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Novel Design Of Detachable Surgical Tool For Robotic Assisted Minimal Invasive Surgery

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Abstract

In modern surgical operation, a surgeon using a robotic surgical system which use a manipulator (a variety of surgical instruments, such as tissue graspers, needle drivers), Each of these structures perform functions for the surgeon such as holding or driving a needle, grasping a blood vessel, cutting or dissecting tissue, for this hand input devices of the surgeon's workstation coupled to the surgical instrument by a servo mechanism (more especially DC servo motors). This servo mechanism provides an interfacing between surgeon's hand input and manipulator surgical tool. The surgeon or assistant will mount robotic surgical instruments having suitable end effectors (grasper forceps, scissors, needle etc.) to the manipulator, and will often pass the end effectors through hollow sleeve for internal surgical site, so as to treat the targeted tissues while minimizing injury to the adjacent tissue structures. We are developing surgical tool with minimally invasive robotic surgical system. To use those tools in surgery, the mechanism of system needs to be simple and durable to reduce the cost of robotic surgery. In this paper, we present mechanism for minimally invasive surgical robot tools that have simple structure, easy to manufacture and control. Through an extensive design process, a compact and dexterous robotic surgical manipulator as well as the supporting control hardware is formed.

Keywords— Robotics surgery, minimally invasive surgery (MIS), surgical robot tool, laproscopy, kinematics, workspace.

1. Introduction

Medical robotics and computer assisted surgery is new and promising field of study that aim to augment the capabilities of surgeons by taking the best from robots and human. Robots are typically thought to be used for industrial purposes however they are beginning to gain the attention of the medical field. A current application pertains to using the precision and stability of a robot arm to assist in minimally invasive surgery.

Minimal invasive surgery (MIS) is the latest trend in medical surgery, where the procedure is less invasive compared with an open procedure, typically involving the use of a laparoscopic device and dedicated surgical protocol.

The tools and usually an Endoscopic camera is inserted through ports into the body; therefore MIS is less invasive, also creating fewer post-operative complications compared with conventional surgery. This results in shorter recovery times, and sometimes, outpatient treatments for previously lengthier. MIS is usually associated with a limited view of the surgical area and difficult handling of the surgical tools, however, which can be overcome through the use of computer and robot assistance. The field of medical robotics offers great potential for improving the capabilities of doctors and surgeons when performing complex surgical procedures, or when there is a need for dexterity and precision in diagnosis and treatment. The first robotic surgery in history dates back to 1985 [1, 2] and, since then, there has been a steady increase in robotic systems and technologies for application to critical surgical procedures [3]. Minimally invasive surgery, which includes procedures on the retina, inner ear, brain, spinal cord, nerves, vascular system, heart, and so on, requires complex and sensitive manipulations that stretch the limits of human performance [4], and some procedures demand such a high level of precision and dexterity that, some would argue, are impossible to achieve by conventional means [5, 6]. Teleoperated systems can scale down hand movements, filter out tremor, and magnify tool forces as displayed to the surgeon, in order to enhance dexterity while providing a more ergonomic and comfortable surgical set-up [7]. Various robotic surgery systems have been developed to provide Electro-mechanical dexterity and precision enhancement.

2. Robotically Assisted MIS System

Innovation in surgery allows surgeons to provide better healthcare to their patients. Minimally invasive surgery (MIS) or minimal access surgery is a revolutionary surgical technique. It is minimally invasive in the sense that the surgery is performed with instruments and viewing equipment inserted through small incisions rather than by making a large incision to expose and provide access to the operation site.

Currently there are some surgical manipulators (see figure 1) applied to clinical use mainly in western countries, such as the da-Vinci (Intuitive Surgical Inc. ,CA) [8] , [9] and Zeus systems(Computer Motion Inc. ,CA), which have been fairly well appraised by clinicians. These systems consist of mainly two parts:

- Master control console
- Robotic apparatus with several manipulator arms that hold several surgical tools and endoscope.

Master control consol or master manipulator [10] is operated by surgeon’s hands to transmit hand movements to the end effector. Control system consists of microprocessors and electrical arrangement to convert the hand movements imparted by hand’s to the wrist attached at the end of the tool. Surgical tool or Slave manipulator [10], a detachable tool carry deflectable instrument tip can moves inside the body, having a driving mechanism located outside the patient body.

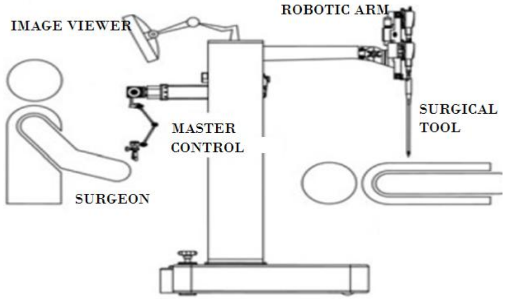

Figure 1: MIS robot system

This tool is mounted on robotic platform. This deflectable tool thus performs the function like wrist of surgeon. For various functions number of attachment can use at the end of tool for e.g. tweezers, scissors, forceps, and needles.

