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Design of a Force-Reflective Master Robot for Haptic Telesurgery Applications: RoboMaster1

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Abstract— **With the increasing trend toward Minimally Invasive Surgery (MIS) procedures, the need to develop new robotic systems to facilitate such surgeries is more and more recognized. This paper describes the design and development of a 4 DOF force-reflective master robot (RoboMaster1) for haptic telesurgery applications. A two-double parallelogram robot is introduced including a novel mechanism at the base for producing and control of the end effector's linear motion. This eliminates the deficiencies caused due to suspending massive actuators at the end effector or cabling from the base. The kinematics and work space of the system were analyzed and a prototype was developed for primary practical evaluations. The results showed that the system can effectively simulate the surgeon's hand maneuvers inside the abdominal cavity with a Remote Center of Motion (RCM) located at the backside. With this important feature, the system is expected to facilitate the key hole surgeries by eliminating the need for inverse and/or scaled maneuvers during minimally invasive surgeries.**

I. INTRODUCTION

MINIMALLY invasive surgery (MIS) is performed by passing rod-shaped endoscopic tools through small incisions on the patient's body. This provides several advantages over conventional open surgeries, e.g., reduced trauma and recovery time for the patient [1]. However, the surgeon's maneuvers are more difficult due to the fact that the tip of the surgical tool moves in the opposite direction of the surgeon's hand. This requirement for scaled and reverse movements, as well as the lack of haptic sensation or weak force feedback from the internal organs, has emerged the idea of using surgical robots to facilitate the surgery. Moreover, robotic endoscopic tools can help surgeons to manipulate large body organs through small incisions that otherwise would need the insertion of one hand inside the abdomen through a 7- 8 cm incision, as happens in Hand Assisted Laparoscopic Surgery (HALS) [2].

Currently robotic surgery systems are generally Master-Slave systems, in which the surgeon controls the slave robot by manipulating the master unit [3]. Considering the fact that the master robot is the main interface of surgeon with the surgery site, it has been the center of attention of many research works in recent years. Several researches have investigated the use of commercial haptic modules as the haptic master robots [4, 5]. However, such systems cannot solve the problem of inverse and scaled movements involved in MIS procedures. On the other hand, in the Da Vinci robotic surgery system (Intuitive Surgical Inc., California, USA), the need of scaled and reversed movement has been eliminated by using articulated instruments which can isolate rotational and linear motions. However, this solution cannot provide the surgeon with the sense of touch and force-reflection needed [6]. An effective master robot has been suggested to require to constrain the surgeon's forearm through a center of motion and let him/her feel to move his/her hand inside the patient's body, similar to what happens in HALS [1]. This provides a more feasible solution to a software approach due to using a mechanism with the least DOFs.

This paper describes the design and evaluation of a force-reflective master robot with a unique mechanism which provides a backside RCM for the surgeon's hand without constraining his/her forearm. So the surgeon will have a sense of open surgery but with a constrained orientation for the instrument toward the backside incision point. A novel, innovative mechanism is also introduced which produces and controls the linear motion of the robot's end effector at the base of the robot, reducing the floating mass and inertia.

II. DESIGN CONSIDERATIONS

There are some general requirements for haptic tools, e.g., high structural stiffness and low friction, backlash, and inertia, to improve the capability of the system to provide high transparency in force reflection. On the other hand, there are some specific considerations for a telesurgical master robot, e.g., sufficient degrees of freedom and workspace. During MIS procedures, the surgical instrument pivots at the incision point at which it enters the patient's body. Such constraint enforces the surgical tool to be manipulated with four degrees-of freedom (DOF), including three rotational DOFs pivoted at the insertion point (Pitch, Yaw, and Roll) and one translational DOF along the tool axis [7]. An effective master robot needs to provide the same

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degrees of freedom and workspace of a real surgical tool of MIS.

An important feature of an effective MIS master arises from the fact that there is a need for conformity of surgical instruments' orientation from the view of master and slave robots to let the surgeon feel his/her hands inside the patient's body and provide the sense of open surgery[8]. Considering the fact that during MIS, the tool pivots at an incision point located behind the tool tip, the movements of surgeon's hand and the tool tip of the surgical are in opposite directions. It means that when the surgeon moves the handle toward the right, the tip of the tool moves toward left and vice versa. In order to solve this problem and provide the sense of open surgery, the center of rotation should be transferred to the back of the surgeon's hand in the master robot. This adapts the orientation of surgical tool and the surgeon's hand so that the surgeon feels his/her hand inside the patient's body at the same position of the tool's end effector.

