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A Novel Remote Center-of Motion Parallel manipulator for Minimally Invasive Celiac Surgery

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ABSTRACT : *In order to improve the security and expand the work space of minimally invasive celiac surgical robot, a new remote center-of motion (RCM) mechanism is designed. The remote center-of motion (RCM) mechanism can be used to hold surgical instrument instead of doctors, and then help doctors complete surgical operation (such as holding、stapling or resecting the patient's diseased tissue and organs). In this paper, the function of the remote center-of motion (RCM) mechanism of minimally invasive surgical (MIS) robot in the process of surgery are analyzed in detail. the design requirements of the remote center-of motion (RCM) are described. And then, a detailed analysis of the kinematic principle and motion decouplability of the circular tracking arc and double parallelogram structure are gave. On these foundations, a novel parallel robotic remote center-of motion (RCM) mechanism which owing a circular track structure and some series bar is proposed. Through analyzing the degree of freedom of this institution, the kinematics principle and decoupling characteristics, we find that the new institution has a good performance on "Fixed point motion" and the three rotational degrees of freedom of this mechanism can be fully decoupled. with respect to the remote center-of motion (RCM) mechanism which was made by the circular tracking arc and double parallelogram structure, the novel remote center-of motion (RCM) mechanism can realize the robot's lightweight, improve the structural rigidity, reduce motion inertia, and also expand the working space. As a result, the new remote center-of motion (RCM) mechanism would be a good choice for a minimally invasive surgical robot.*
Keywords –*Minimally Invasive Surgical Robot; Remote Center-of Motion; Decouple; Circular Tracking Arc ; Double Parallelogram Structure*

I. INTRODUCTION

Minimally invasive surgery (MIS) is a type of surgery which received a lot of support and favor from surgeons and patients. The basic operation concept of MIS is to cut tree or four small incisions (usually between 5 ~ 10mm in diameter) in the abdominal cavity of the patient, then the long thin surgical instruments can be inserted into patient's body. This kind of operation can do lots of good benefits to patients including small scars, less pain and shorter recovery time. The concept of minimally invasive surgery is proposed firstly by Payne and Wickham in 1985 [1]. with the help of this technique, the patient can be treated with less trauma, less pain,and quicker recovery [2]. Currently, the mature application of MIS system in the world are ZEUS system produced by company of Computer Motion in American [3] and Da Vinci system created by the company of Intuitive Surgical in the United States [4]. In the traditional MIS, it is needed for the doctor to hold the surgical instruments used to finish the operation during the surgery. After a long time of accurately grasping the doctor's surgical instruments, doctor would be tired. So, in order to reduce the labor intensity of the doctor and to avoid surgical accidents which caused by the quiver of doctor's hands, a kind of robot which can clamp surgical instruments should be designed. With the help of robotic technology, MIS would be more security, accuracy and convenience [5]. Manipulator, a part of MIS robot , is designed to hold the surgical instruments. And according to the requirement of MIS, A good manipulator should be designed as a remote center-of motion mechanism[6]. As so far, many methods that can be used to design a manipulator were applied. For example, Zeus, a MIS robotic system proposed by Computer Motion, used the passive RCM mechanism to hold surgical instruments[3]; A parallelogram RCM mechanism was applied in the Da Vinci surgical robotic system[4]; Researchers came from Simon Fraser University of Canada made use of a spherical linkage and realized RCM in their endoscopic clamping robotic system [7]. the kinematic design of end- effector has become a hot topic During the study of MIS robot.

In this paper, a novel Parallel RCM mechanism with 4 degrees of freedom (DOF) is designed for celiac MIS robot. The novel mechanism take advantage of a circular orbit to create a rotational DOF which are always pivoting at a fixed point (i.e., insert point). While by making use of the principle that the axis of robot arm contains the fixed point, the mechanism achieved the other rotational DOF of the RCM mechanism. This new RCM mechanism can separate the motor which control the two rotation DOF from robot structure itself. So, the robotic motion inertia would be reduced and the safety of operation can be enhanced. At the same time, a larger workspace volume generated by the structure of circular track is produced.

