prostate biopsy, powered by non-magnetic ultrasonic motors [39]. This robot employed two stages to provide a 2 degrees of freedom (DOFs) Cartesian motion and 2-DOF angular motion. But the transversely placed trapezoid stages have a relatively large width, requiring patients to maintain a legs-raised position and reducing the available working space within the MRI bore. The Smart Template, proposed by Moreira *et al.* in 2021, also used ultrasonic motors to guide the needle to the target tissues [40]. But it contains a large number of components, the large size and utilization of transmission system like timing belts restrict its applicability within the confined MRI bore. In 2022, Biswas *et al.* proposed a robot with four powered DoFs [41]. This work utilized four discs with grooved profiles to guide the spherical joints and manipulate the biopsy needle. This design is innovative, while the electromagnetic motors used were not for the MR

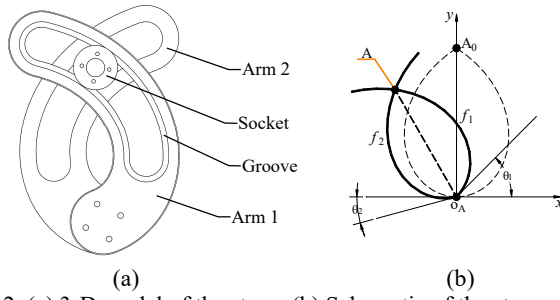


Fig. 2. (a) 3-D model of the stage. (b) Schematic of the stage.

environment, and the configuration of the concentric discs geometrically prevents the intersection point from aligning with the disc's center point.

This paper presents a new MR-safe robot for prostate biopsy, utilizing a motor design based on the harmonic drive mechanism. The entire system is MR-safe with no use of any metallic or conductive materials. The main contributions of this work are as follows: 1) The robot system employs a simplified driving mechanism consisting of dual-arm actuation at each stage, which significantly reduces the number of required transmission components while maintaining operational efficiency; 2) The motors used are non-back drivable, allowing the robot to hold its position when the power is lost during an emergency. With a small step size of 0.9° , it can be driven directly without the need for gearboxes, reducing the overall system size; 3) The robot features a concentric motor arrangement that yields an elongated axial profile, enabling optimal positioning alongside the patient within the MRI bore. This compact, linear configuration is specifically designed for prostate interventions, facilitating precise device placement.

II. METHODS AND MATERIALS

A. Robot Design

Fig. 1a shows the computer-aided design (CAD) model of the robot system, in which four motors are mounted on the base in a line with all the output shafts coaxial. The robot consists of two stages (the front and rear stages), located at a distance of 124 mm from each other. Each stage consists of two arms, powered by two motors. The two arms and two half-sockets are bonded together with a ball joint fit in. Each arm has a groove that allows the socket to slide inside when the arm rotates. As a result, the ball joint is always at the intersection of the two grooves of the arms. Therefore, the combination rotations of the two arms can drive the socket to move translationally in a Cartesian plane. The rotations of the two arms are controlled by coupling with two motor shafts.

The two intersection points on the two stages are recognized as two support points. The needle holder is placed between the two stages and connected to the two support points. Then, the position and rotation of the needle can be obtained by controlling the positions of two support points in two stages. The two half-sockets form a ball joint structure; one side of the needle holder is a ball joint and fits in the sockets so that the needle holder can rotate around left-right and anterior-posterior axes. When the support point on one stage moves, the distance between the two points changes. Therefore, a linear moving structure is proposed on the rear

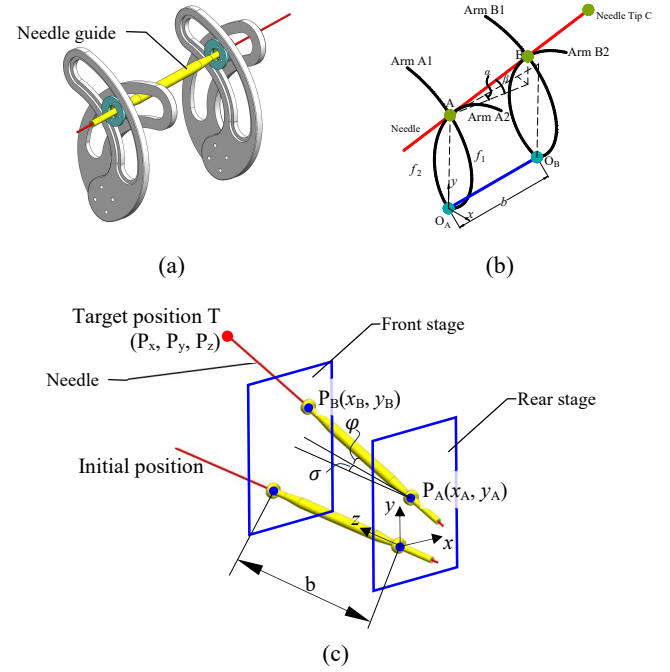


Fig. 3. (a) CAD drawing of the two stages. (b) Schematic of the two stages. (c) Schematic of the needle demonstrating the parameters.

stage, allowing the needle holder to slide along the ball joint. Five fiducial markers are mounted on the robot base for the registration between the robot and the patient.

