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KINEMATIC ANALYSIS OF A MECHANISM WITH DUAL REMOTE CENTRE OF MOTION AND ITS POTENTIAL APPLICATION

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ABSTRACT

Development of a mechanism with dual remote center of motion (dual-RCM mechanism) intended for teleoperated ophthalmic surgery is reported in this paper. First, characteristics of RCM mechanisms are analyzed. Then, a method to synthesize dual-RCM mechanisms is proposed. Further the mechanical design parameters are optimized to synthesize types of mechanisms meeting functional requirements as well as workspace constraints. The dual-RCM mechanism intended for teleoperated ophthalmic surgery includes two end-effectors: one provides the tool insertion, the other tracks eye movement. The superiority is embodied in the self-synchronized motion of double end-effectors, which allows RCM point of the working instrument to track the penetration point real-time, thereby enhancing microsurgical accuracy. In the proposed implementation, a conceptual helmet mechanical architecture integrating surgical tools with triple-parallelogram linkages is introduced to release the surgeon's hands by enabling more robotic technologies during the procedures. The vision of the research is to help revolutionize the ophthalmic surgical procedures from bimanual fashion to master-slave teleoperation.

INTRODUCTION

Ophthalmic surgery is a surgical procedure performed on an eye or the adnexa of an eye to address ocular conditions. In current practice, local anesthetic is commonly used and the patient is awake; surgeons coordinate to perform the surgical tasks under an operating microscope. It is typical one of such microsurgeries that is associated with extreme delicate tissues and thus strictly requires the skill of a specialist. However, the constraints of tool manipulation, physiological tremors and involuntary eye movements all lead to the procedure being more difficult and somehow risky.

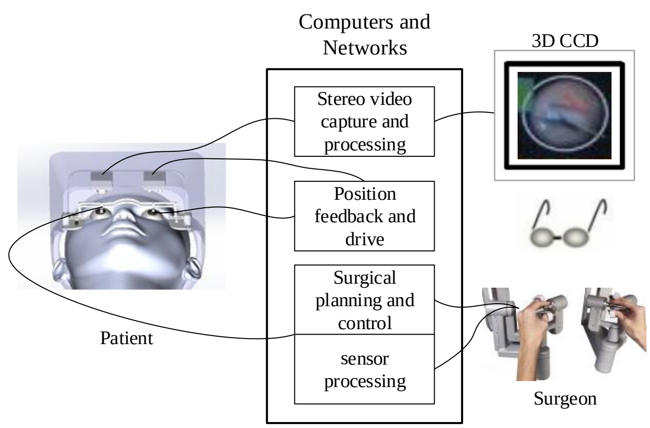


Figure 1. BLOCK DIAGRAM OF TELEOPERATED ROBOTIC SYSTEM FOR OPJTHALMIC SURGERY

Researches on medical robotics, sensing and visualization techniques are proposed to enhance the surgery outcomes. In the last two decades, there have been remarkable developments: many new mechanisms emerged and various clinical applications were demonstrated [1, 2, 3]. Historically, a commercialized master-slave surgical telerobot [4] - da Vinci surgical system (Intuitive®)-has been designed to perform the minimal invasive surgery (MIS) as well as microsurgery in general. Feasibility study of utilizing the da Vinci surgical system particularly for ophthalmic surgery has been assessed and it is reported that the system provided adequate dexterity [5]. Additionally, it is desirable to integrate various working instruments and avoid surgeon's hand tremor.

Compared to the manual procedure, computer integrated teleoperation would have the potential to improve efficacy and accuracy of the microsurgical procedures [6]. However, there present novel challenges with changing the traditional manner of hand-eye coordination and access to intraoperative information [7]. In order to address these limitations, mechanical approaches establish the first fundamental support. Mechanical RCM designs achieve several critical advantages [8, 9].It is generally designed to constrain the pivotal motion of the instrument around an RCM that coincides with the penetration point especially for MIS.