II. REMOTE CENTER-OF -MOTION MECHANISMS

To accomplish a surgical task, the MIS robot should manipulate its surgical instruments insert inside the patient's body and rotating around a fixed point on the patient's body. Meanwhile, there should no any collision between the instrument during surgery. It goes without saying that the manipulator of the robot should be designed with 6 DOFs For the purpose of reaching the specified spatial location. However, 2 DOFs have already been constrained by the abdominal wall, and the manipulator can complete the surgical procedure only with 4 DOFs. We have learned that the 4 DOFs should include three rotational DOFs and one translational DOF(i.e., a 3R1T motion where "R" denotes rotational DOF and "T" the translational DOF). For the reason of no collision, the three rotational DOFs should always pivot at the trocar point (i.e., insert point) on the patient's body, while the translational DOF should move along the penetrating direction. An illustration for such a 4-DOF of motion for a MIS mechanism was described in Fig.1. As shown, the robot manipulator is inserted into patient's body with a special trocar through a small incision. There are four DPFs including three rotational DOFs and one translational DOF. And, three rotational DOFs which described as pan, tilt and spin rotation rotate around a fixed point (i.e., trocar point in the figure). The translation DOF make the surgical tool achieve the function of insertion and retraction. It can be seen that surgical tool, with the help of four DOFs, can reach every point of the limited small spatial volume workplace in the patient's body. A general multi-DOF robot can, of course, also realize this function through a perfect control strategy. However, it would make the mechanism become very heavy and complicated. So, a more simple mechanism which named remote center-of-motion (RCM) mechanism was devised and it can also accomplish these required motion depend on the structure constraint itself. In conclusion, a link that has a fixed center of rotation and locate outside the workspace of the mechanism can be called an RCM, and an RCM mechanism should own one RCM at least. For an RCM robot, it would be composed by one or more RCM mechanisms for generating RCMs.

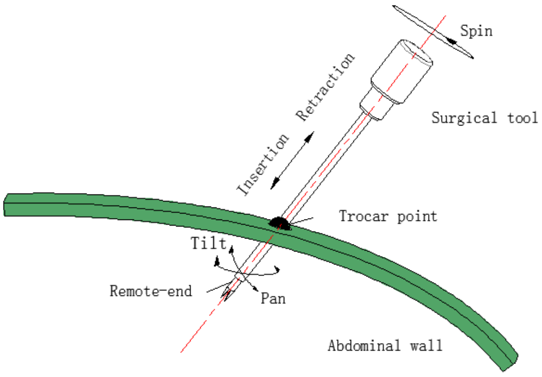

Figure 1. The four DOFS of motion for an MIS mechanism

III. TYPICAL RCM MECHANISMS

3.1 the view of RCM mechanism

In order to improve safety, reduce costs and expend the operating room of minimally invasive surgery (MIS), a variety of remote center-of-motion (RCM) mechanisms were designed, such as, circular tracing arc, parallelogram, spherical linkage, gear train, non-mechanical RCM, passive RCM and parallel wrist mechanism and so on. Every kind of mechanism has its' own advantages and shortcomings. Two typical RCM mechanisms are analyzed in the following paragraphs.

3.2 circular track mechanism

This kind of remote center-of-motion (RCM) mechanism has two DOFs, and there are rotational DOFs. one of rotational DOF is generated by the translational joint placed on the circular orbit, the constraint of the translation joint can make the end effect instruments achieve yaw motion around the center of the circle of circular orbit (i.e., trocar point); the other rotational DOF is created by the rotational joint whose rotation axis go through the center of the circle of circular orbit (i.e., trocar point) and locate on the robot arm. That means that it can accomplish two required motion depend on the structure constraint itself, and the other two DOFs can be generated directly by two actuator. An RCM constituted with a circular track mechanism is depicted in Figure 2.