The whole design has a compact overall size of $230 \text{ mm} \times 84 \text{ mm} \times 180 \text{ mm}$ (shown in Fig. 1b). For the requirement of MR compatibility, all the components used, including bearings and screws, are made of plastic, and the fabricated parts are made of polylactide (PLA) and white resin using 3-D printing.

B. Kinematic Analysis

Fig. 2a demonstrates the 3-D model of one stage, and Fig. 2b shows the trajectory of the grooves, in which curves f_1 and f_2 are the two profiles showing the geometry of the grooves. O_A is the center point that the two arms rotate around, A is the intersection point between the two curves. f_1 is a spiral, while f_2 is symmetric to f_1 about line $O_A A$. The distance between O_A and A is in proportion to the rotating angle of the motor. Then, the trajectory of f_1 is calculated as:

$$r = 65\theta \quad (1)$$

where r is the distance between the center point and the intersection point, and θ is the rotating angle of this arm. In Cartesian coordinates, the position of one point on curves f_1 and f_2 can be described as:

$$\begin{cases} f_{1x} = 65\theta \cdot \cos(\theta) \\ f_{1y} = 65\theta \cdot \sin(\theta) \end{cases} \quad (2)$$

$$\begin{cases} f_{2x} = -65\theta \cdot \cos(\theta) \\ f_{2y} = 65\theta \cdot \sin(\theta) \end{cases} \quad (3)$$

In Fig. 2b, point A_0 represents the original position of the intersection point, where arms A1 and A2 are at the start positions, and the socket is at the end of each arm with the two arms symmetric to axis y . The position of point A depends upon the rotating angles of these two curves, and its position is calculated as:

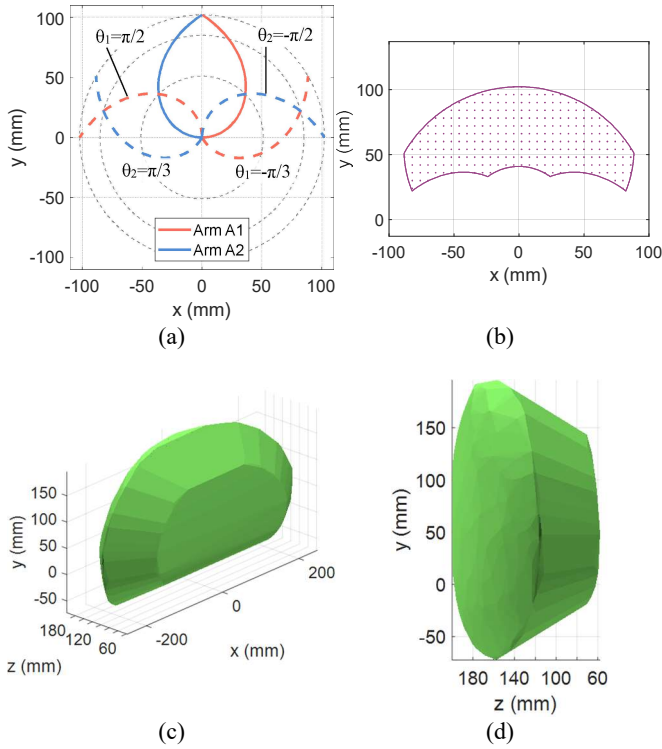


Fig. 4. (a) Working range of the two curves. (b) Workspace of a moving point on a stage. (c) 3-D view of the workspace of the needle tip. (d) Side view of the workspace.

$$\begin{cases} x_A = -65 \sin\left(\frac{\theta_1 + \theta_2}{2}\right) \cdot \frac{\pi - \theta_1 + \theta_2}{2} \\ y_A = 65 \cos\left(\frac{\theta_1 + \theta_2}{2}\right) \cdot \frac{\pi - \theta_1 + \theta_2}{2} \end{cases} \quad (4)$$

where (x_A, y_A) is the position of point A, θ_1, θ_2 are the rotating angles of arms A1 and A2. Then, with the given position of the intersection point (x_A, y_A) , the rotating angles of the two arms can be calculated as:

$$\begin{cases} \theta_1 + \theta_2 = 2 \tan^{-1}\left(-\frac{x_A}{y_A}\right) \\ \theta_1 - \theta_2 = \pi - \frac{2}{65} \sqrt{x_A^2 + y_A^2} \end{cases} \quad (5)$$

and

$$\begin{cases} \theta_1 = \tan^{-1}\left(-\frac{x_A}{y_A}\right) + \frac{\pi}{2} - \frac{\sqrt{x_A^2 + y_A^2}}{65} \\ \theta_2 = \tan^{-1}\left(-\frac{x_A}{y_A}\right) - \frac{\pi}{2} + \frac{\sqrt{x_A^2 + y_A^2}}{65} \end{cases} \quad (6)$$

Similarly, the rotating angles of arms 3 and 4 on stage B are calculated as:

$$\begin{cases} \theta_3 = \tan^{-1}\left(-\frac{x_B}{y_B}\right) + \frac{\pi}{2} - \frac{\sqrt{x_B^2 + y_B^2}}{65} \\ \theta_4 = \tan^{-1}\left(-\frac{x_B}{y_B}\right) - \frac{\pi}{2} + \frac{\sqrt{x_B^2 + y_B^2}}{65} \end{cases} \quad (7)$$

where (x_B, y_B) is the position of the intersection point on stage B, and θ_3, θ_4 are the rotating angles of arms B1 and B2. Fig. 3 indicates the position of the two intersection points A, B, and the target point C.

