# Kinematic and Dynamic Analysis of A Surgical Tool Manipulator Towards Robotic Surgery

Sanjeev Soni, Kuldeep Singh, Sanjeev Verma, Dinesh Pankaj, Amod Kumar
Biomedical Instrumentation
CSIR-Central Scientific Instruments Organisation
Chandigarh, India
ssoni@csio.res.in; kuldeepsingh055@yahoo.co.in; sanjeev44in@yahoo.co.in; dineshpankaj@yahoo.co.in; csioamod@yahoo.com

***Abstract*— Robotic surgery reduces the amount of tissues that are damaged during a surgical procedure, thereby reducing the patient recovery time, discomfort and deleterious side effect such as infection. In this article, kinematic and dynamic analysis of a surgical tool manipulator is carried out to perform the desired range of motions for a typical minimal invasive surgical operation. The manipulator having 3 DOF is driven by D.C. servomotors and motion is transmitted through wires/cables pivoted to driving shaft at one end and to the gripper on the other end. Kinematics analysis is done by utilizing the D-H parameters as well as through ADAMS software. The position, orientation and workspace of gripper (end-effector) are calculated analytically using D-H parameters and transformation matrix.**

***Keywords*— Minimal invasive surgery; Robotics; Surgical Tool Manipulator; Kinematics; Workspace***

## I. INTRODUCTION

Robotics is being introduced to medical sciences as it allows for unprecedented control and precision of surgical instruments as well as minimal access port area through human body, thus making it suitable for minimally invasive surgery (MIS) procedures [1, 2]. In MIS, the surgery is performed with instruments/tools along with viewing equipment inserted into the body through small incisions instead of large incisions/cuts made as in the case of conventional surgeries. MIS thus involves use of special surgical tool/instruments with an observation of surgical field through an endoscope. The tool is of 8-12 mm in diameter which is inserted through trocar. Trocar is a cylindrical tube with pointed end for easy insertion and also serves as a constraint for the placement of the surgical tool with respect to the patient's body. Advantages of MIS are better operational inaccuracy due to compensation of tremors, shorter operation time and less fatigue to the surgeons. This also has advantages to the patient like reduced surgical trauma and damage of healthy tissues thus shorter recovery time. Robot assisted MIS is used in operation such as laparoscopy [3, 4], removal of gall-bladder, naval surgery, cardiac surgery [5] and neurosurgery [6].

At present there are several surgical manipulators applied to clinical use such as the *Da-Vinci* (Intuitive Surgical Inc. CA) and *Zeus* systems (Computer Motion Inc. CA) [7, 8], which have been fairly well appraised by clinicians for good manoeuvrability through dextrous manipulators. A typical MIS system consists of four major subsystems [2],

a) Master manipulator
b) control system
c) Slave manipulator or surgical tool manipulator
d) Endoscope

Master manipulator is a type of link system which is operated by surgeon to manipulate, scale and transmit motion to a surgical tool attached to the slave manipulator. Control system consists of microprocessors and electrical arrangement to convert/scale the hand movements (imparted by master manipulator) and transmit the driving signals to the slave manipulator. Slave manipulator, having a driving mechanism located outside the body, imparts motion to a surgical tool which moves inside the body at the surgical site. The surgical tool is mounted on a gross positioning stage or structure which is located outside the body and is responsible for locating the surgical tool with respect to the patient's position. The surgical tool enters the body through a small incision and should have 3 - 6 DOF so that it can effectively move inside the working space. Some motions which the tool has to undergo are rotation or roll, pitch, yaw and translation. This surgical tool attached to the slave manipulator thus performs the functions likewise performed by the wrist of a surgeon. A variety of tools can be attached e.g. tweezers, scissors, forceps, and needles etc to perform various functions at the surgical site. The other part, endoscope provides 3D images of the surgical site so as to provide the surgeon with a real working environment, which can be seen on a monitor.

The robot assisted MIS systems, in practice so far, are costlier, bulky and require lots of training to perform the surgery. The onsite requirement of the assistants to the surgeons is also a limitation. Generally 3 - 4 attendants are required. The drive system and mechanisms used to obtain motions of the surgical tool is also complex with lots of mechanisms and drive wires incorporated in it, thus making the construction of the instrument a bit difficult. In some devices torque tubes, bellows, shape memory alloys and cables are used to achieve the required motions. Metal strings have been widely used for the transmission of motion from one location to the other.

