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A Passive Parallel Master–Slave Mechanism for Magnetic Resonance Imaging-Guided Interventions

A passive, parallel master–slave mechanism is presented for magnetic resonance imaging (MRI)-guided interventions in the pelvis. The mechanism allows a physician to stand outside the MRI scanner while manipulating a needle inside the bore and, unlike a powered robot, does not place actuators in proximity to the patient. The manipulator combines two parallel mechanisms based on the Delta robot architecture. The mechanism also includes a two-axis gimbal to allow for tool angulation, giving a total of five degrees of freedom so that the physician can insert and steer a needle using continuous natural arm and wrist movements, unlike simple needle guides. The need for access between the patient's legs and within the MRI scanner leads to an unusual asymmetric design in which the sliding prismatic joints form the vertices of an isosceles triangle. Kinematic analysis shows that the dexterity index of this design is improved over the desired workspace, as compared to an equilateral design. The analysis is extended to estimate the effect of friction and model the input:output force transmission. Prototypes, with final dimensions selected for transperineal prostate interventions, showed force transmission behavior as predicted by simulation, and easily withstood maximum forces required for tool insertion. [DOI: 10.1115/1.4028944]

1 Introduction

MRI is a rapidly developing diagnostic tool that has the potential to improve the detection and treatment of prostate tumors. Diffusion-weighting and dynamic contrast-enhancement can selectively identify high-risk tumors, and have shown increasing promise as a method to visualize significant prostate cancers [1]. Furthermore, treatment, such as tumor ablation, can potentially be performed on the spot after initial diagnosis of suspect tissue under MRI-guidance. However, such MRI-guided interventions present a significant challenge: the bore of the MRI machine is narrow, providing a limited operating space between the patient's legs, and the physician must stand outside the machine while manipulating a biopsy needle or other tool within the bore. Due to the difficulty to reach the targeted zone, the ability to remotely insert interventional tools would be an advantage for the physician.

Solutions for MRI-guided transperineal prostate interventions range from simple needle guides [2] to general purpose robotic needle-inserting systems [3] and specialized robots for prostate biopsy [4,5]. A fundamental limit to needle guides is that they do not permit active needle manipulation during scanning. At the other end of the spectrum, robotic solutions can be expensive, in part due to the challenges of working with MRI-compatible materials, including actuators and sensors that are nonmagnetic and do not produce RF interference [6]. Robotic and fully teleoperated systems are further complicated by requiring complex sensors and methods for closed-loop control. In addition, pneumatic or hydraulic actuation systems require bulky actuators that are difficult to place between the thighs of obese patients [4,7]. Passive teleoperated mechanisms incorporated in handheld laparoscopic instruments have been considered for applications in minimally invasive surgery [8]. Others have utilized mechanical master–slave systems to remotely reach hazardous environments [9]. The

new class of devices we present is also passive, with only mechanical actuation. A passive manually driven design is preferred due to its intrinsic safety, simplicity, low cost, and ease of MRI-compatibility. In addition, a passive design may encounter an easier path to U.S. Food and Drug Administration approval.

For transperineal procedures, the MRI machine and the patient's legs produce an approximately cylindrical workspace necessitating at least 15 cm of travel in the Z direction, parallel to the MRI bore for needle insertion, and approximately ± 4 cm for lateral (X) and vertical (Y) motions to cover the area of the prostate. In order for a standard trocar needle tip to reach the workspace, the system requires articulation in five degrees of freedom (5DOF), in particular, 3DOF in translation and 2DOF in rotation (not including roll about the needle axis). Mechanisms that couple translations and rotation such as hexaglide systems [10] may not be able to produce the amount of articulation necessary to rotate the needle for procedures. The desired workspace, combined with the documented positioning accuracy and stiffness advantages of parallel mechanisms [11,12] lead to the choice of a double, parallel 3P-U-U (prismatic-universal-universal) mechanism for translations in the X, Y, and Z directions, decoupled from rotations about X and Y (Fig. 1).

Following robotics convention, prismatic joints (P) allow for 1 DOF in translation, revolute joints (R) allow for 1DOF in rotation about a single axis, universal joints (U) allow for 2DOF in rotation about two axes, and spherical joints (S) allow for 3DOF in rotation about all three spatial axes. We designed a double parallel mechanism connected by prismatic joints that form the vertices of an isosceles triangle, as seen in a cross section in the XY plane. Our manipulator is based on the Delta robot, which was presented in Raymond Clavel's doctoral thesis [11]. The Delta robot is a 3DOF parallel chain mechanism, consisting of a triangular platform with three pairs of struts, which allows for translational motions at its end-effector.

Although many variations on Delta parallel mechanisms have been reported (e.g., Refs. [13–20]), few are asymmetric. An asymmetric P-P-R-S manipulator is described in Ref. [21] for a rapid

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Fig. 1 Illustration of the double Delta-based (three P-U-U) manipulator with two-axis gimbals (+2R). Design parameters such as the angle between the prismatic axes and strut lengths can be changed to improve manipulability in the workspace of interest.

prototyping machine; and Ref. [22] describes a parallel mechanism within another parallel mechanism, with asymmetric links lengths. Our mechanism is unique in that there are two sets of moving platforms (hence it is a “double” parallel mechanism). Furthermore, we have designed the mechanism with dimensions chosen to fit inside an MRI scanner and to reach specific anatomies of interest. We compare symmetric and asymmetric versions of our design (with regard to the radial prismatic joint configuration) to achieve a high dexterity and relatively uniform force transmission over the workspace of interest, while fitting between a patient’s legs for interventions in the prostate.