Advantages of MIS

1. Remote surgery can do through robotic assisted MIS. It can use to diffuse bombs, treating patient in battlefield directly.

2. Three-dimensional (3D) image display

3. Reduce the surgical time, ergonomically better than conventional surgery, shorter recovery times, and reduced trauma to healthy tissue

4. High degree of precision and dexterity can achieve.

Limitations of MIS

1. The system developed so far is complex, costlier and requires lot of training to operate.

2. Another problem is that the endoscope is operated by a surgical assistant. This requires the surgeon to communicate motion instructions which becomes difficult when giving instructions such as how far to move the endoscope and in which direction, can cause nausea among the surgical team.

3. Requirement and Design Capability

The goal of the design is to add a two DOF wrist to extend the four DOF , and therefore give enough dexterity to perform complex skills, especially suturing knot typing.teh slave manipulator must be small enough to fit through incisions typically 10 mm wide, but also able to apply forces large enough to manipulate tissue and suture. It must have sufficient workspace to span significant regions in the abdominal cavity and suture at almost arbitrary orientations, yet have a wrist short enough in length to work in constrained spaces.

Performance goals in the design of the tool are given in the Table 1. These values are estimated for a suturing task, force and movement requirements for driving a needle through tissues. The diameter of the instruments is chosen to fit the standard 10 and 15 mm diameter trocars. It is preferable not have larger diameters as it causes greater damage to healthy tissue.

Table 1: Performance specifications of the prototype

Parameter	**Value**
Dimension: overall diameter	10-15 mm
Gripping force for holding the needle (Clamping force perpendicular to the surfaces of jaws)	5N
Force at the tip of the needle to perform the thrust (force needed to drive the needle to perform the thrust)	1.5N min.
Range of motion: roll motion	360 degrees
Range of motion: pitch motion	120-180 degrees
Range of motion: yaw motion	100-160 degrees
Range of motion: Angle of gripper jaw opening	90 degrees min.

4. Concept Design

Through this paper we have suggested to design a prototype of the detachable surgical tool having end effector with 4 DOF's which are rolling, pitching, open grip and close grip.

The proposed concept of the detachable tool design is shown below (see figure 2). It is divided mainly in three parts:

1. Box (base and cover plate)
2. Hollow cylindrical rod called rolling pipe
3. Endo-wrist or end effector of the surgical tool

Box (black colored in figure 2) contains shaft pulley arrangement and provides mechanical interfacing with master control consol system which is control by surgeon hands movements. Rolling pipe (fig: 2) provides a path for cables, it is link between box and end effector. Endo-wrist with gripper in circle (fig: 2) is main part of surgical tool it perform the actual task in surgery, we can attached different attachment like forceps, scissors, grasper etc according to operational requirement. The surgical tool is designed and simulated with the help of computer software Autodesk Inventor.

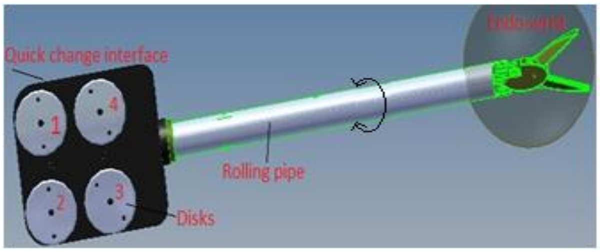

Figure2: Concept design

5. Working of Surgical Tool and performance specification

End effector driven with the help of the servo mechanism (D.C. servomotors) and cables. Motors coupled with pulley shafts (figure 3), cable used to transmit motion from pulley shaft to end effector. Four disks (see fig. 2) coupled with four individual motor. Four motors used to control four different motion of end effector.

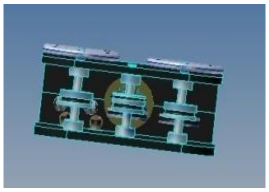

Figure 3: Pulley shaft arrangement

The actuation is carried out with the help of tendons or cable made up of fiber like spectra fiber, which are pivoted between the joints and driving shafts and thus providing maximum amount of strength and preventing any backlash and inaccuracy at the tip of the end-effector.

5.1 Gripping, Pitching and Rolling Motion

Disk 1 and disk 2 (see fig: 2) use to drive the grasper. Cable passed through multiple pulleys to transmit motion. Strong gripping forces are to be generated. For this increase wire tension (fig: 4 pulley used in rolling pipe and housing wrist). Gripper moves in opposite direction with respect to corresponding disk movement.