Once the translational positions of the two support points are established, along with the given position of the target point (P_x, P_y, P_z) , the rotational angles (φ, σ) of the needle around the lateral and longitudinal axes, the position of the support point on each stage is obtained as:

$$\begin{cases} x_A = P_x - P_z \cdot \tan\sigma \\ y_A = P_y - P_z \cdot \tan\varphi / \cos\sigma \end{cases} \quad (8)$$

$$\begin{cases} x_B = P_x - P_z \cdot \tan\sigma + b \cdot \tan\sigma \\ y_B = P_y - P_z \cdot \tan\varphi / \cos\sigma + b \cdot \tan\varphi / \cos\sigma \end{cases} \quad (9)$$

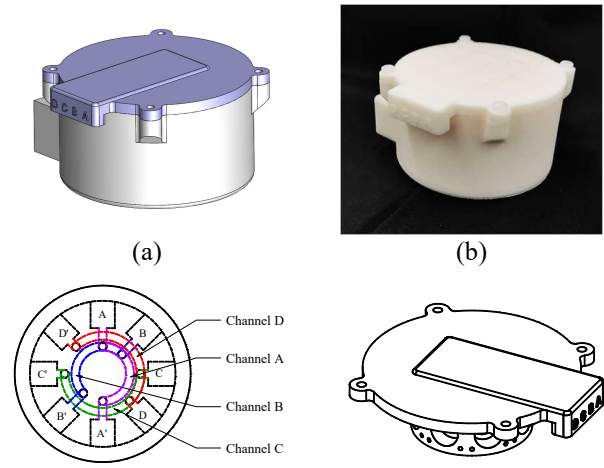


Fig. 5. (a) CAD model of the motor. (b) Photograph of the motor. (c) Air channels inside the bellow

where b is the distance between the two stages. With Eqs. (6) - (9), the rotating angles of the two motors are obtained.

C. Workspace Analysis

Because of the mechanism constraint, the socket can slide along the two grooves with a range of $\frac{\pi}{5} < \theta < \frac{\pi}{2}$, the rotating range of arm A1 is $[-\pi/3, \pi/2]$, and that of arm A2 is $[-\pi/2, \pi/3]$. In Fig. 2b, the distance between point A and the origin is calculated as:

$$o_{AA} = 65 \cdot \frac{\pi - \theta_1 + \theta_2}{2} \quad (10)$$

It demonstrates that the length of o_{AA} is related to the difference between the two rotating angles, and it will remain constant when the two curves rotate in the same direction, simultaneously. Then, the trajectory of the intersection point A is a circle with a radius of o_{AA} . When only one curve rotates, this intersection point moves on the other curve, going inward or outward towards the center point, with these two curves symmetric around the line o_{AA} . Fig. 4a shows the working range of the two curves, and the workspace of the moving point in stage A is shown in Fig. 4b.

The workspace of the needle tip is determined by that of the two support points. Fig. 4c and 4d depict the 3-D and side views of the needle tip's workspace. This workspace is generated with the two support points on stage A and B positioned within the working range shown in Fig. 4b, and with an insertion depth ranging from 100 mm to 200 mm.

D. Motor Design

The motor used in this work is powered by four channels of compressed air and can rotate bidirectionally. Fig. 5 shows the CAD model and photograph of the motor. All the air hoses are connected to the front bellow, and the output shaft is located on the rear side. The internal air channels inside the housing are placed on three different layers (in Fig. 5c). Each pair of opposing cylinders is connected to a shared air pipe, enabling simultaneous activation.

This motor is designed to transfer the linear movement of the pistons into a rotary motion of the output through the deformation of the flex spline. The detailed design is shown in Fig. 6. Four pairs of pistons are equally located around the center of the motor. Fig. 6a and 6b depict the section view, in which the circular spline is mounted on the housing, and the

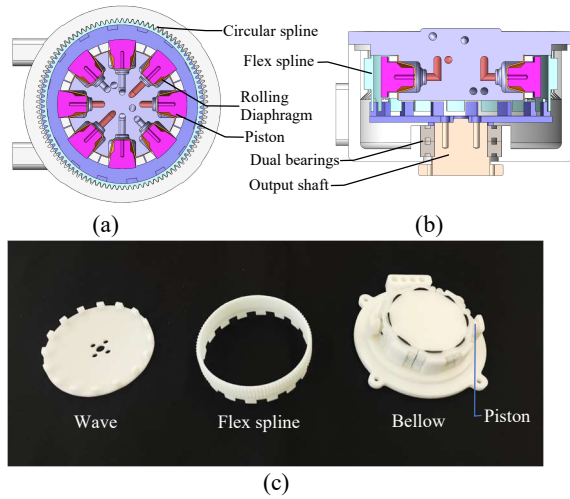


Fig. 6. (a) Section view of the motor showing the splines, pistons, and cylinders. (b) Side view. (c) Photo of the components.