In this article, kinematic and dynamic analysis of a design concept for a surgical tool manipulator having 3 DOF, driven by D.C. servomotors and motion transmitted through wires/cables pivoted to driving shaft at one end and to the surgical tool on the other end. This helps in providing an easy and effective way of controlling the surgical tool, which the surgeon operates through his hands by providing motions through master manipulators. The movements are scaled and transmitted through independent motors.

This paper shows kinematic and dynamic analysis of a surgical tool manipulator having 3 DOF viz. Roll, pitch and yaw. The actuation/transmission was carried out with the help of cables/wires made up of fibre/steel which are pivoted between the joints and driving shafts. Thus may provide considerable strength and minimal backlash and hence better accuracy at the surgical site.

## II. MATERIAL AND METHODS

Fig. 1 shows the details of surgical tool manipulator (STM) with grasper at one end and driving mechanism at the other end. The STM shaft enters inside the body and performs the required operations. The STM was modeled with the help of CATIA and Inventor. The 3D model was imported to ADAMS to carry out the kinematics and dynamics analysis. The STM consists of a housing base plate and cover plate (both yellow in color) which form a support for the backend mechanism. A long and hollow cylindrical tube called 'rolling tube' is assembled with backend mechanism, as shown in Fig. 1, through which wires/cables pass to transmit desired motions i.e. pitch, yaw and gripper effect. The rolling motion is provided to the 'rolling tube' with the help of one of the driving shaft.

The driving shafts are mounted between the base plate and cover plate and motion is transmitted through cables/wires like spectra fiber or titanium etc. These are attached to the driving shafts at one end and to the corresponding joints at the other end. There are four motions through the individual driving shafts i-e roll, pitch, yaw and gripping. These driving shafts are coupled to motors which are assembled on the robot platform with the help of suitable couplings. The gripper motion (open/close) is actuated with the help of a wire and spring. The wire is attached to the sliding part which translates in the gripper housing and helps in converting the translation motion into the angular motion of the grippers about their respective pivot point. The wire when pulled towards back/front end, causes closure of the gripper.

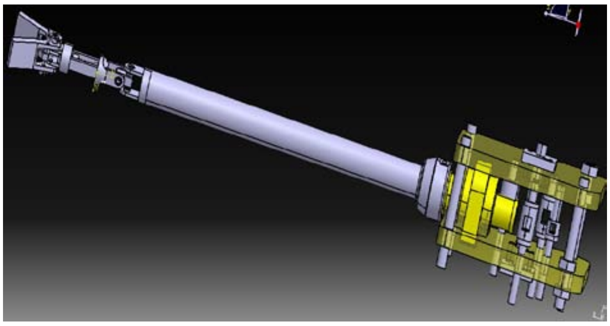

Fig. 1. 3D model of the surgical tool manipulator.

## III. KINEMATIC ANALYSIS

Fig. 2 shows kinematic synthesis of STM mechanism. In this schematic, the z-axis of each frame was aligned with the axis of rotation. Denavit-Hartenberg (DH) parameters [7, 12, 13] were assigned to the mechanism joints in order to specify the position and orientation of the gripper. These parameters describe the link itself as well as the connection between links. The parameters are $a_{i-1}$ (link length) and $\alpha_{i-1}$ (angle between joint axes of a link or link twist). The parameters describing the relation between the connections of two links are $d_i$ (link offset) and $\theta_i$ (joint angle) [13]. To describe the location of each link relative to its neighbours, a frame is attached to each link i-e frame {i} is attached to link i. For assigning the frames to each link/joint, a convention [13] is followed as described below. The $Z_i$ axis of the frame {i}, called $Z_i$, is coincident with the joint axis i. The origin of frame {i} is located where the $a_i$ perpendicular intersects the joint i axis. $X_i$ point along $a_i$ in the direction from joint i to joint i+1.

In case of $a_i$ =0, Xi is normal to the plane of $Z_i$ and $Z_{i+1}$.

$\mathbf{a_{i-1}}$ = the distance from $Z_{i-1}$ to $Z_i$ measured along $X_{i-1}$.

$\boldsymbol{\alpha_{i-1}}$ = the angle from $Z_{i-1}$ to $Z_i$ measured about $X_{i-1}$.

