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A new 7-degree-of-freedom 2-PRRRRR parallel remote center-of-motion robot for eye surgery*

Yinglun Jian, Yan Jin, Mark Price, Johnny Moore

Abstract— Millions of patients suffering from eye disease cannot receive proper treatment due to the lack of qualified surgeons. Medical robots have the potential to solve this problem and consequently are attracting significant attention in the research community. This paper introduces a new 7-degree-of-freedom (DOF) 2-PRRRRR parallel robot with remote-center-of-motion for eye surgery. Mobility requirement, robot mechanism synthesis, kinematics, singularity, and dimensional optimization for the prescribed workspace, are analyzed and presented. A number of configurations were explored focusing on cataract surgery resulting in one being identified that covers the area completely and has excellent dexterity, but further work will be needed to enhance accuracy.

I. INTRODUCTION

Over 60 million people around the world suffer from visual impairment many of whom could benefit from eye surgery [1]. Approximately one third of such visual impairments are caused by cataracts, which are the largest contributor to blindness in middle and low income countries [2], and second largest in the UK [3] and the US [4]. However, there is a worldwide deficiency in trained eye surgeons, which is particularly prevalent in developing countries. Eye surgery requires highly delicate and precise fine motor skills, which are not common, and cannot always be achieved by training and practice. However, a robot can provide the high precision necessary and has the potential to be an assistance tool for a doctor to achieve effective and efficient high quality surgery in partnership.

Minimally invasive surgery (MIS) uses long and thin surgical tools to complete all the surgical procedures. The tools are inserted into the patient's body through small incisions consequently resulting in only small scars, little blood loss and rapid recovery. These advantages make MIS a popular procedure. However, it does require significant skills as surgeons need to concentrate on keeping surgical tools at these small incisions without enlarging them. For eye surgery such as a cataract surgery, a surgeon typically holds two tools, one in each hand, which are inserted through two incision points, one on each side of the eye to collaboratively tear up the malfunctioned lens and replace it with an artificial one. For each tool, this action requires four degree-of-freedom (DOF)

motion including three rotations (3R) about the incision point and one translation (1T) through the incision point. If a robot is to be used to replace the surgeon's hand, it must provide the same 3R1T DOFs after locating the incision point. The incision point is commonly defined as the remote-center-of-motion (RCM) of the robot. In case of the robot, the RCM point has to be a virtual point, with no physical joint over the center in order to avoid the collision with the eye.

Figure 1. Four types of RCM mechanisms. (a) Circular rail RCM mechanism. (b) Double-parallelgram RCM mechanism. (c) Serial spherical RCM mechanism. (d) Parallel spherical RCM mechanism.

One way to limit the robotic tool motion in 3R1T DOFs is to apply an RCM mechanism to mechanically constrain the surgical tool. Four types of RCM mechanisms are widely used in MIS robots, i.e. circular rail, double-parallelgram, serial spherical, and parallel spherical. The four types of RCM mechanisms are shown in Fig. 1. One of the first MIS robots for eye surgery with an RCM mechanism was the Stereotaxical Micro-telem manipulator for Ocular Surgery (SMOS) [5], which was proposed by Guerrouad et al. in 1989. SMOS uses the circular rail RCM mechanism, which has also been applied in some MIS robots in the last decade [6]. The Double-parallelgram RCM mechanism is the most widely used in MIS robots. It has been applied to the da Vinci Surgical Robotic System [7] and some recent robots for retinal surgery [8][9]. The double-parallelgram mechanism has many advantages including a simple structure, a large workspace, decoupled motion, and the dynamics are easy to solve. Its disadvantage is relatively low stiffness due to the large number of revolute joints [10]. Some MIS robots apply serial spherical RCM mechanisms [11]. But these tend to have a low precision because of the accumulation of errors propagated through the kinematic chain. Parallel spherical RCM mechanisms recently attracted interests because of their theoretical advantages over serial ones, in particular their high precision, light moving structures and high stiffness [12]. Most of them are designed specifically for laparoscopic

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surgery and cannot be directly applied to eye surgery due to different requirements in scale and precision. The small size of human eye limits the workspace and the precision must be very high (10 micro meter [13]) to avoid damage to the eye. Therefore, although the parallel spherical RCM mechanism has potential to provide the required precision, to date, only a few eye surgery robots applying parallel spherical RCM mechanisms have been introduced. DIAMOND is one of the them, which was proposed by Molaei et al. in 2015 [14]. Further research on applying parallel spherical RCM mechanisms specifically for the eye surgery is needed.