The device we present has two moving platforms for mechanical teleoperation, and has design parameters that have been chosen specifically for MRI-guided interventions in the pelvis. Contributions of this paper include kinematic and friction analysis to influence the design parameters, and an experimental assessment to prove efficacy of the device with respect to the application requirements and expected force transmission behavior.

2 Design Description

The device consists of a double parallel mechanism that is able to replicate the physician’s wrist and arm motions during needle manipulation. The basic structure employs two Delta-like parallel mechanisms, one each on the master and slave end, connected by prismatic joints (Fig. 1). The prismatic joints are parallel to the nominal needle insertion direction, allowing essentially limitless travel in the Z-direction. Each half of the manipulator is an identical three P-U-U mechanism, with prismatic and rotational universal joints as shown in Fig. 2. The three P-U-U mechanism is similar to a design presented by Tsai and Tahmasebi [14], yet the prismatic joint axes are parallel to the Z axis, akin to a three P-U-U manipulator presented by Giberti et al. [16]. However, to our knowledge, we are presenting the first double, passive master–slave manipulator of this type, with two moving platforms.

The three P-U-U mechanism provides the three translational degrees of freedom in X, Y, Z. Two additional rotational degrees of freedom are provided by gimbals at the master and slave ends, to allow the physician to control needle orientation about X and Y. These gimbals are coupled by a set of three light rods with ball joints at each end, shown in black in Fig. 1. In addition, the platform at the slave end protrudes forward to provide better access to the perineum. As discussed further in Sec. 3, the overall dimensions are determined by the need to fit between a patient’s legs inside the 70 cm diameter bore of the MRI machine. Within these constraints, the spacing of the prismatic axes, strut lengths, and moving platform dimensions is determined from a compromise between manipulator dexterity and fidelity of force transmission.

Fig. 2 Schematic of half the double parallel mechanism, with joint and end-effector positions labeled. For clarity of the illustration, only some universal joint axes are indicated. Gimbal not shown.

3 Kinematic Analysis

Kinematic analysis is important to understanding the velocity and force transmission of the manipulator from master to slave. It can also be used to predict dexterity of the device based on certain design parameters.

3.1 Inverse Jacobian Solution. The symmetry between the input and output sides of the manipulator ensures that motions at the master and slave are identical. However, it is of interest to explore how rapidly the sliders move for a given motion of the platform, which determines how significant the effects of slider friction and inertia are at different parts of the workspace. The kinematic mapping is also useful for choosing link lengths and platform dimensions that will avoid singular conditions in the workspace, as discussed in Secs. 3.2 and 3.3.

Looking at half of the double three P-U-U mechanism (Fig. 3), one can find the mapping between the slider positions’ Z-coordinates and the platform position. Let the platform center be $P_o = (x, y, z)$. The slider Z-coordinates are the joint variables of interest $(s_{1z}, s_{2z}, s_{3z}) = (q_1, q_2, q_3)$. The inverse Jacobian relates the velocities of the slider positions and platform

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = J^{-1} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \frac{\partial q_1}{\partial x} & \frac{\partial q_1}{\partial y} & \frac{\partial q_1}{\partial z} \\ \frac{\partial q_2}{\partial x} & \frac{\partial q_2}{\partial y} & \frac{\partial q_2}{\partial z} \\ \frac{\partial q_3}{\partial x} & \frac{\partial q_3}{\partial y} & \frac{\partial q_3}{\partial z} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \quad (1)$$

Figure 3 illustrates the design parameters of interest looking at a cross section in the XY plane cutting through all three prismatic axes (sliders). The basic frame is a triangle, which may be equilateral or isosceles. The global origin is at the centroid of the triangle produced by the intersection of the universal and prismatic joints in an end-view (in the XY plane). The Z-position of the origin is set at half the maximum desired insertion length. For the equilateral configuration, $a = b = 60^\circ$, $L_{P1} = L_{P2}$ and $L_{S1} = L_{S2}$. To test the shape of various workspaces, we may describe the triangle as pointing upward from the global origin or downward.

The inverse kinematic equations described here are for an isosceles triangle pointing upward (toward the +Y axis). For ease of description, the global Y axis intersects with S_1 . Similarly, P_1 is only translated in the Y-direction from P_o . The sliders and platform corners are numbered clockwise from the top. The X and

Fig. 3 End-view diagrams of the manipulator to illustrate dimensions of interest. Note: L_{Sj} and L_{Pj} ($j = 1, 2$) lie in the XY plane because the platform does not tilt or twist; and the strut lengths are not purely in the XY plane. S_1 , S_2 , and S_3 represent the slider locations, and P_1 , P_2 , and P_3 represent the corners of the platform. In the equilateral case, r intersects the origin at the triangle centroid, in the isosceles case, r intersects the circumcenter.