For intraocular procedures, the mechanical RCM must be accurately positioned and assure the necessary movement range of tool. There exist two mainstream robotic systems to assist ophthalmic surgery that have been in research. In [10, 11] the pilot studies were concentrated on actively removing involuntary hand tremor with a handheld stabilized tool (which is called MICRON system) during the ophthalmic surgery. It improves the surgeon's ability to carry out precision manipulation and increases accuracy in microsurgery. However, the MICRON system does not share control of the surgical tool with computers. In contrast, another creative design of the Steady-Hand Robot [12, 13] was implemented in a cooperative control manner. Here the system possesses the ability to sense forces exerted on the tool handle by the surgeon, whilst providing computer assistance to the surgeon. Further, a mechanically constrained RCM [14] is designed to filter out some unwanted movements to improve the safety and comply with high precision.

In this paper, the proposed dual-RCM mechanism is intended for teleoperated ophthalmic surgery, which integrated a conceptual helmet design. It enabled a new way of computer-assisted master-slave ophthalmic procedure (see Fig. 1). The surgical tool is mounted on one of end-effectors of the triple-parallelogram linkages, and meanwhile it is mechanically constrained with a separate RCM point. Another end-effector tracks eye movements via a stereo vision system. Note that the double end-effectors are inherently self-synchronized. Thus, computer can make the decision and share the control with the surgeon by processing the input signals from the inspection end-effector. Throughout the real-time tracking of the ophthalmic procedure, the surgeons at the master station will decrease the influence of involuntary eye movements and hand tremor such that improving the outcome of the surgery.

NOMENCLATURE

P_i Revolute joints of a mechanism.

O_i Remote centres of motion of a mechanism.

φ Angle of the first angulated link $P_{01}P_1P_{12}'$.

ψ Angle of the second angulated link $P_{01}'P_1P_{12}$.

η Angle of the third angulated link $P_{12}P_2P_{23}'$

γ Angle of the third angulated link $P_{12}'P_2P_{23}$

a, b, c, d, e, f Lengths of links.

β Rotation angle of drive link.

U One rotational axis.

V Another rotational axis.

1. DUAL-RCM MECHANISM DESIGN

1.1 CHARACTERISTICS OF THE RCM MECHANISM

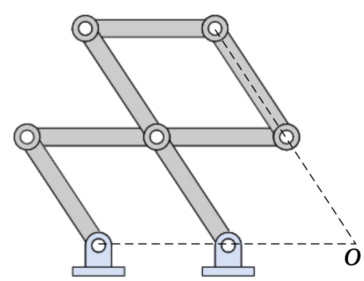


Figure 2. MODEL OF DOUBLE PARALLEL FOUR-BAR RCM MECHANISM.

Double parallel four-bar linkages [15] are initially used as an RCM mechanism as shown in Fig. 2. This mechanism has one remote center of motion at point O.

By investigating the structural characteristics of the optimized RCM mechanism, it can be seen that its basic component contains two parallelograms as illustrated in Fig. 3. The dimension and shape of parallelogram determine the RCM position of the mechanism. In Fig. 3, point C represents a hinge joint and parallelograms $P_0P_{01}P_1P_{01}'$ and $P_1P_{12}P_2P_{12}'$ represent two parallelograms with different lengths a, b, c and d. ψ and φ denote the angles of two angulated links [16] $P_{01}P_1P_{12}'$ and $P_{01}'P_1P_{12}$.