In the case of eye surgery the robot part of the challenge is that in addition to the 4-DOF motion for the surgical operation, three more translational DOFs are required to move the robot RCM point coincident with the eye incision point. Therefore, seven DOFs are required for the entire robot system. To date most literature has focused on the 4-DOF surgical motion part while the three translational DOFs have been neglected.

Figure 2. The new 7-DOF parallel RCM mechanism.

In this paper, as shown in Fig. 2, a new 7-DOF 2-PRRRRR (R represents rotational joints, P represents prismatic joints) parallel RCM robot for eye surgery is presented to address the knowledge gaps mentioned above. The following sections will first analyze the requirements of robot-assisted eye surgery, then describe the generation of the new mechanism, analyze the singularity and workspace, and finally conduct the workspace-oriented dimension optimization.

II. REQUIREMENT OF ROBOT-ASSISTED EYE SURGERY

A. Cataract Surgery Workflow

Figure 3. The procedure of cataract surgery [15].

As shown in Fig. 3 [18], cataract surgery is a procedure to remove the lens in the eye and replace it with an artificial lens through small incisions. For robot-assisted cataract surgery, there are five phases in the workflow. Phase I is “approaching”,

in which the robot approaches the patient’s eye and locates its RCM point at the incision point. Phase II is “insertion”, which means inserting the surgical tool into the patient’s eye through the located incision. Phase III is “manipulation”, where the robot manipulates the surgical tool to perform the 3RIT motions that break and remove the diseased lens, implant artificial lens. Phase IV is “removal”, which means removing the surgical tool from the patient’s eye. Phase V is “leaving”, in which the robot moves away from the patient.

B. Specification of the Robot

It is reported that a precision of 500 microns about an RCM point on the surface of the incision are required for robot-assisted cataract surgery [16]. Considering the potential applications on vitreoretinal surgery, the robot proposed in the herein paper aims to achieve a precision of 10 microns [17]. The speed of the surgical tool is measured by existing manual operation. The tool tip speed of Phase III is less than 1 mm/s. The tool tip speed of Phase II and Phase IV is 1~5 mm/s. The tool tip speed of Phase I and Phase V is 5~10 mm/s. In addition, the majority of forces applied during in-vitro retinal manipulation in porcine cadaver eyes were found to be below 7.5 mN [18]. The design specifications of the robot are shown in Table I.

TABLE I. DESIGN GOALS OF THE ROBOT

Robot Specification	Value
Precision	10 μm
Tool tip speed – Phase I & V	5~10 mm/s
Tool tip speed – Phase II & IV	1~5 mm/s
Tool tip speed – Phase III	<1 mm/s
Force	7.5 mN

C. Workspace Requirement

Figure 4. The required workspace.

Figure 5. Incisions and the incision angles of all three lens-eye models.

During surgery, the robot must be able to manipulate the surgical tool so that it reaches the whole area of the whole lens through the small incision. The yellow volume in Fig. 4. shows the required workspace based on average human ocular dimensions as presented by Charles and Brown [19]. The incision point is located at the junction of cornea and sclera referred to the usual incision in cataract surgery. Considering the variation in a human eye, apart from the average ocular dimensions, two additional dimensions are used to build 3D lens-eye models. These cover the cases of deep lying lens and

shallow lying lens [19]. The deep lying lens sits deeply from the cornea with a smallest thickness and a largest diameter. Similarly, the shallow lying lens sits close to the cornea with the largest thickness and the smallest diameter. The three key eye dimensions there include the average condition and two extreme conditions. As shown in Fig. 5, the incision angle in each lens-eye model is recorded.