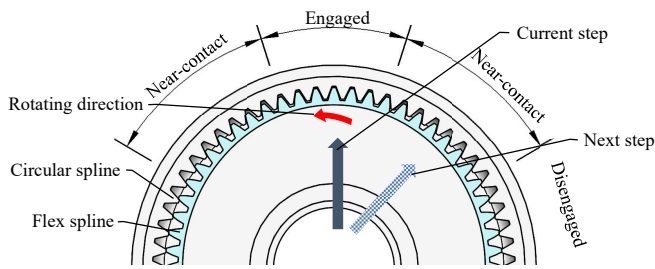


Fig. 7. Teeth contact status of the flex spline and circular spline.

output is connected to the flex spline. A rolling diaphragm is applied to each piston and cylinder to minimize the air leakage and frictional losses. Compared with rubber seals, it can generate a reduced friction force. The photo of the components is shown in Fig. 6c.

Along with the working of the pistons in the bellow diaphragm, the flex spline is reshaped by each of the two opposite pistons. Thus, the teeth of the flex spline are engaged with the circular spline at different zones by deforming the flex spline at different points. For the convenience of hose arrangement, all the ports are placed on one side of the bellow. As the arm is connected to the output shaft directly, two bearings are placed between the housing and the output shaft to minimize any radial deformation and movement.

E. Motor Working Principle

The contact of the teeth inside the motor is separated into three zones according to their engagement status: near-contact, engaged, and disengaged. Fig. 7 shows the contact status of the teeth when a force is applied to the near-contact zone from the engaged zone. Due to this force, the relevant teeth are engaged with the circular spline. At this moment, both sides next to the engaged zone are in near-contact status. When a force is applied to the near-contact zone in the right area, the teeth in the second quadrant will mesh in, and the teeth in the first quadrant will mesh out due to the elasticity of the flex spline. As the flex spline is symmetric, the teeth at a circumferential difference of 180° are always at the same working status. Along with the engagement of the teeth, the flex spline will be rotating counterclockwise. Then, the output shaft connected to the flex spline is able to rotate to generate an output torque.

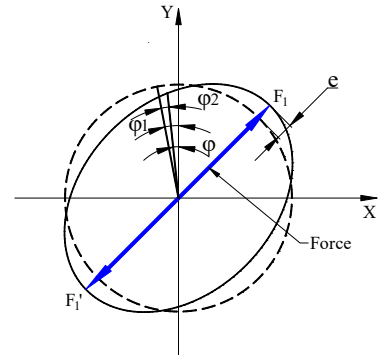


Fig. 8. Schematic diagram of the deformation of the flex spline.

As the near-contact areas of the flex spline are on double sides shown in Fig. 7, the teeth on the left side of the engaged zone are in left-side contact, while the teeth on the right side of the engaged zone are in right-side contact. Technically, the flex spline exhibits minimal backlash due to its double-sided tooth contact. Therefore, this design has a higher return error than the rigid spur gear-driven motor with the same gear precision.

When the pistons are pressing the flex spline, the flex spline is deforming radially. At the same time, it is rotating around the motor center, causing the circumference movement between the pistons and the inner wall of the flex spline, leading to the abrasion of the flex spline and pistons.

Fig. 8 demonstrates the schematic diagram of the deformation of the flex spline, in which the dashed circle is the original shape of the flex spline without any force applied to it (isokinetic curve), and the ellipse represents the deformed spline under the forces. When forces F_1 and F_1' are applied to the flex spline, it rotates counterclockwise due to the engagement of the teeth. Then, the actual rotating angle ϕ is expressed as:

$$\phi = \phi_1 + \phi_2 \quad (11)$$

where ϕ_1 is the rotating angle of the isokinetic curve, and ϕ_2 is the rotating angle caused by the deformation of the flex spline. Therefore, the flex spline is able to rotate continuously by activating different near-contact zones on the flex spline.

For the harmonic gearbox, it is the wave generator that causes the deformation of the flex spline. In this design, four pairs of pistons are applied to mimic the motion of the wave generator [42], [43]. The transmission ratio can be expressed as:

$$i = \frac{z_f}{z_f - z_c} = -50 \quad (12)$$

where z_f is the teeth number of the flex spline, and z_c is the teeth number of the circular spline. It shows that the transmission ratio is inversely proportional to the difference between the circular spline and flex spline. The teeth number of the circular spline is 102, and the flex spline has two fewer teeth than the circular spline. And the teeth of the flex spline and the circular spline have the same module.

As the bellow has four pairs of cylinders, two cycles' movement of the pistons drives the flex spline to rotate by two teeth angle which is $360^\circ/50 = 7.2^\circ$. Therefore, one step movement of the bellow can drive the flex spline to rotate by 0.9° , which is the resolution of this motor.