1.2 ANALYSIS OF THE RCM MECHANISM WITH THREE PARALLELOGRAMS

In this subsection, an advanced mechanism is first proposed by adding a parallelogram. Then a planar mechanism with three

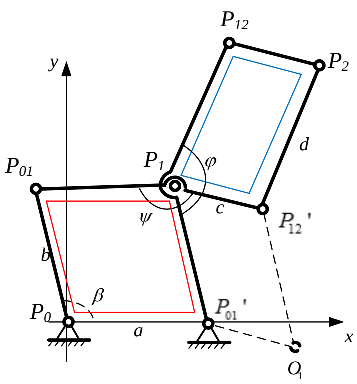


Figure 3. SCHEMATIC DIAGRAM OF RCM MECHANISM WITH TWO PARALLELOGRAMS.

parallelograms is obtained, as shown in Fig. 4. In Fig. 4, P_1 and P_2 are angulated joints of these three parallelograms.

In the following, rotation centers of links of this mechanism coincide with two fixed points as marked by O_1 and O_2 are revealed.

Let us define that the coordinate of P_2 is (x_1, y_1), then with the following vector equation

$$\overrightarrow{P_0P_2} = \overrightarrow{P_0P_{01}} + \overrightarrow{P_{01}P_1} + \overrightarrow{P_1P_{12}'} + \overrightarrow{P_{12}'P_2} \tag{1}$$

An equation set is obtained as

$$\begin{cases} x_1 = a + b\cos\beta - c\cos\psi - d\cos(\varphi+\beta) \\ y_1 = b\sin\beta - c\sin\psi - d\sin(\varphi+\beta) \end{cases} \tag{2}$$

Simplifying Eqn. (2), and then it is derived that

$$\begin{cases} x_1 = A + b\cos\beta - d\cos(\varphi+\beta) \\ y_1 = B + b\sin\beta - d\sin(\varphi+\beta) \end{cases} \tag{3}$$

Where $A = a - c\cos\psi$ and $B = -c\cos\psi$.

According to Eqns. (1-3), it can be derived that

$$(x_1 - A)^2 + (y_1 - B)^2 = b^2 + d^2 - 2bd\cos\varphi \tag{4}$$

Hence, it is concluded that the virtual rotation center of P_2 is (A, B), and meanwhile it is the coordinate of O_1 as well.

Besides, based on Eqn. (4), P_2 will make a rotational motion with the radius of $\sqrt{b^2 + d^2 - 2bd\cos\varphi}$.

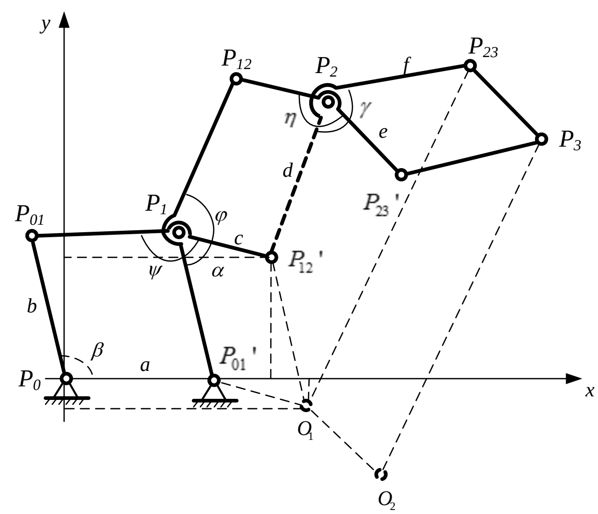


Figure 4. PROPOSED MECHANISM WITH TWO PARALLELOGRAMS.

Secondly, the coordinate of P_{23}' is defined as (x_2, y_2), then another vector equation is obtained as

$$\overrightarrow{P_0P_{23}'} = \overrightarrow{P_0P_{01}} + \overrightarrow{P_{01}P_1} + \overrightarrow{P_1P_{12}'} + \overrightarrow{P_{12}'P_2} + \overrightarrow{P_2P_{23}'} \tag{5}$$

Similarly, the following equation set is obtained

$$\begin{cases} x_2 = a + b\cos\beta - c\cos\psi - d\cos(\varphi+\beta) + e\cos(\eta+\psi) \\ y_2 = b\sin\beta - c\sin\psi - d\sin(\varphi+\beta) + e\sin(\eta+\psi) \end{cases} \tag{6}$$