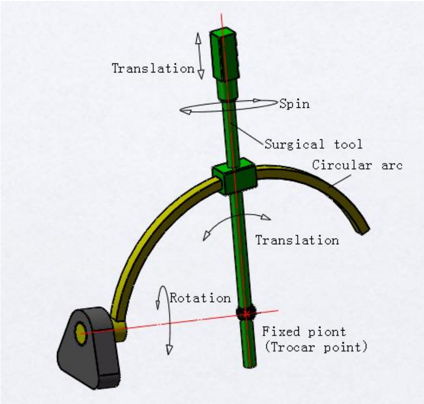

Figure 2. an RCM with a circular track mechanism

The motion principle of circular track mechanism is as following.
(1) Center of circular orbit is the fixed point and the trocar point of the surgery;
(2) The rotational joint whose rotational axis go through the center of circular orbit generate a rotational DOF which rotate around the fixed point.
(3) The specific constraint between the circular orbit and end effect tool create another rotational DOF which rotate around the fixed point by making the translation joint produce rotational DOF .
(4) The third rotational DOF and the translational DOF can achieve through locating two actuators on the manipulator.

This kind of RCM mechanism own 4 DOFs and has a sample mechanical structure. It is easy to achieve three fully-decoupled rotational DOFs or decoupled translational DOF. The drawback of this mechanism is that the processing cost of circular orbit is a little higher and the motion inertia of the mechanism is relatively large.

3.3 Double parallelogram mechanism

An most important advantage of using parallelogram structure in MIS robot is higher stiffness over a serial one. Although it has a small operation room, a parallelogram can be a good choice for an MIS robot. The other apparent advantage of parallelogram structure is that the two actuators can be apparent out from end effect instrument and be stationary on the base in a parallel manipulator. The double parallelogram mechanism have two DOFs and can realize the tilt and pan rotational DOF. One of the most simple double parallelogram mechanism is shown in Figure 3.

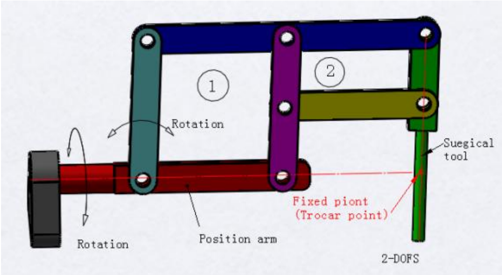

Figure 3. RCM mechanism of Double Parallelogram

The kinematic principle of this remote center-of-motion mechanism is as following:
(1) the point of intersection of the rotational axis of robot arm and the rotational axis of end effect instrument is the fixed point(i.e., trocar point in the figure);
(2) The rotational joint located in robot arm and whose rotational axis go through the fixed point can generate a rotational DOF which rotate around the fixed point;
(3) The mechanical constraint of the double parallelogram Mechanism can create the other rotational DOF which rotate around the fixed point;
(4) The third rotational DOF and the translational DOF can achieve through locating two actuators on the end-effect instrument .

The two advantages described above make the parallelogram Mechanism be popular and widely accepted. Kuo and Dai created a fully decoupled 4-DOF RCM parallel manipulator for MIS [7]. Pantoscope robotic system of Swiss Federal Institute of Technology in Switzer –land contains the parallelogram Mechanism[8].