III. GENERATION OF THE MECHANISM

Inspired by a 6-DOF parallel manipulator with decoupled translation and rotation proposed by Jin et al. [20], the conceptual design of a new parallel 7-DOF mechanism is developed. As shown in Fig. 6(a), the 6-DOF parallel manipulator consists of 3 RPPRR legs. The new 7-DOF parallel RCM mechanism is created in three steps, which is shown in Fig. 6, where the actuated joints are highlighted in red. Firstly, for compactness and ease of access to the patient, one leg of the 6-DOF parallel manipulator is eliminated to create a more compact two leg parallel manipulator, as shown in Fig. 6(b). Then, in Fig. 6(c), considering the designs of Sarrus Mechanism [21], the passive prismatic joints are replaced by passive rotational joints. Finally, in order to achieve the motion requirement analyzed in the last section, the two joints R_{E1} and R_{E2} are coincident with the surgical tool axis, and the actuated joints is P_{A1} , P_{A2} , R_{A1} , R_{C1} , R_{C2} , R_{E1} and P_{E2} , which is shown in Fig. 6(d).

Figure 7(a) shows the schematics of one leg of the new 7-DOF parallel RCM mechanism. It is a PRRRRR leg with the axes of the first three R joints A, B and C parallel to each other, as well as the axes of the last three R joints C, D and E intersecting at one point, the RCM point, O_{RCM} .

Figure 6. Design process of the new 7-DOF parallel RCM mechanism.

Figure 7. Schematics of the new 7-DOF parallel RCM mechanism. (a) One leg. (b) Two sections. (c) Passive and actuated joints.

As shown in Fig. 7(b), OA_1 and OA_2 are designed perpendicular to each other to decouple the two translational DOFs on the base. OA_1 and $O_{RCM}C_1$ are parallel; meanwhile OA_2 and $O_{RCM}C_2$ are also parallel. Therefore, $O_{RCM}C_1$ and $O_{RCM}C_2$ are perpendicular to each other. The distances and orientations of $O_{RCM}C_1$ and $O_{RCM}C_2$ are both determined. As a result, the relative position between C_1 and C_2 is constant in the new RCM mechanism. Imagining that there is a virtual linkage between C_1 and C_2 , the top section can be regarded as

a five-bar parallel spherical RCM mechanism. The bottom section provides the positioning function to locate the RCM.

The schematics of the new parallel 7-DOF mechanism with passive and actuated joints is shown in Fig. 7(c), where the actuated joints are highlighted in red. The three actuated joints on the base, P_{A1} , P_{A2} and R_{A1} , provide 3 translational DOFs along x, y, and z axes to locate the RCM to the incision point. The other four actuated joints, R_{C1} , R_{C2} , R_{E1} and P_{E2} manipulate the end-effector to perform a 3R1T DOF motion. R_{C1} and R_{C2} provide 2R DOFs to change the orientation of the surgical tool. R_{E1} and P_{E2} provide 1R1T DOFs along tool axis. During surgery, the three actuated joints in the bottom section, P_{A1} , P_{A2} and R_{A1} are actuated first with the other four actuated joints locked. When P_{A1} actuates the RCM point, O_{RCM} , translates along the x axis. Meanwhile, when P_{A2} actuates the RCM point, O_{RCM} , translates along the y axis. The translation of O_{RCM} along the z axis is controlled by both P_{A2} and R_{A1} . When the y coordinate of O_{RCM} is determined first, the z coordinate of O_{RCM} is only controlled by R_{A1} . As a result, the three translational DOFs are partially decoupled. Once the O_{RCM} is positioned, P_{A1} , P_{A2} and R_{A1} are locked. Then the end-effector can perform a 3R1T motion by actuating the other four actuated joints, R_{C1} , R_{C2} , R_{E1} and P_{E2} .