Fig. 9 shows a four-step rotation of the flex spline, in which the flex spline rotates by one tooth. Because of the pressure of A and A', the teeth in red are engaged, and the teeth next

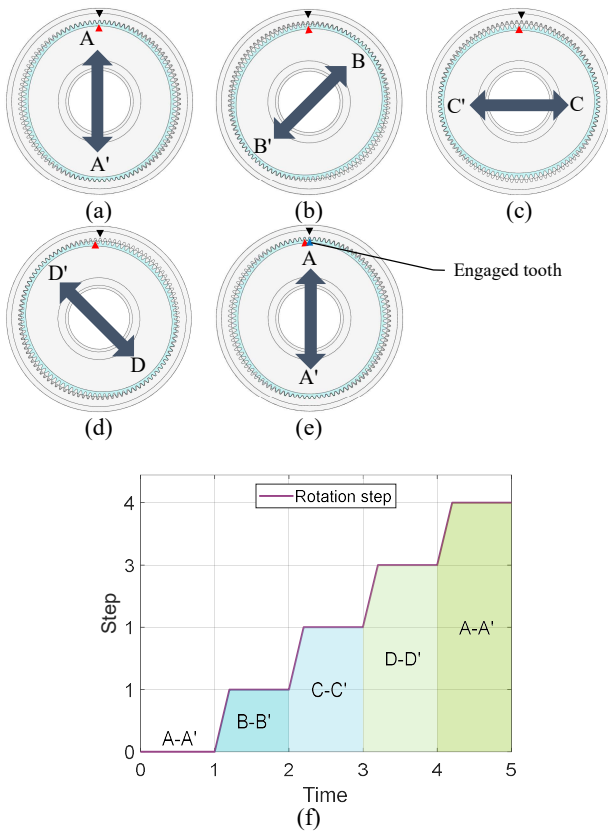


Fig. 9. The working sequence of the motor and the triangles show the positions of the circular spline and flex spline, respectively. (a) Initially, the flex spline and circular spline are aligned vertically. (b) In the first step, the flex spline is engaged in the near-contact zone. (c) After two steps, the flex spline has rotated half a tooth relative to the circular spline. (d) In the fourth step, the adjacent tooth on the flex spline becomes aligned with the circular spline. (e) After four steps, the flex spline has rotated by one tooth pitch, engaging an adjacent tooth with the circular spline. (f) The rotation angle of the flex spline with respect to the activation of cylinders.

to it are in near-contact status. Thus, when the force from pistons A and A' is released and pistons B and B' are activated, their force is applied to the relevant teeth. This drives the near-contact teeth into full engagement with the circular spline, forcing the flex spline to rotate in the reverse direction. At the same time, the previously engaged spline in the contact zone is released and gets into the near-contact status. Therefore, by activating the compressed air in different cylinders in a sequential manner (A, A') – (B, B') – (C, C') – (D, D') – (A, A'), the teeth of the flex spline get in and out of the engagement with the circular spline, driving it to spin around the circular spline anticlockwise. Fig. 9f indicates the rotation angles of the flex spline with respect to the activation of different cylinders. Similarly, the flex spline can spin clockwise by regulating the air in a reverse manner. Theoretically, increasing the number of cylinders can reduce the rotational step size and produce a smoother rotation of the flex spline.

F. Spline Design

The output torque comes from the deformation of the flex spline in different zones. The flex spline is made in a ring shape with a thickness of 1 mm, it is made of white resin V4 (Formlabs, Boston, US) and can be reshaped when an opposed force from the bellow is applied. When a force works

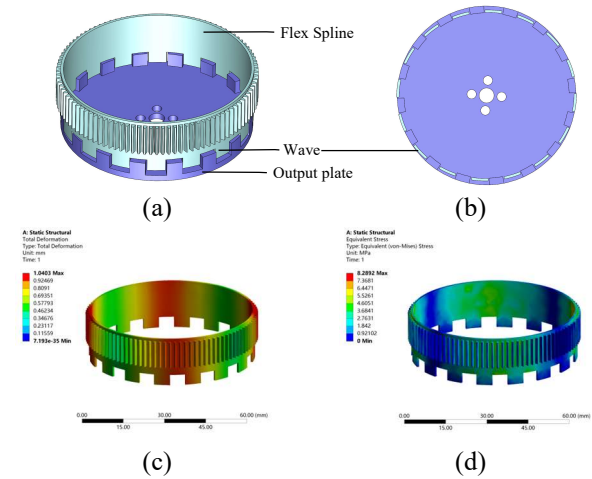


Fig. 10. (a) Flex spline with output plate. (b) The engagement of the wave structure. (c) Deformation simulation of the flex spline. (d) Stress simulation.

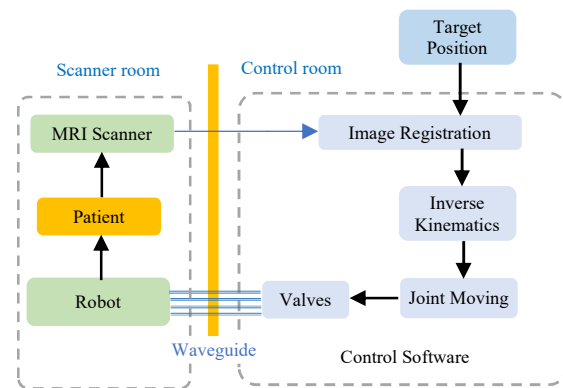


Fig. 11. System setup of the robot inside the MR room and control room.

on two opposite radial sides, the flex spline becomes a convex curve. The teeth in the two convex areas are engaged with the circular spline. As the circumference of the flex spline is constant, it deforms into a smooth curvature.