IV. A NOVEL REMOTE CENTER-OF-MOTION MECHANISM

4.1 The principle of the new REM mechanism

In order to meet the kinematic design requirements of minimally invasive surgery, a novel 4-DOFs remote center-of-motion (RCM) parallel serial robot manipulator is proposed. As shown in the Fig.4.the parallel RCM mechanism, which can make the robotic surgery tool pivot around RCM (as the point O in Fig. 4) in two direction, owns two branches. one is formed by an 4RC-leg while the other is by an CPR-leg (in which "R" denotes the revolute joint, "C" means the a cylindrical joint, and "P" denotes the prismatic joint). They connect with each other by cylindrical joint, i.e., the joint C in Fig. 4. The axis of the revolute joint "R1", The axis of the revolute joint "R5"and the surgical tool are intersecting at the point "O". In the branch of 4RC-leg, the revolute joint "R1" is perpendicular to the revolute joint "R2",and the revolute joint "R2", "R3"and"R4"are parallel to each other. While the rotational axis of the cylindrical joint "C"in the 4R-C-leg is coplanar with the rotational axis of the revolute joint "R1" and perpendicular to other joints of the 4R-C-leg. In the branch of CPR-leg, the revolute joint "R5" which owned by the circular tracking arc is parallel to the revolute joint "R1". And at the same time, the rotational axis of these two joints are collinear relationship and always pass through the point "O" no matter what the input motions are. The circular tracking arc and the surgical tool are connected with the prismatic joint "P". As a result, the track of arc would make the surgical tool produce a rotation that rotate around the center of the circular track (i.e., the point O in Fig.4). And the rotational axis of the cylindrical joint "P" and the axis of surgical tool are dead in line. Owning to the fact that the cylindrical joint "P"in the two franches is the same one, the new parallel RCM mechanism can also be described as 4R-C-PR mechanism. From the arrow shown in the Fig.4, we can get that the revolute joint "R1" generate a rotational DOF that rotate around the center of the circular track (i.e., the point O in Fig.4) and the prismatic joint "P" can create another rotational DOF that rotate around the center of the circular track (i.e., the point O in Fig.4). Therefore, the new parallel RCM own two degree of freedom.

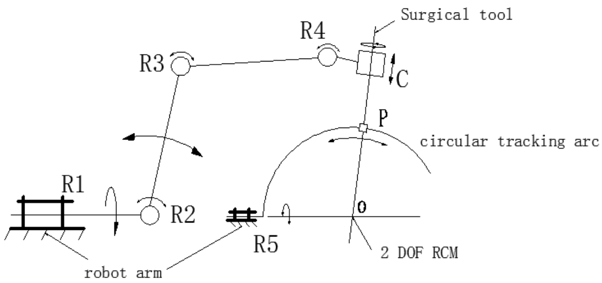

Figure 4. The kinematic model of the new parallel RCM

4.2 The new robot end-effetor

The new robot end-effect has only a RCM mechanism mentioned above. The new RCM can provide two DOFs for the manipulator, and the two DOFs can make the surgical tool of the manipulator rotate around a fixed point in two different directions. However according to the analysis in the introduction of this paper, we can understand that the robot manipulator need 4 DOFs at least to accomplish the surgical task. So the new robot manipulator has to get the other two DOFs. As shown in the Fig.5, we can add a revolute joint and a prismatic joint on the axis of surgical tool. The revolute joint can make the surgical tool spin and execute a rotational DOF for the manipulator. The prismatic joint can make the surgical tool insert and retract along with the surgical tool and execute the translational DOF for the manipulator.