Y coordinates of slider S_1 and platform P_1 are (s_{1y}, s_{1y}) and (p_{1y}, p_{1y}) , respectively. The other points are labeled in the same manner. The platform corners all have the same Z -coordinate as $P_o = (x, y, z)$. Due to the choice of coordinate frame, and the fact that the platforms remain in the XY plane, it can be seen from geometry that the X - and Y -coordinates of the platform corners are

$$\begin{aligned} p_{1x} &= x \\ p_{1y} &= y + \frac{2L_{P2}\sin(a)}{3} \\ p_{2x} &= x + \frac{L_{P1}}{2} \\ p_{2y} &= y - \frac{L_{P2}\sin(a)}{3} \\ p_{3x} &= x - \frac{L_{P1}}{2} \\ p_{3y} &= p_{2y} \end{aligned} \quad (2)$$

Also from geometry, the X and Y components of the slider positions can be found

$$\begin{aligned} s_{1x} &= 0 \\ s_{1y} &= \frac{2L_{S2}\sin(a)}{3} \\ s_{2x} &= \frac{L_{S1}}{2} \\ s_{2y} &= -\frac{L_{S2}\sin(a)}{3} \\ s_{3x} &= -\frac{L_{S1}}{2} \\ s_{3y} &= s_{2y} \end{aligned} \quad (3)$$

The strut length, L_{Tj} , relates the slider positions to the platform position by the distance formula

$$L_{Tj} = \sqrt{(p_{ix} - s_{ix})^2 + (p_{iy} - s_{iy})^2 + (p_{iz} - s_{iz})^2} \quad (4)$$

for $j = 1$ if $i = 1$ and $j = 2$ if $i = 2, 3$. Solving for the Z -coordinate of the slider in the general case leads to

$$q_i = z - \sqrt{L_{Tj}^2 - (p_{ix} - s_{ix})^2 - (p_{iy} - s_{iy})^2} \quad (5)$$

The partial derivatives of the $q_i(x, y, z)$ equations populate the inverse Jacobian, as expressed in Eq. (1). The final column of the inverse Jacobian matrix consists of ones, as motions of the platform along the Z axis correspond to equal motions of the sliders.

3.2 Singularities. In this system, singularities occur when struts become perpendicular to the sliders or when the gimbal is rotated by 90 deg on either axis. The former is described when the quantity under the square root in Eq. (5) is zero. Due to physical stops on the prismatic axes and at the gimbal ball and socket joints, the only reachable singularity in the workspace with strut lengths chosen to satisfy dexterity criteria, as discussed in Sec. 3.3, occurs for the tip-down isosceles design when the platform is raised to its maximum height, such that the L_{T1} pair of struts is perpendicular to S_1 . This singularity also could be precluded with mechanical stops at the universal joints or by a constraining frame. In practice, however, this singularity can only be reached when a patient is not present, and it becomes a convenient resting stance for the platform preprocedure or postprocedure. It is easily identified and simple to get out of by pushing on the manipulator handle in the $+Z$ direction.

3.3 Dexterity. Apart from singularities, regions of well and poorly conditioned kinematics can be identified to evaluate the effects of link lengths and platform dimensions for ease of movement and an increased workspace. Given the reciprocal nature of transmitted forces and velocities, measures of isotropy, and dexterity are useful for comparing the force transmission properties of designs. However, as noted in Ref. [23], such measures are not sufficient for estimating positioning errors in parallel mechanisms. In the present case, the mechanism is being used as a passive extension of the physician's motions. However, human proprioception is not particularly accurate. Moreover, the position and orientation of the base of the needle will be tracked using RF coils and the MR scanner. Therefore, the precision of the mapping from joint variables to platform motions and the dependence on manufacturing errors are of less concern than providing a uniform transmission of forces and inertial effects between the master and the slave. For these reasons, we focus on isotropy of motions and forces to compare designs with various link lengths and platform dimensions to reach the workspace of interest. In Sec. 3.4, we examine the transmission of forces, including the effects of friction in the prismatic joints, where friction is often most significant.

3.3.1 Manipulability Polyhedra. Kinematic manipulability quantifies the manipulator's velocity transmission ability. The

classic interpretation of the manipulability ellipsoid is that its size and shape give the amplification between joint space variations and generalized coordinate variations for the robot [23]. The lengths of the ellipsoid's principal axes are determined by the eigenvalues of $J^{-T}J^{-1}$, and the orientation is determined by the corresponding eigenvectors. The closer the eigenvalues ($\lambda_{\min}$, $\lambda_{\max}$) are to each other, the closer the manipulability ellipsoid is to a sphere. A more realistic representation of manipulability uses the infinity norm, in which the absolute values of the joint errors are independently bounded by 1. A manipulability polyhedron shows that there are no perfect mappings having a constant velocity amplification factor over the whole workspace [23].

Because the Jacobian is configuration dependent, a new inverse Jacobian is calculated for each end-effector position (x, y, z) in the robot workspace, and using $J^{-T}J^{-1}$, the manipulability polyhedra for the given pose are found. λ_1, λ_2 , and λ_3 refer to the eigenvalues in increasing magnitude, and determine the length of each axis in the polyhedra. Figure 4 shows the manipulability polyhedra for platform positions across the workspace for equilateral and isosceles designs whose parameters have been selected to decrease the difference between the minimum and maximum eigenvalues.

Ideal manipulability polyhedra would be cuboid ($\lambda_1 = \lambda_2 = \lambda_3$). In this type of manipulator, whether equilateral or isosceles, it can be seen that toward the center of the workspace, the preferred direction of motion is along the Z axis, which is the insertion degree of freedom. At the edges of the workspace, the robot favors moving toward the sliders. Further analysis of the friction at the sliders is necessary to evaluate force transmission behavior at the periphery of the workspace.