III. MECHANISM DESIGN

The constraint of instrument rotation around a fixed point is a fundamental requirement for surgical robots used in MIS. This requirement has motivated researchers to design Remote Center-of-Motion (RCM) mechanisms [7], in which the rotational and translational movements of instrument are kinematically constrained around a fixed point at some distance from the structural base of the robot. We investigated three RCM mechanisms in search for the most appropriate one for transferring the center of rotation behind the surgeon's hand.

A. Single-revolute-joint RCM mechanisms (Series Combination)

Using a series combination of single revolute mechanisms is the most common way of producing a RCM mechanism [9, 10]. Figure 1 illustrates a design of this kind of mechanism which can produce three rotational DOFs around a fixed point, and transfers this specific point to the back of the surgeon's hand. Employment of a series combination of the single revolute mechanisms for master robot of MIS has the disadvantage of needing larger actuators duo to the considerable floating inertia.

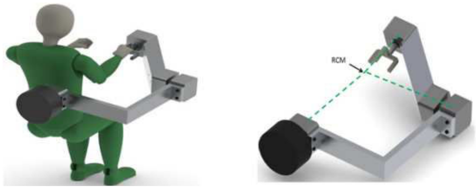

Fig. 1. Single-revolute-joint RCM mechanism (Series Combination)

B. Single-revolute-joint RCM mechanisms (Parallel Combination)

The main advantage of a parallel combination in comparison with a series combination is the possibility of installing actuators at the base of the mechanism which reduces the floating inertia [11]. However, such mechanism needs to be accurately constructed due to the fact that there is a potential risk of self locking. Figure 2 shows a design of a parallel combination mechanism which produces three rotational DOFs at a fixed point, and transfers this point to the back of the surgeon's hand. The problem of needing large actuators is resolved in such mechanisms by locating the actuators at the base and reducing the inertia. However, it produces a new problem of locating the RCM inside the structure which limits the surgeons maneuvering abilities.

Fig. 2. Single-revolute-joint RCM mechanism (Parallel Combination)

C. Double parallelogram RCM mechanisms

A main feature of the double parallelogram mechanism which looks attractive at the first glance is the fact that the center of rotation is located at a tunable distance from the body of the mechanism. So, this mechanism can effectively transfer the remote center of rotation to the back of surgeon's hand without limiting surgeon's maneuvers. Figure 3 presents a design of this mechanism which was found to be the best choice for the master robot of MIS.

Fig. 3. Double parallelogram RCM mechanism

A major concern in the implementation of an effective double parallelogram mechanism for MIS master robot is the way that the linear motion is produced and controlled. We developed a novel mechanism for this purpose in which the actuator of the linear motion of the end effector is placed at the base of the mechanism, so the floating mass and inertia are reduced. The main idea behind is sliding the second parallelogram (2 in figure 4 a) on the two links of the first parallelogram (1 in figure 4 a). However, since having parallel links is a basic requirement for the RCM, adding these two new DOFs to the system disturbs the parallelogram 1 and causes the RCM to be lost due to the rotation of parallelogram 2. In order to maintain the links parallel while adding two DOFs, a retentive link might be added to the parallelogram 1 (figure 4 c). However, there would be still possibility of losing the RCM when crossing the vertical position. In this configuration (figure 4 d), the sliders can move in opposite directions producing a trapezoidal architecture. For solving this problem and having a stable RCM mechanism, we added another double parallelogram to the mechanism with some offset from the first one as is illustrated in figure 4 (e). In this mechanism when the first parallelogram reaches the vertical position, the other one would be in vertical position, and it prevents losing the RCM motion. Thus, proposed RCM mechanism can transfer the center of rotation behind the surgeon's hand to induce sense of hand inside the patient's body, while it can produce and control linear motion at the base of the robot.