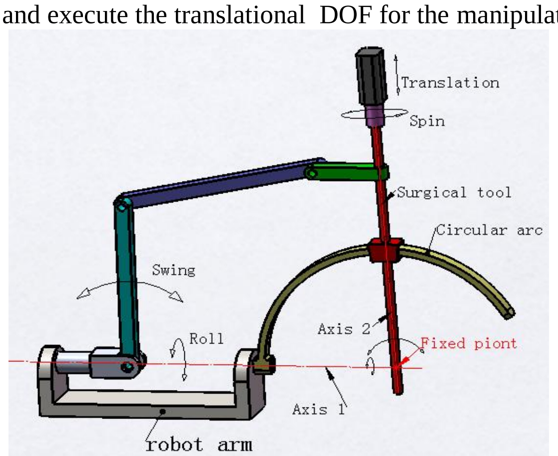

Figure 5. The illustrative of manipulator

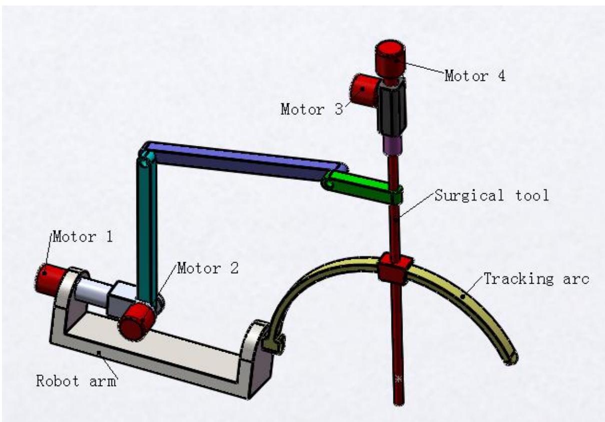

Figure 6. the control strategy of the new mechanism

The control strategy of the new robot manipulator is shown in the Fig.6. the first electric motor is installed on the revolute joint “R1”,which can make the robot manipulator realize pan rotation of the surgical tool. the second motor would be arranged on the revolute joint “R2”, which can execute a tilt rotation of the surgical tool. We set the third motor on the surgical tool instrument, so that it can provide the translational DOF for the manipulator. The surgical tool can insert and retract in the fixed direction by the driving of the active motor. The fourth motor can also be installed in the end of surgical tool, and it can make the surgical create spin motion. With the arrangement of these four control motor, the new manipulator execute a 4 DOF RCM motion at the point O. in other word, the surgical tool of this robot can always pass through the incision on the patient’s body during the surgery.

4.3 The decoupling characteristics of the new manipulator

Generally, to further improve the manipulation convenience and reduce the complexity of control, the decoupled RCM mechanism has been suggested [20]. The decoupled kinematics can also increase the confidence in safety. So, for the 4-DOF RCM mechanism, it is the best goal that every DOF can decouple with each other. In other words, a fully-decoupled RCM mechanism is the best choice for an MIS robot. However, most of the current RCM mechanism are partially decoupled. Our new manipulator contains an RCM, and can be called a new RCM mechanism. In our RCM mechanism, the 4 DOFs, which include three rotational DOFs and a translation DOF, are controlled by four active motor. The three rotational DOFs are control by motor 1,2 and 3 respectively, and they motion have not any effect with each other. That is to say that the three rotational DOFs of the new RCM mechanism are fully decoupled. However, the translational DOF is not only determined not only by the prismatic joint which mount on end of the surgical tool, but also effected by the revolute joint “R2”. So, the translational DOF of this new RCM mechanism is not decoupled. In conclusion, our new RCM mechanism is a robot manipulator that has three fully-decoupled rotational DOFs and the translation DOF is controlled together by two motor.

4.4 The advantages of the new robot manipulator

The new mechanism is comprised by a circular tracking arc and a parallel structure. As a result, it makes full use of the advantages the two structures and also improves some defects of the two structures. The circular tracking arc designed in the new mechanism simplifies the whole mechanism, and realize the lightweight of the organization. While the use of the parallel structure not only enhances the stiffness, but also reduces its motion inertia by separating the control motor from the surgical tool. Shortly, it would be good choice for an MIS robot to own such an robot manipulator.

V. CONCLUSION

In this paper, a novel RCM parallel manipulator for MIS robot is proposed. The new RCM mechanism is made up of a circular tracking arc and a parallel structure, and owns four degrees of freedom which is required by an MIS robot. At the same time, the three rotational DOFs of the mechanism is fully-decoupled, and its translational DOF is determined by a prismatic joint and a revolute joint together. the new CMR parallel mechanism not only makes the MIS robot become more light, but also make a great contribution to enhancing the stiffness and reducing the motion inertia of MIS robot.

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