Simplifying as

$$\begin{cases} x_2 = C + b\cos\beta - d\cos(\varphi+\beta) \\ y_2 = D + b\sin\beta - d\sin(\varphi+\beta) \end{cases} \tag{7}$$

where

$$C = a - c\cos\psi + e\cos(\eta+\psi)$$

$$D = -c\sin\psi + e\sin(\eta+\psi)$$

According to Eqn. (5-7), it can be derived that

$$(x_2 - C)^2 + (y_2 - D)^2 = b^2 + d^2 - 2bd\cos\varphi \tag{8}$$

Hence, it is concluded that the virtual rotation center of P_{23}' is (C, D), and meanwhile it is the coordinate of O_2 as well. Based on Eqn. (8), P_{23}' will make a rotational motion with the radius of $\sqrt{b^2+d^2-2bd\cos\varphi}$.

Because O_1P_2 is equal to the rotation radius P_{23}', the virtual center O_2 can be obtained via geometrography.

In a similar way, a relation is derived

$$\overrightarrow{P_0P_3} = \overrightarrow{P_0P_{01}} + \overrightarrow{P_{01}P_1} + \overrightarrow{P_1P_{12}'} + \overrightarrow{P_{12}'P_2} + \overrightarrow{P_2P_{23}'} + \overrightarrow{P_{23}'P_3} \quad (9)$$

And the following equation set is holded

$$\begin{cases} x = a + b\cos\beta - c\cos\psi - d\cos(\varphi+\beta) + e\cos(\eta+\psi) - f\cos(\gamma-\varphi+\beta) \\ y = b\sin\beta - c\sin\psi - d\sin(\varphi+\beta) + e\sin(\eta+\psi) - f\sin(\gamma-\varphi+\beta) \end{cases} \quad (10)$$

Finally, the result is obtained that rotational center P_3 coincides with O_2. Based on the aforementioned discussion, the configuration conformed by fixed points P_{01}', O_1, O_2 coincide with link $P_{12}P_2P_{23}'$ as in Fig. 3. These mechanisms with two remote centers are named dual-RCM mechanisms.

1.3 TYPE ANALYSIS OF DUAL-RCM MECHANISM

As mentioned in subsection 1.2, a mechanism with two remote centers is obtained by adding parallelograms. Also the positions of remote centers are related to the angulated links of mechanisms. In this way, schematic diagrams of dual-RCM mechanisms contain at least three parallelograms. This type of mechanism is coined as the triple-parallelogram linkages. Figure 5 shows a much more simplified type of the dual-RCM mechanism. It is a mechanism with remote centers aligning along the fixed positions.

Other two types of the triple-parallelogram mechanisms with six movable links are presented in Fig. 6. The figure shows a mechanism with its two frameworks fixed at both sides of two RCMs, whilst Fig. 6(b) shows that two RCMs are separated by part of the framework.

These three types of the dual-RCM mechanisms mentioned above are all over-constrained linkages. However, due to the geometrical particularity of parallelogram, these dual-RCM mechanisms have only one degree-of-freedom (1-DOF).

This subsection focused on type consideration of dual-RCM mechanisms. It can be seen that the necessary parameters of the dual-RCM mechanism depend on the dimensions of three integrated parallelograms. This theoretical analysis contributes to design of the basic robotic mechanism for teleoperated ophthalmic surgery.

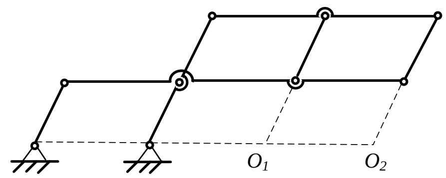


Figure 5. TRIPLE-PARALLELOGRAM MECHANISM WITH TWO REMOTE CENTRES.