All the geometrical constraints are listed below:

- $R_{i1} // R_{i2} // R_{i3}$. ($i=1,2$)
- $OA_1 \perp OA_2$.
- The axes of R_{C1} , R_{C2} , R_{D1} , R_{D2} , R_{E1} and R_{E2} intersect at one point, O_{RCM} .
- R_{E1} and R_{E2} are coincident with the surgical tool axis.

Motions are listed below:

- Bottom section: 3T (locate the RCM point).
- Top section: 3R1T, or 2R+1R1T (orientate tool axis + roll at and translate along tool axis).

IV. KINEMATICS ANALYSES

Table II shows the input kinematics parameters of the seven actuators. All the kinematics parameters are illustrated in Fig. 8. All angles are anticlockwise positive. For the O frame, the Z axis is along OA_1 , and the X axis is along OA_2 . l_1 is the distance of OA_1 ; l_2 is the distance of OA_2 ; θ_{A1} is the angle from the Y axis to axis A_1B_1 ; θ_{B1} is the angle from linkage A_1B_1 to linkage B_1C_1 ; θ_{C1} is the angle from linkage B_1C_1 to linkage C_1D_1 ; θ_{D1} is the angle from linkage C_1D_1 to linkage D_1E_1 ; θ_{A2} is the angle from Y axis to axis A_2B_2 ; θ_{B2} is the angle from linkage A_2B_2 to linkage B_2C_2 ; θ_{C2} is the angle from linkage B_2C_2 to linkage C_2D_2 ; θ_{D2} is the angle from linkage C_2D_2 to linkage D_2E_2 . d_1 is both the length of linkage A_1B_1 and linkage A_2B_2 ; d_2 is both the length of linkage B_1C_1 and linkage B_2C_2 . r is all the length of $O_{RCM}C_1$, $O_{RCM}C_2$, $O_{RCM}D_1$, $O_{RCM}D_2$ and $O_{RCM}E_1$. α_0 is the angle from $O_{RCM}C_1$ to $O_{RCM}C_2$. α_1 is both the angle from $O_{RCM}C_1$ to $O_{RCM}D_1$, and the angle from $O_{RCM}C_2$ to $O_{RCM}D_2$; α_2 is both the angle from axes $O_{RCM}D_1$ to $O_{RCM}E_1$, and the angle from $O_{RCM}D_2$ to $O_{RCM}E_2$. The tool central point (TCP/End-effector) is the tool tip point. l_T is the distance of E_1TCP .

TABLE II. ACTUATORS AND CORRESPONDING INPUT PARAMETERS

Actuators	P _{A1}	P _{A2}	R _{A1}	R _{C1}	R _{C2}	R _{E1}	P _{E2}
Parameters	l_1	l_2	θ_{A1}	θ_{C1}	θ_{C2}	θ_T	l_T

Figure 8. (a) Schematics of the 7-DOF parallel RCM mechanism with kinematics parameters. (b) 3D model with kinematics parameters.

Following the Denavit-Hatenberg (D-H) frame assignment, frames are assigned to the mechanism joints where the Z axis of each frame points outward along the corresponding joint, and the X axis of each frame is along the linkage that links the next joint. D-H parameters are summarized in Table III. The transformation matrix is the typical 4x4 translation and rotation matrix, as shown in (1).