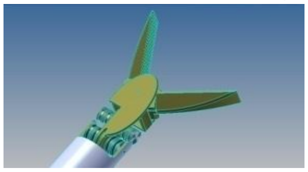

Fig: 4 Open grip of wrist

Disk 3 (see fig: 2) use to pitch motion of endo-wrist about wrist and rolling pipe axis. Disk 4 use to rotate the rolling pipe and endo-wrist with respect to box (see fig: 2). Performance specification of prototype based on the design made on designing software Inventor comes out as shown below in the Table 2.

Table 2: Performance goals for our prototype detachable tool

Parameter	Value
Dimension: Shaft diameter	14.5mm
Gripping force for holding the needle (Clamping force perpendicular to the surfaces of jaws)	5.5N
Force at the tip of the needle to perform the thrust(force needed to drive the needle to perform the thrust)	2.5N
Range of motion: roll motion	340 degree max.
Range of motion: pitch motion	±90 degree
Range of motion: yaw motion	±90 degree
Angle of gripper jaw opening	90-180 degree

6. Kinematic Design

A kinematic model of surgical tool is shown in Figure 5. The base frame {0} is located at the base plate. Frame {1} and {2} at the end of rolling pipe. Frame {3} is located at the wrist of surgical tool. Frame {4} is located on the tip of the end effector

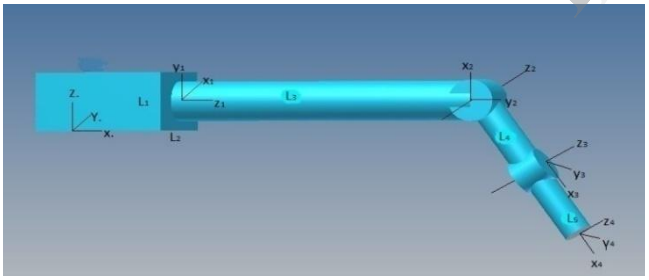

Figure 5: Co-ordinate frames

6.1 Denavit-Hartenberg Parameters

The Denavit-Hartenberg parameters defining the robot are shown in Table 3. Parameters L_1, L_2, L_3, L_4 and L_5 are constants defining the link lengths. L_1 height of the box and equal to 13.5 mm. L_2 is the half width of the base plate or box and is equal to 33 mm. L_3 is the length of the rolling pipe and is equal to 200 mm. L_4 is the length of the wrist housing and is equal to 30 mm. L_5 is the length of grasper and is equal to 35 mm.

Rolling pipe angle (θ_1), housing pitch (θ_2), elbow yaw (θ_3), and end effector rotation (θ_4) define rotations of the robot with respect to intermediate frames of reference. Working joint ranges are also given.

Table 3: DH parameters of the prototype tool

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	90^0	L_2	L_1	Θ_1
2	90^0	0	L_3	Θ_2
3	-90^0	L_4	0	Θ_3
4	0	L_5	0	Θ_4

6.2 Forward Kinematics

Forward kinematics is used to determine the orientation and position of the end effector, given the joint angles and link lengths of the robot arm. The forward position kinematics (FPK) solves the following problem: "Given the joint positions, what is the corresponding end effector's position?" In the serial chains, the solution is always unique: one given joint position vector always corresponds to only one single end effector position.

To obtain kinematics equation [11] of mechanism we need parameters to describe the link itself and connection between the links. The link parameters [11] are a_{i-1} (which is the length of the link) and α_{i-1} (which is the angle between joint axis of the link or link twist) and the parameters describing the relation between the connections of two links are d_i (link offset) and θ_i (joint angle). The Denavit-Hartenberg parameters can then be used to construct the transformation matrices that define frame $\{i\}$ relative to frame $\{i\text{-}1\}$. This transformation is a function of the four link parameters listed in the Denavit-Hartenberg parameters. The general form of this transformation is shown in Equation matrix below.

$$ {}^{i\text{-}1}{}_{i}T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Where (${}^{i-1}T_i$) represents the homogeneous transformation matrix from the i^{th} frame to the $(i\text{-}1)^{th}$ frame on the user interface side. By pre-multiplying the homogeneous transformation matrices for successive coordinate transformations, we use the transformation matrix for the end-effector as seen in the base frame, namely (${}^0T_4 = {}^0T_1\, {}^1T_2\, {}^2T_3\, {}^3T_4$). Utilizing the general form of the transformation matrix results in:

$$ {}^{0}T_{1} = \begin{pmatrix} C\theta_1 & -S\theta_1 & 0 & L_2(33) \\ 0 & 0 & -1 & L_1(-13.5) \\ S\theta_1 & C\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad {}^{1}T_{2} = \begin{pmatrix} C\theta_2 & -S\theta_2 & 0 & 0 \\ 0 & 0 & -1 & L_3(-200) \\ S\theta_2 & C\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

$$ {}^{2}T_{3} = \begin{pmatrix} C\theta_3 & -S\theta_3 & 0 & L_4(30) \\ 0 & 0 & 1 & 0 \\ -S\theta_3 & -C\theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad {}^{3}T_{4} = \begin{pmatrix} C\theta_4 & -S\theta_4 & 0 & L_5(35) \\ S\theta_4 & C\theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} $$