3.3.2 Global Dexterity Measures. Manipulability polyhedra give a general idea of the mobility of a manipulator design. However, it is useful to have a metric to quickly compare the dexterity

of various geometries. As Ref. [24] explains, spatial manipulators ($m=3$) should use the order-independent definition for manipulability

$$M = \sqrt[m]{\det(JJ^T)} \quad (6)$$

For a given configuration, M represents the geometric mean of the axes of the manipulability ellipsoid. Although M is order-independent, by itself, it is not scale-independent. One can look at the arithmetic mean of the eigenvalues

$$\Psi = \frac{\text{trace}(JJ^T)}{m} = \frac{\lambda_1 + \lambda_2 + \dots + \lambda_m}{m} \quad (7)$$

On its own, Ψ is independent on order, yet still dependent on scale. The isotropy of a manipulator is [24]

$$\Delta = \frac{M}{\Psi} \quad (8)$$

The isotropy is upper bounded by 1. The arithmetic mean is related to the manipulability, as $\Psi \geq M$. Therefore, equal eigenvalues imply the isotropy of an m -dimensional sphere. The isotropy can also be thought of as the ratio of the geometric mean to the arithmetic mean of the Jacobian's eigenvalues, which is scale-independent. However, it cannot predict proximity to singular configurations.

The conditioning of the Jacobian matrix, on the other hand, gives insight to a given pose's proximity to singularity. The condition number of the Jacobian matrix is

$$\kappa = \frac{\sigma_{\max}}{\sigma_{\min}} = \|J\| \|J^{-1}\| \quad (9)$$

Fig. 4 Manipulability polyhedra as viewed in the XY plane and isometrically for manipulators with the following parameters: (a) $a = b = 60$ deg, $L_{S2} = 0.178$ m, $L_{T1} = L_{T2} = 0.152$ m, and $L_{P2}/L_{S2} = 0.36$. (b) $a = 45$, $b = 90$ deg, $L_{S2} = 0.171$ m, $L_{T1} = L_{T2} = 0.135$ m, and $L_{P2}/L_{S2} = 0.44$.

The minimum possible value for κ is 1, which gives the most isotropic manipulability (infinity signifies a singularity). $\sigma_{\max}$ and $\sigma_{\min}$ are the largest and smallest singular values ($\sqrt{\lambda_{\max}}$ and $\sqrt{\lambda_{\min}}$ of JJ^T). The condition number is used as a measure of kinematic accuracy. It is scale-independent, but is not an analytic function of joint angles.

The global dexterity index uses the condition number and considers the entire workspace volume, V [25]

$$\text{GDI} = \frac{\int_V \frac{1}{\kappa} dV}{V} \quad (10)$$

As mentioned, the optimal value of both κ and Δ is 1. When they are both equal to 1, control is the same for any m -dimensional task space. Advantages of Δ over κ include that Δ can be expressed analytically as a function of joint angles, and that it takes into account the middle axis of higher order manipulators. Optimal designs are those for which the length of the middle axis is equal to the arithmetic mean of the major and minor axes.

The global isotropy index [26] is the ratio of the smallest and largest sphere contained in all the velocity ellipsoids

$$\text{GII}(p) = \frac{\min(\sigma_{\min}[J(p, x)])}{\max(\sigma_{\max}[J(p, x)])} \quad (11)$$

where σ_i are the singular values of J , p represents the manipulator parameters to optimize, and x represents the manipulator pose. The GII is the ratio of the maximum and minimum singular values of the entire workspace. It is closely related to the condition number based GDI index, yet considers all possible poses in one metric.

3.3.3 Regional Dexterity Measures. Based on related work analyzing manipulator dexterity [19,24], to make informed design decisions, we propose the regional isotropy measure (RIM), and the regional dexterity index (RDI), which numerically average isotropy and condition numbers only over the workspace of interest

$$\text{RIM} \approx \frac{1}{N_w} \sum_{w \in V} \frac{M}{\Psi} = \frac{1}{N_w} \sum_{w \in V} \frac{\sqrt[m]{\det(JJ^T)}}{\lambda_1 + \lambda_2 + \dots + \lambda_m} \quad (12)$$

$$\text{RDI} \approx \frac{1}{N_w} \sum_{w \in V} \frac{1}{\kappa} = \frac{1}{N_w} \sum_{w \in V} \frac{\sigma_{\min}[J(p, x)]}{\sigma_{\max}[J(p, x)]} \quad (13)$$

where w is one of N_w points uniformly distributed over the workspace volume V in the region of interest. Looking at the workspace of interest allows one to consider only regions where the end-effector needs to be in order to accomplish a specific task—in our case, the ability to reach all areas of the prostate. Conversely, dexterity near the edges of the workspace is not particularly important.

The regional indices are scalable in that scaling up the manipulator parameters (link lengths) and pose does not change the index value. Only the RIM however, takes into account the order (three for spatial manipulators). Changing the strut lengths to match in proportion to the medians of the isosceles triangle helps to improve manipulability for some configurations. For example, given the strut length L_{T2} for struts between platform corners and sliders 2 and 3, an adequate choice of L_{T1} is

Isotropy Measure for Equilateral and Isosceles Manipulators

Fig. 5 Isotropy measure throughout the workspace ± 4 cm from the origin for an equilateral tip-up and isosceles tip-down design as shown in the photos. Values close to 1 imply high isotropy. RIM calculated is for $w \pm 4$ cm and $N_w = 900$. (Top) Equilateral parameters: $a = b = 60$ deg, $L_{S2} = 0.191$ m, $L_{T1} = L_{T2} = 0.152$ m, and $L_{P2}/L_{S2} = 0.40$. (Bottom) Isosceles parameters (tip-down): $a = 45$ deg, $b = 90$ deg, $L_{S2} = 0.203$ m, $L_{T1} = 0.117$ m, $L_{T2} = 0.165$ m, and $L_{P2}/L_{S2} = 0.4$.