TABLE III. D-H PARAMETERS

i-1	i	θ_i	α_i	x_i-x_{i-1}	y_i-y_{i-1}	z_i-z_{i-1}
O	A1	0	0	0	0	1
A1	B1	θ_{A1}	0	$-d_1 \sin \theta_{A1}$	$d_1 \cos \theta_{A1}$	0
B1	C1	θ_{B1}	0	$-d_2 \sin \theta_{B1}$	$d_2 \cos \theta_{B1}$	0
C1	D1	θ_{C1}	α_1	$-r \sin \alpha_1 \sin \theta_{C1}$	$r \sin \alpha_1 \cos \theta_{C1}$	$-r(1 - \cos \alpha_1)$
D1	E1	θ_{D1}	α_2	$-r \sin \alpha_2 \sin \theta_{D1}$	$r \sin \alpha_2 \cos \theta_{D1}$	$-r(1 - \cos \alpha_2)$
E1	TCP	θ_T	0	0	0	l_T
O*	A2	0	0	0	0	1
A2	B2	θ_{A2}	0	$-d_1 \sin \theta_{A2}$	$d_1 \cos \theta_{A2}$	0
B2	C2	θ_{B2}	0	$-d_2 \sin \theta_{B2}$	$d_2 \cos \theta_{B2}$	0
C2	D2	θ_{C2}	α_1	$-r \sin \alpha_1 \sin \theta_{C2}$	$r \sin \alpha_1 \cos \theta_{C2}$	$-r(1 - \cos \alpha_1)$
D2	E2	θ_{D2}	α_2	$-r \sin \alpha_2 \sin \theta_{D2}$	$r \sin \alpha_2 \cos \theta_{D2}$	$-r(1 - \cos \alpha_2)$

$${}^{i-1}T = \begin{bmatrix} {}^{i-1}R & {}^{i-1}P \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

where

$${}^{i-1}R = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i \\ 0 & \sin \alpha_i & \cos \alpha_i \end{bmatrix}, \quad (2)$$

$${}^{i-1}P = P_i - P_{i-1} = \begin{bmatrix} x_i - x_{i-1} \\ y_i - y_{i-1} \\ z_i - z_{i-1} \end{bmatrix}, \quad (3)$$

$$\begin{bmatrix} P_i \\ 1 \end{bmatrix} = {}^{i-1}T \begin{bmatrix} P_{i-1} \\ 1 \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}, \quad (4)$$

P_i is the vector from O to the corresponding joint.

The frame of O* is calculated in (5).

$$\begin{bmatrix} P_{O^*} \\ 1 \end{bmatrix} = \begin{bmatrix} \cos 90^\circ & 0 & \sin 90^\circ & 0 \\ 0 & 1 & 0 & 0 \\ -\sin 90^\circ & 0 & \cos 90^\circ & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} P_O \\ 1 \end{bmatrix}. \quad (5)$$

Using this kinematics model, the forward kinematics was calculated and two solutions were found. As shown in Fig. 9, one solution with ψ larger than 180° is called Up-configuration, the other solution with ψ smaller than 180° is called Down-configuration. ψ is the angle from linkage E_2D_2 to E_1D_1 anticlockwise.

Figure 9. The two solutions in forward kinematics. (a) Up-configuration. (b) Down-configuration.

V. SINGULARITY AND WORKSPACE ANALYSES

The difference of the two configurations are entirely in the top section of the mechanism (shown in Fig. 9). In order to find which configuration is more suitable for robot-assisted eye surgery, the singularity and workspace of the top section are analyzed here.

Figure 10. The 2-DOF 5-bar spherical parallel mechanism.

A. Singularity Analysis

Figure 11. The six types of singularities of the 2-DOF 5-bar spherical parallel mechanism..

Figure 12. The singularities and workspace of E_1 .

Figure 13. The singularities and workspace of the E_1 in different conditions.

In the top section, a singularity appears when two adjacent linkages parallel to each other. For the 3R1T DOF motion in the top section, the 1R1T DOFs are not related to the singularity. When we ignore the 1R1T DOFs and lock the 3T DOFs in bottom section, the top section of the mechanism can be regarded as a 2-DOF 5-bar spherical parallel mechanism.