Based on the general definition of the homogeneous transformation matrix given by:

$$ T = \begin{bmatrix} R_{11} & R_{12} & R_{13} & d_1 \\ R_{21} & R_{22} & R_{23} & d_2 \\ R_{31} & R_{32} & R_{33} & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

After the frame transformations are found, they can be concatenated to find a single transformation that relates the end effector frame to the base frame. The Cartesian coordinates of the end effector with respect to the base frame can then be extracted from the transformation matrix to give the forward kinematics of the robot.

We can obtain the displacement vector, D = [d_1, d_2, d_3]^T for the location of the end effector in the base coordinate frame. As a result:

$$ D = \begin{pmatrix} 35\,(c_1\, c_2\, c_3 - s_1\, s_3) + 30c_1\, c_2 + 200s_1 + 33 \\ -35\, c_3\, s_2 - 30\, s_2 - 13.5 \\ 35\,(c_1\, c_2\, c_3 - s_1\, s_3) + 30c_2\, s_1 - 200c_1 \end{pmatrix} $$

7. Workspace Estimation

We developed an algorithm to determine this volume to verify the reachable workspace of the haptic device was sufficient for the range of motion in MIS procedures.

In order to determine the workspace, we started with analyzing the workspaces of the user interface. We approached this analysis by developing Mat lab code using the kinematics to track the end effector position in the global coordinate frame. During this process, each joint is tracked through its full range of motion and results in an array of points within the workspace of the given mechanism. Fig 6.a show the workspace with respect to the global coordinate frame. Next, we take the cross-section (figure 6.b) of the reachable workspace of endo-wrist. This is achieved by taking the boundary of the spatial mechanism's workspace and finding all the points from the user interface's workspace that are within this boundary. This reachable workspace represents an estimated volume of 0.0005 cubic meters. An algorithm was developed for volume estimation that discretizes the achievable workspace and determines which 3D elements are located in the workspace.

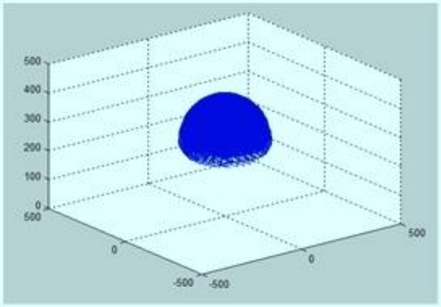

Figure 6(a) Workspace

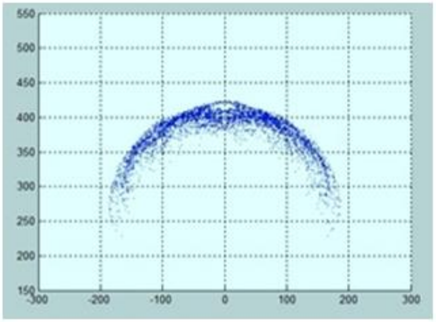

Figure 6(b) Cross section of workspace

8. Conclusion

We discussed a design idea for developing a hybrid actuator, as a local actuation system. We developed a prototype to test the feasibility of the design idea and tested it to determine the amount of gripping force generated.

This study addressed various aspects of MIS. We first introduced MIS system designed considering the special requirements of minimally invasive surgery, followed by its kinematic analysis, control, and experimental evaluation. A flexible endo-wrist with 2-DOF and a stroke of 180º (± 90º) has been developed. A prototype of the system was developed taking into account the functional requirements for general laparoscopy. Based on the parameters of the prototype, a workspace find out. A control scheme to actuate the combined motion was presented. From the experimental results, the system was determined to have sufficient response characteristics at each joint. A 4-DOF laparoscopic system provides a sufficient workspace to perform general laparoscopic surgeries. In comparison with other systems, the proposed system involves less external motion due to the use of endo-wrist mechanism. Thus, it is expected to lower the potential for interference with the surgeon or the patient. Moreover, the system can be mounted onto a bed and is compatible with existing surgical environments.

9. Future Development

Most importantly for the future of the project, a prototype representation of the design must be constructed than maturing the system. Successful completion of one-way teleoperation control of the surgical manipulator is the first step toward a fully functioning, haptically enabled surgical robot system. The possibility of including a pressure sensor or tectile sensors to alert the surgeon as to the amount of pressure translating from his grip to the tissue surface. Adding a sensor would be relatively easy for an actual-size prototype provided the pressure sensor is small enough to be housed between the wavy outer tissue gripping edges of each gripping member.

Acknowledgement

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