The difference between the flex spline and the circular spline is 2; the flex spline is squished by 1 mm on each side when the force is applied. Consequently, the flex spline design represents a compromise between minimizing structural deformation and maximizing torque transfer capability. One way is to increase the depth to allow the flex spline to bend and transfer torque simultaneously, but this would bring a lot of extra space on the axial side, making the overall design large. In this study, the flex spline is connected to the output plate through a square wave mechanism. As shown in Fig. 10a, 10b, the bottom side of the flex spline is in a square wave structure that can fit into the top side of the output plate. Unlike the harmonic gearbox, the output plate is not connected to the flex spline directly, allowing it to deform under a force and to transfer the torque. This can reduce the length between the flex spline and the output shaft. However, the lateral sides of the flex waves slide against that on the plate when the flex spline is deformed, resulting in an unexpected energy loss, particularly under high loads. To simulate the deformation and stress of the flex spline, the Finite Element Analysis (FEA) was carried out using Workbench (Ansys, USA). Fig. 10c and 10d depict the deformation and stress of the flex spline under the forces of

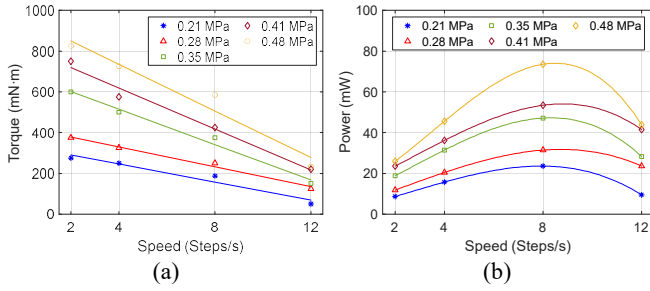


Fig. 12. (a) Output torque with respect to speed at different pressures. (b) Output power with respect to speed at different pressures.

12 N and a load of 50 mN·m.

Technically, the forces applied to the opposite sides of the flex spline drive the teeth on the two sides to get meshed in synchronously, so the meshing teeth at the two sides drive the flex spline to rotate. However, in practice, air transfer delays and friction differences between the two pistons introduce a time lag in force application, and then different areas of the flex spline start deforming. This asynchrony causes non-uniform deformation across the flex spline, affecting meshing behavior, which could generate potential vibration on the output side.

III. EVALUATION

A. Measurement Setup

In the system setup, each motor requires four pneumatic 3/2-way valves to activate the relevant cylinders to achieve dual-direction motion; as a result, 16 pneumatic valves were applied to power the four motors of the robot. Control of the robot was performed through a user interface (UI) developed using Matlab App Designer, through which the kinematic model was calculated with the given target positions. With the calculated moving steps of each motor, a DAQ controller (USB-6501, National Instrument) was applied to generate the control signal, which was transferred to the valve drivers. In clinical applications, robots with motors are located inside the MR room, components like drivers, controllers, and electrical power are placed in the control room, and they are connected with long air hoses. The configuration of the robot and control system is shown in Fig. 11.

B. Output Torque Test

The output torque of the motor was tested by coupling with a pulley on the output side. The torque was calculated by adjusting the maximum number of loads the motor can lift. Compared to the dynamic torque measurement, this is easy to achieve but may underestimate the output torque. Fig. 12a indicates the output torque with respect to speed at different pressures with air hoses of 8 m, in which the maximum output torque was measured as 825 mN·m running under an air pressure of 0.48 MPa at a speed of 2 steps/s. And the output torque decreases quickly at a speed of over 10 steps/s.

The maximum unloaded speed of the motor was measured as 20 steps/s (3 rpm). This speed is directly related to the step response time and represents the duration between the introduction of compressed air into the air hose and the motor's completion of the corresponding step movement.

Fig. 12b shows the output power with respect to speed and air pressure. The power generally increases with speed when

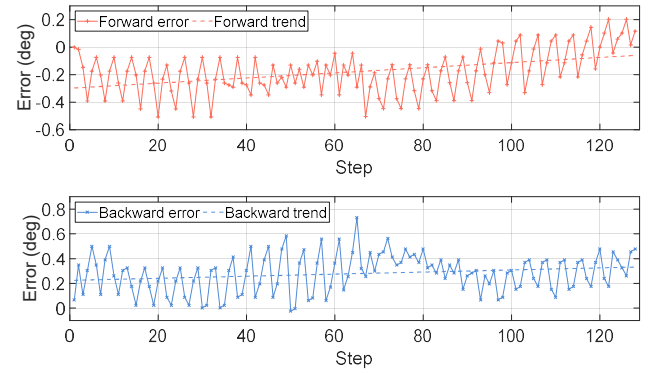


Fig. 13. Forward and backward error distribution.

the motor operates within its optimal range. However, a significant power drop occurs at 12 steps/s, likely due to insufficient torque output at higher speeds, showing that the motor's performance is limited by its ability to maintain full-step integrity.

C. Error Measurement

In the accuracy test, the rotating angles of the motor were measured by coupling with an encoder (EB38S6A-5000-3CG2) with a resolution of 0.072°. The motor rotated 120 steps in both directions corresponding to a total rotation of 108° in each direction under an external load of 100 mN·m. The actual angular position was recorded during each trial. Fig. 13 depicts the forward and backward errors, which have the mean values of 0.2° and 0.28°, respectively. The maximum error was measured as 0.72°. Both errors fluctuate in a 4-step period with the increase of rotation steps, which is a one-cycle movement. The trendlines show irregular deviations corresponding to the step increases, which are probably caused by the fabrication-related issue. Moreover, most forward errors are positive, whereas the majority of backward errors are negative. The mean backward error is also slightly larger than the mean forward error, likely due to changes in wave-flex spline interaction when the rotation direction reverses.