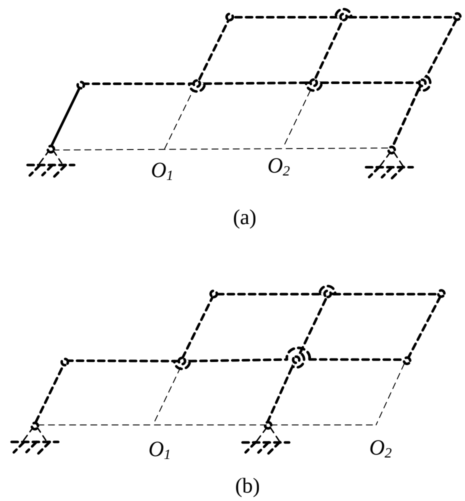


Figure 6. OTHER TWO TYPES OF DUAL-RCM MECHANISMS WITH SIX LINKS.

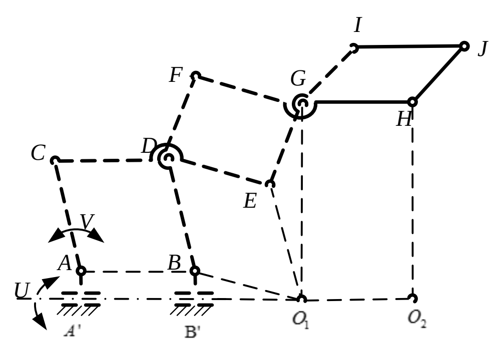


Figure 7. SCHEMATIC OF DUAL-RCM MECHANISM WITH TWO ROTATIONAL DOFS.

1.4 DESIGN OF THE DUAL-RCM MECHANISM WITH TWO DOFS

In subsection 1.2, Fig. 4 shows a mechanism with two RCMs and its inherent rotations are only about the *x* axis with 1-DOF. However, it is reasonable that the mechanism may have more than one DOF in practical applications. Thus, in this subsection, analyzing and designing a mechanism containing two RCMs attempted and the mechanism has more than one DOF.

Referring to Fig. 7, suppose that an extra rotational DOF is about the axis *U*, which is not intersecting with the axis *Vi*. So it is necessary to guarantee that the positions of the two RCMs are along the axis *U*.

Based on the analysis mentioned in the last paragraph, the dual-RCM mechanism with two rotational DOFs is obtained. Besides, considering the differences of three types of the dual-RCM mechanisms mentioned in Fig. 5 and Fig. 6, and their workspace constraints, stiffness and symmetry in practical applications, a dual-RCM mechanism is finally designed as shown in 3D model of Fig. 8. It possesses two rotational DOFs along axis *V* and *U*, and satisfies the functional requirements of ophthalmic surgery.

An experiment of dual-RCM mechanism was presented. A 3D printing model is shown in Fig. 9. It is a dual-RCM mechanism with two DOFs. Figure 9 also shows four tilting sides of this mechanism. According the experiment, tilting angles of backward and forward of dual-RCM mechanism are 60°; tilting angles of rightward and leftward of dual-RCM mechanism are 45°. These tilting angles will change according to the practical application and the dimensions of links of the dual-RCM mechanism.

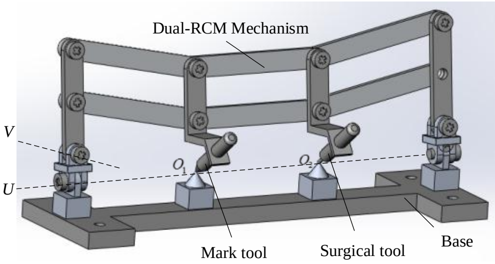
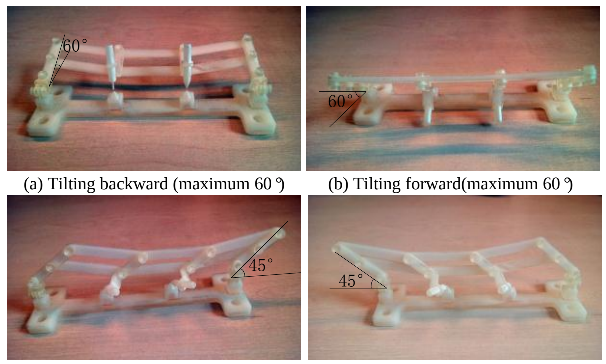


Figure 8. 3D MODEL OF A DUAL-RCM MECHANISM WITH SIX LINKS AND TWO ROTATIONAL DOFS.