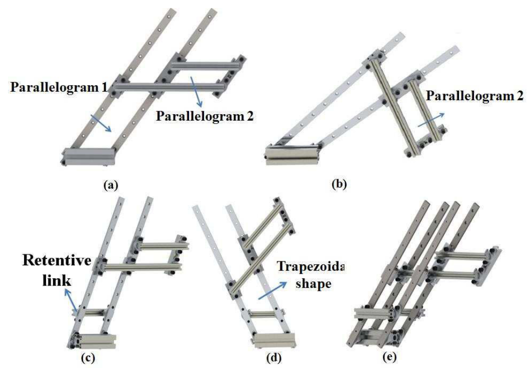

Fig. 4. Modified double parallelogram mechanisms to provide linear motion from the base: Adding two links provides two new DOFs (a) but disturbs the parallelogram 1 (b); Adding a retentive link saves the parallelogram 1 (c) but the system is subjected to instability in some configurations (d); The final two-double parallelogram mechanism (e).

IV. KINEMATICAL ANALYSIS

In order to simplify the kinematical analysis of the complicated two-double parallelogram mechanism, we focus on its basic mechanism and implement the effect of other links by applying the relevant constraint to the joints' motions. Figure 5 illustrates the coordinate systems attached to the mechanism. Using Denavit-Hartenberg method [12] the transfer function between the coordinate system number 6 and the base of robot can be obtained from Eq. (1).

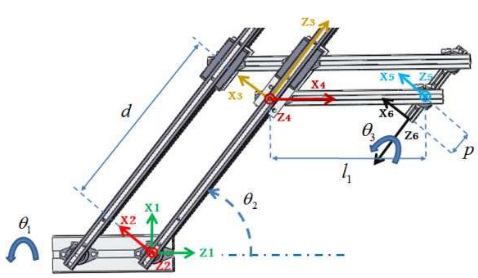

Fig. 5. Coordinate systems attached to the links.

TABLE I. DENAVIT-HARTENBERG PARAMETERS

i (link number)	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	-90	0	0	θ_2
3	90	0	d	0
4	-90	0	0	$-(90+\theta_2)$
5	0	l_1	0	$(90+\theta_2)$
6	-90	0	p	θ_3

$$ {}^{0}_{6}T = \begin{bmatrix} s_1s_3 + c_1c_2c_3 & s_1c_3 - c_1c_2s_3 & c_1s_2 & (d-p)c_1s_2 \\ s_1c_2c_3 - c_1s_3 & -c_1c_3 - s_1c_2s_3 & s_1s_2 & (d-p)s_1s_2 \\ -s_2c_3 & s_2s_3 & -c_2 & l_1 + (d-p)c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

So, the inverse kinematical equations of the robot are obtained from Eq. (2):

$$ \begin{aligned} &\cos(\theta_2) = -r_{33} \quad \theta_2 = \cos^{-1}(-r_{33}) \\ &\theta_3 = A\tan 2(-r_{32}, r_{31}) \\ &\theta_1 = A\tan 2(r_{23}, r_{13}) \\ &d = \frac{r_{24}}{\sin(\theta_1)\sin(\theta_2)} + p \end{aligned} \quad (2) $$

Considering the forward kinematical equations, the dimensions, and the required range of motion of each joint, the workspace of robot might be obtained. The result, shown in figure 6, depicts a part of a sphere.

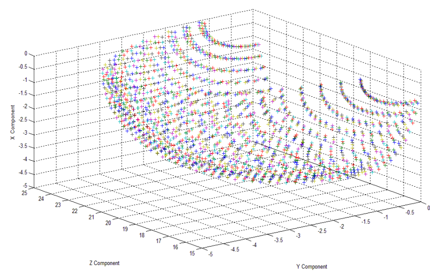

Fig. 6. Workspace of RoboMaster1

On the other hand, by using the forward kinematical equations of the robot, the Jacobian matrix might be obtained in the coordinate system of base:

$$ {}^{0}J = {}^{0}_{6}R\,{}^{6}J = \begin{bmatrix} -\sin\theta_1 \sin\theta_2 (d-p) & \cos\theta_1 \cos\theta_2 (d-p) & \cos\theta_1 \sin\theta_2 \\ \cos\theta_1 \sin\theta_2 (d-p) & \sin\theta_1 \cos\theta_2 (d-p) & \sin\theta_1 \sin\theta_2 \\ 0 & -\sin\theta_2 (d-p) & \cos\theta_2 \end{bmatrix} \quad (3) $$

So, the singular points are determined to be:

$$ \det({}^{0}J) = \det({}^{6}J) = -(d-p)^2 \sin\theta_2 = 0 \Rightarrow \theta_2 = 0, \pi \qquad d = p \quad (4) $$

V. SIMULATION AND EXPERIMENTS

The designed offset between the two double parallelograms of the proposed mechanism formed a triangle shown in figure 7. The change of the dimension of this triangle due to the relative movement of the two parallelograms provides a linear motion for the end effector. Thus with rotation of the two parts of the mechanism, using actuators placed at its base, we can obtain both the yaw and the linear motions.