The main error of the motor comes from the deformation of the flex spline. The waved structure allows the radial deformation of the spline, but it also causes gaps between the flex spline and the output plate, which leads to rotational error. Combining the plate and the flex spline using materials with high stiffness and toughness would be a solution. Plus, the gaps inside the plastic bearings used to hold the output shaft also contribute to the positioning error. Another error source is the fabrication and assembly of the components. The flex spline's output is produced through spline engagement/disengagement, which inherently requires loose fitting due to manufacturing tolerances. This design constraint may result in intermittent meshing irregularities and introduce rotational positioning errors.

D. Fatigue Test of the Flex Spline

The flex spline converts pneumatic energy into output torque through elastic deformation; it remains deformed when the motor is working. Due to the cyclic stresses involved, fatigue testing of the flex spline is critical to ensuring long-term reliability. In this test, the motor was

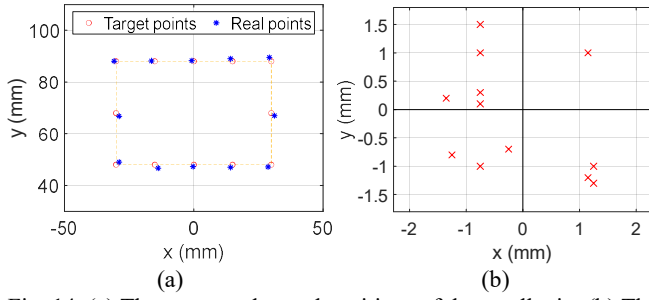


Fig. 14. (a) The target and actual positions of the needle tip; (b) The error distribution.

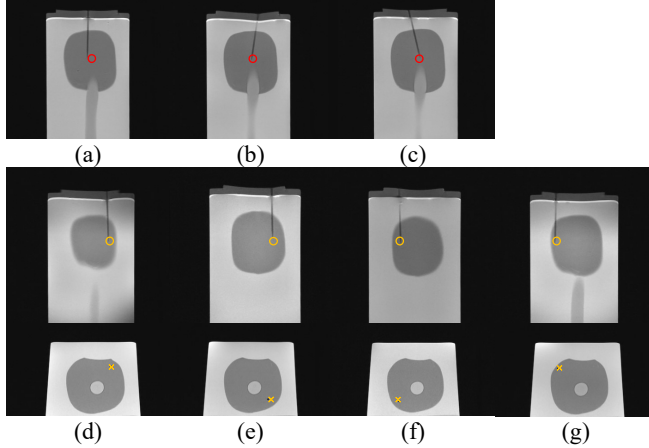


Fig. 15. (a) – (c) The target and actual positions of the needle tip from three directions; (d) – (g) Coronal and transverse view of the needle inside the phantom at four positions.

subjected to a 0.48 MPa air pressure and an external load of 500 mN·m. Each test cycle comprised 2000 clockwise steps followed by 2000 counterclockwise steps. This test cycle was repeated 20 times, resulting in a total 80 000 steps over the duration. Over the test, the flex spline was not cracked, and post-test measurements of output torque and speed showed no significant change in torque or positional error. Additionally, the flex spline's mass was measured before and after the test (3.92 g vs 3.90 g), showing a negligible mass change. This confirms its wear resistance and durability under the given operating conditions.

E. Positioning Accuracy Test

In the accuracy test, the robot was placed in front of a template at a distance of 100 mm, with all the motors actuated under an air pressure of 0.48 MPa at a speed of 4 steps/s, and 12 target points were selected. The needle holder was automatically controlled to move to the desired position, and then an 18-gauge needle was inserted into the template manually. Fig. 14a shows the target positions and real positions of the points, with the distribution error shown in Fig. 14b. It shows that the robot has a mean error of 1.33 mm with a standard deviation (SD) of 0.14 mm. A maximum error of 1.58 mm was observed, which is comparable with the works in [44], [45]. For the error distribution, the majority of the error points are located on the left side around the center line.

Several factors should be considered for the positioning accuracy. First, the two arms are supported by the output shafts of the motor directly, although double bearings are

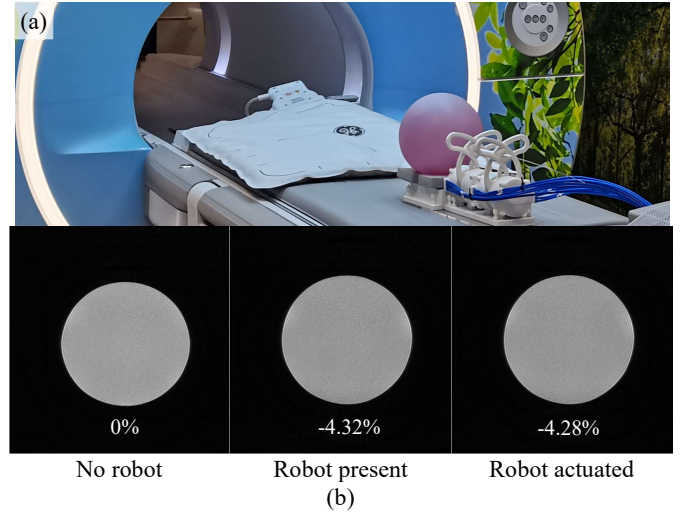


Fig. 16. (a) The photo of the robot inside the scanner with a phantom. (b) SNR of MR images under three different scenarios: no robot, with robot present, and with robot actuated.

applied to minimize the swing of the shafts, the movement of the sockets is still enlarged by the long arms. Besides, the deformation of the 3-D printed structure plays a role in the target positioning, especially with relatively long arms. Moreover, the rotating error of the motor is important for the final targeting accuracy. As there is no gearbox applied, the movement of the arms is affected by the motors directly, and the motor error has been analyzed in Section C.