(a) Tilting backward (maximum 60°) (b) Tilting forward(maximum 60°)

(c) Tilting rightward(maximum 45°) (d) Tilting leftward(maximum 45°)

Figure 9. EXPERIMENT OF A 3D PRINTING MODEL OF DUAL-RCM MECHANISM.

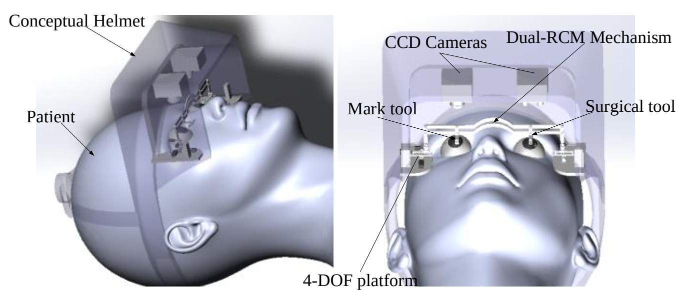


Figure 10. 3D MODEL OF A HELMET-LIKE CONCEPTUAL DESIGN.

2. SYSTEM IMPLEMENTATION ON CONCEPTUAL HELMET

Local anesthesia is often conducted during ophthalmic surgery. However, the eyes will still have involuntary movements when the eye's nerve is stimulated. It is usually not considered, or eyes are fixed by using some instruments during current ophthalmic surgical procedures. The former situation makes the position of remote center invalid, which may lead to the incision much larger; the later will damage the eyes with long time motionlessness. Thus, it is extremely important to find a suitable method to overcome this type of eye random motions.

Research shows that motion of the two eyes of human beings is usually synchronized. The vision of our proposed dual-RCM mechanism is to enable ophthalmic surgical procedures from bimanual fashion to master-slave teleoperation with increased accuracy.

The proposed robotic system consists of a mechanism with two RCMs as mentioned in the previous Section. One of dual-RCM tracks the motion of eyes, and another holds the surgical instrument on behavior of the surgeon at the remote master station. Meanwhile, motions and positions of eyes are captured by a CCD camera. This information is sent back to computer for calculation and processing. Thus, the computer shares the control of the working instrument with the surgeon. The computer then sends the signal to actuation motors based on the corresponding rotational requirements. The dual-RCM mechanism has the superiority of coupled motion of two end-effectors such that the surgical tool actively tracks to the penetration point in real time. In Fig. 10, a helmet-like conceptual model is designed. It is integrated with a dual-RCM mechanism, CCD cameras, motors and some connectors. The tracking information and calculating work will be processed by computers off the helmet. This conceptual design can not only locate the position of RCM precisely, but also assist the surgeon to operate in a master-slave teleoperation manner.

3. CONCLUSIONS AND FUTURE WORK

A dual-RCM mechanism used for the teleoperated robotic system for ophthalmic surgery was presented in this paper. In order to solve the problem of involuntary eye movements during the procedure and keep the RCM with safety protection, a dual-RCM mechanism was presented and analyzed. One type of dual-RCM mechanism with two RCMs located in the middle of the frame was chosen as the mechanism of ophthalmic surgical robot. Then a conceptual helmet was designed and the operation procedure of ophthalmic surgery using this equipment was described. Further investigation is to be carried out on the teleoperated robotic system for ophthalmic surgery.

ACKNOWLEDGMENTS

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