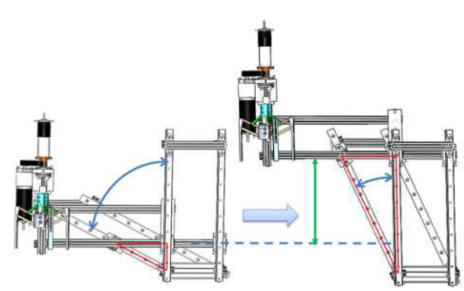

Fig. 7. Producing linear motion with relative movement of the two double parallelograms of the proposed mechanism.

A basic simulation study was conducted to evaluate the performance of the proposed mechanism and its innovative method of producing and controlling the linear motion. The simulation was performed in SimMechanics environment of MATLAB (R2010a, MathWorks Inc., Massachusetts, USA) using a basic model of the RoboMaster1 (Figure 8). Figure 9 illustrates the x component of end-effecter's velocity obtained by SimMechanics (continuous curve) in comparison with the results of the analytical solution (dots) when an arbitrary motion was applied to the joints of the robot. A similar correspondence was found for the other components of the end effector's velocity. It was revealed that the mechanism behaves as predicted in the design course, providing a stable RCM and a linear motion for the end effector from the relative movements of the two double parallelograms.

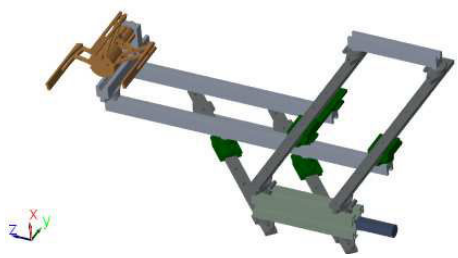

Fig. 8. Model of RoboMaster1 in SimMechanics

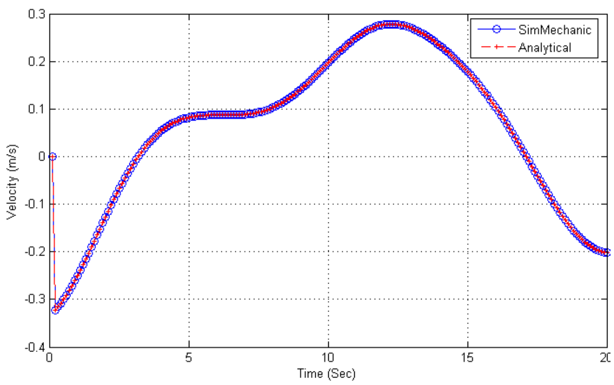

Fig. 9. The X Component of the end effector's velocity obtained from SimMechanics and analytical method when an arbitrary motion was applied to the joints of the robot.

Following dynamical and kinematical analysis and simulation of the RoboMaster1, a prototype of the proposed mechanism was fabricated to evaluate its capability of providing the required motions experimentally. Figure 10 illustrates the first prototype of the robot with 3 initial DOFs. The results of testing the prototype confirmed the design concept of producing and controlling the linear motion of the robot at the base in order to reduce the floating inertia and size of actuators.

VI. CONCLUSION

A force-reflective master robot was designed and evaluated that provides the required DOFs for the surgeon with acceptable ranges of motion, and guarantees the consistency of surgical instruments' position/orientation in master and slave sides. This induces the sense of open surgery for the surgeon allowing him to feel his hands to move inside the patient's body. The innovative mechanism employed allows the robot to produce and control the linear motion at its base reducing the floating mass and inertia and providing a more transparent force-reflection. Further work is going on to complete the prototype of the robot and perform technical and application tests.

Fig. 10. The prototype of RoboMaster1

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