In this case, shown in Fig. 10, the coordinates of C_1 and C_2 are fixed, meanwhile E_1 performs as the End-effector. The blue curves in Fig. 11, illustrates the six types of singularities classified. Singularity (a) in Fig. 11(a) appears when linkages C_1D_1 and D_1E_1 are parallel to each other without coinciding. Singularity (b) in Fig. 11(b) appears when linkages C_2D_2 and D_2E_2 are parallel to each other without coinciding. Singularity (c) in Fig. 11(c) appears when linkages C_1D_1 and D_1E_1 coincide. Singularity (d) in Fig. 11(d) appears when linkages C_2D_2 and D_2E_2 coincide. Singularity (e) in Fig. 11(e) appears when linkages D_1E_1 and D_2E_2 are parallel to each other without coinciding. Singularity (f) in Fig. 11(f) appears when linkages D_1E_1 and D_2E_2 coincide. As shown in Fig. 12, Singularities (a)(b)(c)(d)(f) form the boundary of the workspace of E_1 , meanwhile Singularity (e) divides the workspace of E_1 into two parts, Up-configuration workspace and Down-configuration workspace.

Figure 13 shows the Up-configuration and Down-configuration workspaces in different conditions. Among all conditions, α_1 and α_2 vary while the sum of α_1 and α_2 is kept as 90° to fix singularities (a)(b). It is obvious that in all the seven conditions, the Up-configuration workspace is larger than the Down-configuration workspace. As a result, Down-configuration is chosen for the new mechanism.

VI. WORKSPACE-ORIENTED DIMENSION OPTIMIZATION

Figure 14. The GCI of all sets of α_1 and α_2 .

Figure 15. Flow chart of the dimension optimization program.

Figure 16. The GCIs of the qualified sets of α_1 and α_2 .

In this section, the two angle parameters, α_1 and α_2 , are optimized to achieve two objectives. The first is to meet the workspace requirement of cataract surgery. The second is to make the dexterity of the mechanism in the workspace as good as possible. For the first objective, as the 3D lens-eye models

are built (Section II), all coordinates of the points inside the lens are covered. By traversing every point and testing if it is reachable by the mechanism, the qualified sets of α_1 and α_2 are found. For the second objective, Global Condition Index (GCI) [22] is used to evaluate dexterity. In the workspace-oriented dimension optimization, firstly, as show in Fig. 14, the GCI of the mechanism in each set of α_1 and α_2 in average lens-eye model is calculated. Then, by running the program shown in Fig. 15, the qualified sets of α_1 and α_2 are picked up. Results are shown in Fig. 16.

In Fig. 15, firstly, for each point inside the lens, the coordinates of the point are obtained from the 3D lens-eye models. Then, these coordinates are used to calculate the corresponding position in the frame of the mechanism. To achieve the two objectives of dimension optimization, every corresponding kinematics model should be solvable to ensure the robot can reach the position, as well as the condition number of each position being smaller than 20 for good dexterity. If either of the requirements is not met in any point traversed, the current set of α_1 and α_2 cannot achieve the dimension optimization objectives. This is repeated for every set. When every point is reachable with the condition number smaller than 20, the current set is qualified. The program works for all three 3D lens-eye models (Section II). By running this program three times using all three 3D lens-eye models, the sets of α_1 and α_2 qualify all three lens-eye models are found.

Figure 16 shows the GCI of qualified sets of α_1 and α_2 . The largest GCI occurs at the set $\alpha_1=63.4^\circ$ and $\alpha_2=70^\circ$, which is 0.4483. For easier manufacturing, the qualified sets with integral angle parameters are more attractive. The largest GCI of integral qualified sets occurs at the set $\alpha_1=63^\circ$ and $\alpha_2=69^\circ$, which is 0.4461. As a result, the optimized dimension is $\alpha_1=63^\circ$ and $\alpha_2=69^\circ$.

VII. CONCLUSION

In this paper, a new 7-DOF 2-PRRRRR parallel RCM robot for eye surgery is presented. Its parallel design brings theoretically high stiffness and high precision. There are only eight linkages in the new robot, which contribute to a light structure and small inertia. By analyzing the singularity and workspace of E_1 , one configuration (the Down-configuration) has been shown to meet the design criteria. The workspace-oriented dimension optimization ensures the new robot for manipulating the surgical tool such that it can reach the whole area required in cataract surgery maintaining very good dexterity.

Further research will focus on building a prototype with control system and calibration, followed by tests to evaluate the accuracy of the new mechanism.

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