Fig. 6 Regional dexterity index for varying single design parameters, over a workspace ± 4 cm from the origin. Values are normalized with respect to frame radius r . Initial design: $a = 70$ deg, $b = 40$ deg, $L_{S2} = 0.19$ m, $L_{T2} = 0.19$ m, and $L_{P2}/L_{S2} = 0.50$. L_{T1} was changed according to Eq. (14).

$$L_{T1} = L_{T2} \frac{\sin(a)}{\sin(b)} \quad (14)$$

Figure 5 shows the isotropy over the workspace of interest for equilateral (top) and isosceles (bottom) versions of the manipulator for design parameters chosen to improve the RIM. Although the region of relative isotropy is more uniform in the equilateral case, the isosceles version provides an increased space for the patient's legs above the manipulator. Modifying the strut lengths for this version leads to higher isotropy over the usable workspace.

Analysis of regional dexterity indices (Fig. 6) shows that increasing or decreasing any specific parameter does not necessarily lead to a better design. In addition, decreasing strut length, although it improves dexterity at the center, starts to limit the size of the usable workspace. Therefore, combinations of design parameters need to be analyzed together while taking into account the desired workspace.

Table 1 shows the regional and global isotropy and dexterity measures for various designs. In the table, r measures the radius from the center to the periphery of a circle enclosing the frame, and is taken as a characteristic length. Note that, depending on the shape of the triangle, some designs can have a somewhat larger r than others. The global measures consider all possible poses in the workspace, whereas the regional measures only consider points ± 4 cm from the origin. All things being equal, the equilateral design has the highest isotropy. Yet, in order to fit the size of the

scanner, asymmetric designs with varying strut lengths are considered. Changing the strut length per Eq. (14) improves both the regional dexterity indices and RIMs for the 45–45–90 deg isosceles configuration, as shown in cases 5 and 6 of Table 1. However, it does not produce much improvement in the regional indices in the 70–70–40 deg isosceles configuration (cases 3 and 4), and the global manipulability deteriorates. Furthermore, if the strut lengths were based on other formulas taking into account the slider spacings, or the angle bisectors of the triangle formed by (s_{xi}, s_{yi}) , then the RDI and RIM would correlate differently. Therefore, caution should be taken when basing designs on a single definition for manipulability. In all cases explored, regional indices of manipulability were more favorable than the global indices.

3.4 Force Transmission and the Effect of Friction.

Although the slave duplicates motions of the master in this device, friction can change the transmitted force, especially as the platform moves away from the center of the workspace. The largest source of friction is in the sliders. When we consider the manipulator without the inner gimbal, all the transmitted loads in the insertion DOF are carried by the sliders. Hence, here we analyze the worst case scenario. To analyze its effect, we use the previously calculated Jacobian to account for friction in the serial linkages. J^T maps input forces at the platform center (F_{in}) to forces along the sliders (f_s) at the master-side

$$f_{s_master} = J^T F_{in} \quad (15)$$

Table 1 Isotropy measure and dexterity indices ± 4 cm from the manipulator origin in the XY plane for various designs. Global values consider the full extent of the workspace.

Case	a/b	r (cm)	L_{T1}/r	L_{T2}/r	L_{P2}/r	Isotropy		Dexterity	
						Global	RIM	Global	RDI
1	1	7.71	1.97	1.97	0.831	0.604	0.685	0.262	0.320
2	1	8.79	1.88	1.88	0.693	0.652	0.749	0.300	0.376
3	1.75	8.36	1.82	1.82	0.766	0.519	0.554	0.207	0.223
4	1.75	8.36	2.65	1.82	0.766	0.510	0.556	0.196	0.224
5	0.5	6.29	2.42	2.42	1.02	0.546	0.601	0.237	0.269
6	0.5	6.29	1.72	2.42	1.02	0.626	0.728	0.290	0.360
7	0.5	7.18	1.63	2.30	0.849	0.674	0.775	0.335	0.411

Fig. 7 Simulation of forces at the slave for an input force of $F = (1 \text{ N}, 1 \text{ N}, 1 \text{ N})$ at the master, with coefficient of friction $\mu = 0.05$. Manipulator parameters: (top) tip-up equilateral – $a = b = 60 \text{ deg}$, $L_{S2} = 0.191 \text{ m}$, $L_{T1} = L_{T2} = 0.152 \text{ m}$, and $L_{P2}/L_{S2} = 0.40$; (bottom) tip-down isosceles – $a = 45 \text{ deg}$, $b = 90 \text{ deg}$, $L_{S2} = 0.171 \text{ m}$, $L_{T1} = L_{T2} = 0.135 \text{ m}$, and $L_{P2}/L_{S2} = 0.44$.

The forces are mapped from the master and slave platforms to the internal slider loads, which are then equated to each other, in order to find the final output load at the slave end given an input load at the master end.