F. MR Guided Needle Insertion

To evaluate the performance of the robot under an MR environment, a variety of needle insertions were performed with a prostate phantom (053S, Sun Nuclear, Norfolk, VA, USA) in a 3T scanner (SIGNA Premier, General Electric, USA). The robot was placed in front of the phantom at a distance of 60 mm from the front stage. In the first test, a specific virtual point was selected, with the needle pointed to this target from three directions (-10° , 0° , 10°). The rotation of each motor was calculated automatically. When the robot arrived at the desired position to align with the target point, the needle was inserted into the phantom manually. Then, four more targets around the prostate were selected, with the distance between each two adjacent points of 24 mm, and the needle was inserted straight ($\alpha = 0^\circ$).

The orientation and position of the needle were obtained through the T2-weighted sequence, with the FCO: 160×160 mm, image Matrix: 512×512 , TR: 2000 ms, TE: 100 ms. Fig. 15a – 15c show MR images of the needle inserted into the phantom from three directions (left, middle, right), and the red circles show the target positions. Fig. 15d – 15g show the MR images with the needle inserted into the phantom straightly, with an insertion depth of 20 mm, and the amber circles and crosses indicate the positions of the target points. In this test, the mean targeting error was calculated as 1.56 mm with a standard deviation of 0.93 mm. The positioning error in the prostate phantom is larger than that in the open-air test, this is caused by the deviation of the needle tip due to the resistance of the phantom.

G. SNR Test

An MR compatibility study of the robot was conducted to

evaluate its influence on image quality, in which the robot was placed in front of a phantom inside the scanner. T2-weighted protocol was applied to evaluate its MR compatibility in three scenarios: 1) without the robot; 2) with the robot in static; and 3) with the robot in motion. Fig. 16 illustrates images of the SNR test in different configurations. SNR is calculated as the mean signal of the image center divided by the noise in the corner. The mean signal is the mean pixel intensity in the image center, while the noise is the mean signal intensity in the corner.

SNR reduction of less than 6% was calculated in the test in all scenarios, falling within the acceptance range [46].

IV. DISCUSSION

To improve the accuracy of the robot, several factors should be given consideration. First, the two arms in each stage remain in direct contact; while a loose fit is intentionally designed to accommodate fabrication and assembly inaccuracies, this clearance introduces unintended backlash, ultimately compromising positioning precision. Self-lubricated materials and high-precision manufacturing techniques should be considered for use under extreme conditions. Second, the arm in each stage is supported by the output shaft. Although double bearings are applied, the deformation of the shaft and the arm itself can lead to the unexpected movement of the sockets. Accurate fabrication and assembly of the components to ensure the motors are in line with each other can reduce this error. Besides, the rotating error of the motors can affect the position of the intersection point, which then influences the final positioning accuracy. The current prototype exhibits backlash due to fabrication limitations. Future work will focus on optimizing the spline geometry to minimize this error.

The output torque of the motor is affected by the strength of the flex spline. Ideally, the flex spline is required to be thin enough to be able to reshape when a force is applied, however, the extremely thin spline wall limits the maximum torque it can withstand due to its strength limitations. Therefore, the use of materials with high flexibility and strong strength can significantly increase the performance of this motor. Plus, by using materials with greater flexibility and higher strength, the flex spline and the output shaft are able to be combined into one single part, decreasing the number of fabrication parts and reducing the rotating error caused by the inaccurate power transfer. Finally, by changing the gear ratio of the flex spline and circular spline, greater torque and higher resolution can be obtained. For instance, with teeth numbers 200 and 202, a transmission ratio of 1:100 can be obtained, resulting in a step size of 0.45°. Currently, four pairs of pistons with four air hoses are applied to have a smooth motion of the output with higher accuracy. Technically, three pairs of air hoses are capable of achieving the dual-directional motion of the motors, as demonstrated in [35].

V. CONCLUSION

This study presents a pneumatic-powered robot specifically designed for MR environments, representing a compact design for MRI-guided interventional procedures. The use of harmonic pneumatic motors translates pressurized air into an effective output torque, achieving a high

transmission ratio. This mechanism not only enhances the resolution but also eliminates the need for a reducer, thereby simplifying the system while reducing the number of components. This design is compact, allowing for easy integration within the confined space of an MR scanner. Furthermore, the use of MR-safe materials ensures minimal interference with the scanner's functionality while maintaining the excellent image quality essential for tumor targeting. The robotic positioning accuracy, combined with its negligible impact on the SNR, underscores its potential as an interventional tool for MRI-guided prostate therapy.

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