Given the slider forces ($f_s = [f_{s1z}, f_{s2z}, f_{s3z}]$) at a platform position $P_o = [x, y, z]$, the slider normal forces (f_N) are found by decomposing the slider force to find the forces along the struts, then projecting the strut forces onto the slider normals. To account for friction on the slider, we use a coefficient of friction, μ , and the slider normal in the strut-slider plane. Let P be a geometry dependent matrix that maps the platform load to the magnitude of the slider normal loads. P incorporates the Jacobian and angles between the struts and sliders. If all strut lengths are equal, we can assume P is the same on both the master and slave sides. At the master

$$f_{N_{\text{master}}} = P F_{\text{in}} \quad (16)$$

Accounting for friction, the slider loads at the master-side become

$$\tilde{f}_{s_{\text{master}}} = f_{s_{\text{master}}} - \mu f_{N_{\text{master}}} \quad (17)$$

Note that because friction is a passive force and cannot add energy to the system, each element of the slider force accounting for friction, $\tilde{f}_{s_i}$ for $i = 1, 2, 3$, must have the same sign as and a smaller magnitude than f_{s_i} . If the magnitude of μf_N is larger than f_s , the slider is said to be jammed (incapable of motion), and $\tilde{f}_{s_i} = 0$. However, for reasonable values of μ , this does not occur unless the manipulator approaches a singular configuration outside of the workspace of interest.

Next, the slave-side slider loads after subtracting friction forces are related to the output platform force by the Jacobian transpose

$$\tilde{f}_{s_{\text{slave}}} = J^T F_{\text{out}} \quad (18)$$

Similar to Eq. (17), the force along the slave-side slider has a component due to friction

$$\tilde{f}_{s_{\text{slave}}} = f_{s_{\text{slave}}} - \mu f_{N_{\text{slave}}} \quad (19)$$

By equating the slider force $\tilde{f}_s$ at the slave to the force that includes the normal component, $\tilde{f}_s$ at the master, we know the output platform loads in terms of the input loads

$$F_{\text{out}} = [J^T + \mu P]^{-1} [J^T - \mu P] F_{\text{in}} \quad (20)$$

Figure 7 shows the output forces at the slave platform over the full workspace for equilateral and isosceles configurations, when the input force is 1 N in the X, Y, and Z directions. Generally, the most uniform force output is at the center of the workspace yet, because normal forces on the sliders are larger when the platform is at the center, there is a decrease in overall force output. However, when the platform is at the edge of the workspace and the struts become more aligned with a slider, the normal component at that slider is smaller, leading to better force transmission. In some poses, when the output platform F_x and F_y forces are near their minimum values in Fig. 7, the output F_z force can be slightly higher than the input F_z force, although the corresponding X and Y components will be reduced. The overall magnitude of F_{out} is always less than F_{in} , demonstrating the intrinsic safety of this passive mechanism design.

The effect of friction on the force transmission cannot be isolated from isotropy as a design criteria. Additional simulations showed that asymmetric strut lengths ($L_{T1} \neq L_{T2}$), although had better dexterity measures, limited the overall workspace size and did not always improve force transmission. Therefore, equal strut lengths with reasonable manipulability were used in the physical prototypes.

Fig. 8 (a) Prototype on a scanner table with a model patient and torso coil. (b) End-view from patient's feet, with patient and manipulator in procedure position for transperineal access. (c) Axial localizer image of the pelvis, with prostate outlined. (d) Fast spin echo image (ETL 14, TE 96.9, TR 4205) of the prostate of a canine taken from an animal study using the manipulator to guide a needle to targets in the prostate. Workspace of interest in (a) and (b) outlined as a square in the XY plane.

4 Physical System

We have shown that for the constraints of our desired workspace, isosceles geometries can provide reasonable dexterity and force transmission, while fitting inside an MRI scanner. The choice of the most optimal design parameters is thus very complex, and is also dependent on subjective evaluation by physicians. We constructed prototypes of several equilateral and isosceles variations of the mechanism and presented these prototypes informally to physicians for feedback. Final systems composed of fully MRI-compatible parts, including: acetal and glass ball bearings¹; ceramic bearings²; linear ball slides³; machined Garolite and 3D-printed plastic components; carbon fiber rods and tubes; brass pins; and Nylon and brass screws. The final shape was an isosceles mechanism, with $a = 45$ deg and $b = 90$ deg. The overall width, height, and length were chosen to fit in the MRI scanner while allowing for adequate space for the patient and enough reach for the physician at the master-side while maximizing dexterity and force transmission criteria. The design allows for continuous steering of the needle by the physician into the prostate, unlike other positioning devices for prostate interventions [5]. In order to reduce friction in the prismatic sliding joints,

roller bearing elements were used. The final gimbal design also allowed for ± 30 deg of articulation in yaw and pitch as specified by physicians.

For transperineal access, the patient lies supine in the scanner. As mentioned, the tip-down isosceles configuration allows for a flat top and more space for the patient's legs to rest above the manipulator. Figure 8 shows the mechanism and a model patient in a 70 cm bore MRI scanner (3 T Signa MR750w⁴). The bore size limits the patient from spreading his knees and legs; however, the manipulator provides access to the prostate, and the prostate is on target for the manipulator as can be seen in the axial view. A higher resolution image is also shown from a canine study regarding prostate cancer treatment, which was approved by our Institutional Animal Care and Use Committee. A typical prostate biopsy using a coaxial needle may be performed after locking the manipulator sliders. The stylet of the needle can be removed, if another tool, such as an aspiration or biopsy device is to be inserted in the needle sheath. As seen in Fig. 9, the slave gimbal is mounted on an extension that protrudes 7 cm from the platform to provide more room between the patient's legs to the needle to access the perineum. However, an equivalent extension at the master was omitted, as it led to the application of high bending moments on the mechanism, which compromised force transmission.

4.1 Dynamic Behavior Evaluation. Benchtop experiments were performed on an isosceles prototype. It used low friction roller bearing elements, with custom Garolite tracks with cross-mounted glass and plastic bearings for the prismatic joints. Its universal joints were composed of glass and plastic ball bearings and clevis and rod ends. More detailed views of the prototype and the mechanism's degrees of freedom can be seen in Fig. 9.

The final dimensions, as well as the RIM and dexterity index of this prototype are listed in Table 2. After assembly, the actual inner angles reflect the final joint positions. Therefore, platform and slider lengths were no longer in proportion. Angles a_s and a_p reflect the slider and platform equal angles, respectively. With the manipulator in its frame, the end-effector could easily reach 125–250 mm above the table, and ± 50 mm from the center, without encountering any region of poor force transmission or singularity. These dimensions fit within the average patient size to reach the prostate while supine in semilithotomy position [27].

F_z force transmission was measured with the manipulator held vertically and counterbalanced against gravity to focus on the effects of friction at the sliders. A six-axis force-torque sensor (ATI Nano 17⁵) was mounted to the slave end, and weights were placed on the master platform to change the overall mass of the system. The tool-side of the force-torque sensor had an end-effector with a small cylinder that fit inside circular holes cut every 1 cm in a lasercut fiberglass template. The array of holes extended ± 4 cm from the center of the workspace, and was used as a guide for setting the position of the slave platform. The slave platform was moved slowly upward until a constant load was measured in the Z-direction. Figure 10(a) shows the manipulator test apparatus.

As noted in Sec. 3.4, due to friction in the sliders, the output load will deviate from the input load, and the amount of deviation is configuration dependent. We define the force deviation as the percent error between the input load at the master-side platform and the output load at the slave-side platform

$$\delta F = \frac{F_{in} - F_{out}}{F_{in}} \times 100\% \quad (21)$$

Figure 10(b) illustrates the expected force deviation for various points over the workspace with a load of $F_z = 4.9$ N (500 g). The coefficient of friction was found to be between 0.04 and 0.06 for

¹KMS Bearings, Inc., Anaheim, CA.

²Xi'an Hua Ying Te Bearing Co., Ltd., Shaanxi Province, China.

³THK Co. Ltd., Tokyo, Japan.

⁴GE Healthcare, Waukesha, WI.

⁵ATI Industrial Automation, Apex, NC.

Fig. 9 (a) Oblique view of the passive masterslave manipulator, annotated with its 3DOF in translation. (b) The mechanism includes a set of gimbals for pitch and yaw rotations. The manipulator thus has five total degrees of freedom, and is shown in different articulations, with the platform (c) up and (d) lower down.

Table 2 Final physical dimensions and dexterity measures of the prototype tested in force transmission experiments

a_s	b_s	a_p	b_p	L_{S2}	L_{P2}	L_{T1}	L_{T2}	RIM	RDI
44.6	90.8	47.4	85.3	0.175	0.079	0.135	0.135	0.543	0.238

Angle units in (deg) and lengths in (m).

this prototype; accordingly a value of $\mu = 0.05$ was used in computing predicted force variations. Labels A–I correspond to locations with comparisons of predicted and measured force deviations. The predicted and measured force deviations are similar, and are generally small, although they are slightly higher near the upper central region of the workspace.

As an additional test of the performance of the device under expected maximum loads, a digital scale⁶ was fixed at the slave end and a force-torque sensor⁵ and handle at the master (Fig. 11). Typical master and slave loads are shown in Table 3. These loads are substantially larger than the maximum loads reported for needle insertion in the perineum and prostate using 17 G and 18 G needles, which range from 6.2 to 15.6 N axially and are less than 2 N transversely [28]. As shown in Table 3, this manipulator can safely exert and sustain loads above 20 N axially and 7 N transversely without any sign of failure. For the loads and configurations tested, the force deviation from master to slave was at maximum 3% for F_z loads, 7% for F_x loads and 15% for F_y loads.

4.2 Stiffness. The overall stiffness of the mechanism is dependent on radial play in the roller bearing elements (prismatic joints) and flexibility of the carbon rods (struts) used in the prototype. A small amount of compliance in the system is not a concern because, as mentioned earlier, human proprioception is not good at distinguishing small changes in displacement. The parallel architecture has inherently good rigidity, and the final tool position is tracked while in the scanner.

We performed a simple test to assess stiffness by fixing the slave platform at the center of the workspace, applying known loads at the master platform, and measuring displacements of the master platform with a digital gauge. The setup was varied for applying loads in X, Y, and Z, and each direction was measured three times. For the prototype described that used custom roller bearing elements on Garolite tracks (Fig. 9), the average stiffness of the X, Y, and Z directions is 1.7 N/mm. For a stiffer prototype

that used full ceramic linear ball slides³, the average stiffness in the X, Y, and Z directions is 30 N/mm at the center of the workspace. These results show that this architecture using the stiff sliders has sufficient rigidity for transmitting forces necessary for needle manipulation in tissue.

4.3 Effective Inertia. Although velocities for needle insertion are low, inertia in the mechanism can affect the dynamic forces felt by the physician. Hence, it is worthwhile to examine the major contributions to the effective inertia and how they vary as a function of position. To obtain the effective mass in a direction, we use the relation that the kinetic energy in each direction is the sum of the kinetic energies of all components while moving in that direction. The kinetic energy matrix is

$$\mathbf{A}(x) = (m_{p1} + m_{p2})\mathbf{I} + \mathbf{J}^{-T}(m_s)\mathbf{J}^{-1} \quad (22)$$

where m_{p1} and m_{p2} are the master and slave platform masses and m_s is the mass of each slider. The pseudo kinetic energy equation allows us to solve for the effective mass along any direction u

$$M_{eu}(\mathbf{A}) = \frac{1}{u^T \mathbf{A}^{-1}(x) u} \quad (23)$$

where

$$\mathbf{A}^{-1}(x) = \mathbf{J}^{-1} \mathbf{A}^{-1}(x) \mathbf{J}^{-T} \quad (24)$$

Given the component masses of two sample tip-down isosceles prototypes, Table 4 summarizes the effective mass over the workspace of interest. The effective masses along Y and Z are coupled due to the configuration of the sliders and the Y axis, which causes a comparable displacement of q_1 (i.e., s_{1z}) given a displacement of P_o in Y. To obtain a more uniform effective mass over the workspace, it is desirable to minimize the weights of the sliders.

⁶M4-50, Mark-10 Corp., Copiague, NY.

Fig. 10 (a) Benchtop test showing the manipulator mounted vertically to compare force transmission for input load F_z . (b) Predicted force variations for $F_z = 4.9 \text{ N}$ and $\mu = 0.05$ over the workspace of interest.

Fig. 11 Benchtop maximum loading test apparatus showing prototype 1 with (a) digital force scale at slave end and (b) six-axis sensor at master end to test force capability. Configuration shown is to test F_z loading.

Table 3 Loads felt by the force scale at the slave platform and by the six-axis force-torque sensor at the master platform

Load case	Trial 1		Trial 2		Trial 3	
	Master	Slave	Master	Slave	Master	Slave
F_x	7.7	7.2	7.1	6.6	6.9	6.4
F_y	7.1	6.1	7.1	6.0	6.9	6.0
F_z	27.7	26.9	23.8	23.3	23.4	23.0

Units in N.

Table 4 Summary of effective mass in Cartesian space $\pm 4 \text{ cm}$ from manipulator origin

	Component masses	Effective mass	Mean	Maximum	Minimum
Prototype 1	$m_{p1} = 0.055$	M_{ex}	0.290	0.338	0.217
	$m_{p2} = 0.055$	M_{ey}	0.366	0.393	0.310
	$m_s = 0.100$	M_{ez}	0.366	0.393	0.310
Prototype 2	$m_{p1} = 0.200$	M_{ex}	0.502	0.568	0.409
	$m_{p1} = 0.200$	M_{ey}	0.561	0.594	0.498
	$m_s = 0.065$	M_{ez}	0.561	0.594	0.498

Units in kg.

5 Conclusions and Future Work

We developed an MRI-compatible master-slave mechanism specialized for transperineal interventions in the prostate, such as biopsy, brachytherapy, and cryoablation, under real-time image guidance. Manipulability polyhedra and Jacobian-based force transmission analysis showed the preferred direction of motion is along the (axial) Z-direction. Experimental results on a physical prototype showed that the change in input to output force is

relatively small, and matches simulated results accounting for friction in the sliders. There was increasing distortion in force transmission from master to slave at the edges of the workspace when viewed in the XY-plane. This analysis is useful when designing mechanical stops to prevent motion into regions of high friction or close to singularities, while constraining movements to the desired workspace. In our presented designs, singularities are never reached in the desired workspace.

MRI-compatible prototypes were used to test design configurations and confirm predictions about transmitted forces. The prototype described easily reached the desired workspace as well as regions based on clinical data of human prostate sizes [27]. The prototype also was capable of exerting forces necessary for needle puncture in the prostate [28].

Improvements to the basic manipulator design include methods for gravity counterbalancing and brakes to hold the platforms in any pose. Counterbalancing has the effect of decreasing the required forces for manipulation, making the manipulator easier to move and able to hold a desired position without effort. Methods to counterbalance the presented design require the addition of springs—weights are undesirable as they increase inertia. Solutions include torsional springs at the rotating shafts, and elastic bands or leaf springs between the platforms and sliders. Brakes are also important for avoiding unwanted motions of the manipulator and ensuring patient safety during procedures. For braking, it suffices to use pneumatic or cable-actuated brakes on the sliders. A prototype braking system is undergoing testing. Note that the addition of brakes does not compromise the passivity of the device, as brakes can only remove energy.

When the manipulator is used inside the MRI-scanner, its frame of reference will be registered to the scanner coordinate frame. Then, tool navigation can be enabled to help guide the interventionist. For in-scanner active tracking of the end-effector and tool position and orientation, the slave platform will utilize embedded RF coils for MR tracking [29]. An annotation of the tool will then be overlaid on the MR images. Future work includes in-scanner feasibility tests to ascertain the ability to reach targets from outside the scanner bore, with tissue phantoms and in vivo.

Another future feature for physicians is a method for two-handed control. Variations to the design include a manipulator co-axially nested within a manipulator to independently move two different parts of an interventional tool. A possible extension of this work is to use multiple decoupled parallel mechanisms, as in Ref. [22], but with two moving platforms connected for passive master-slave manipulation. Due to its elongated workspace, this type of design may also be suitable for MRI-guided neurosurgery, yet at reduced cost and complexity compared to fully robotic approaches [30,31]. Extended parallel mechanisms for MRI-guided interventions can enable access to other parts of the body which are difficult to reach due to the constraints of the scanner bore, such as the liver or breast.

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