$\mathbf{d_i}$= the distance from $X_{i-1}$ to $X_i$ measured along $Z_i$.

$\boldsymbol{\theta_i}$= the angle from $X_{i-1}$ to $X_i$ measured about $Z_i$.

The D-H parameters are used to construct the transformation matrices that define frame {i} relative to frame {i-1}. The general form of this transformation [13] is,

$$
{}^{i-1}T_i = \begin{pmatrix} c\theta_i & -s\theta_i & 0 & \alpha_{i-1} \\ s\theta_i\, c\alpha_{i-1} & c\theta_i\, c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}\, d_i \\ s\theta_i\, s\alpha_{i-1} & c\theta_i\, s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}\, d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

The reference frames [8, 12] are assigned to STM mechanism as shown in Fig. 3. The z axis passes through the centre of each joint. The base frame (base plate) is represented as ($X_o$ $Y_0$ $Z_0$), the joint between base plate and rolling pipe has a frame represented by ($X_1$ $Y_1$ $Z_1$), the joint between rolling pipe and universal joint has a frame represented by ($X_2$ $Y_2$ $Z_2$), the joint between universal joint and gripper housing is represented by ($X_3$ $Y_3$ $Z_3$) and the end-effector frame (frame assigned to the gripper end) is represented by ($X_4$ $Y_4$ $Z_4$).

The transformation matrix [13, 14] relating the end-effector and the base frame is given by,

$$
{}^{i-1}T_i = \begin{pmatrix} R_{11} & R_{12} & R_{13} & P_x \\ R_{21} & R_{22} & R_{23} & P_y \\ R_{31} & R_{32} & R_{33} & P_z \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

Where,

$R_{11} = (C_1C_2C_3 + S_1S_3)$

$R_{21} = -S_2C_3$

$R_{31} = S_1C_2C_3-C_1S_3$

$R_{12} = -C_1C_2S_3+S_1C_3$

$R_{22} = S_2S_3$

$R_{32} = -S_1C_2S_3-C_1C_3$

$R_{13} = C_1S_2$

$R_{23} =C_2$

$R_{33} =S_1S_2$

$P_x = (C_1C_2C_3+S_1S_3)\ L_4+C_1C_2L_3-S_1L_2$

$P_y= -S_2C_3L_4-S_2L_3-L_1$

$P_z = (S_1C_2C_3-C_1S_3)\ L_4+S_1C_2L_3-L_2C_1$

Required performance specifications of a typical MIS manipulator are summarized in Table I. These values are estimated for the suturing task i-e force and movement requirements for driving the needle through tissue [9-11].

TABLE I. Required performance specifications for a typical suturing task

| **Parameters** | **Value** |
|---|---|
| Shaft diameter | 10 mm |
| Gripping force for holding the needle | 8 N |
| Force at the tip of the needle to perform thrust (force needed to drive the needle) | 3 N |
| Range of ROLL motion | ±360º |
| Range of PITCH motion | ±45º |
| Range of YAW motion | ±45º |
| Angle of gripper jaw opening | 45º |
| Torque for orienting the needle | 100 Nmm |
| Speed of roll motion | 540 º/s (min.) |
| Speed of pitch and yaw motion | 360 º/s (min.) |

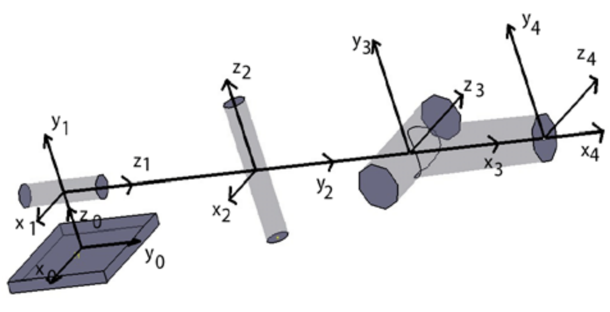


Fig. 2. Kinematic synthesis and D-H representation of STM.

## IV. RESULTS AND DISCUSSION

*Kinematic Analysis:*

The D-H parameters for STM configuration were calculated and are listed in Table II.

TABLE II. D-H parameters of the surgical tool manipulator

| ***i*** | $\alpha_{i-1}$ | $a_{i-1}$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| 1 | -90° | 0 | $d_1$ ($L_1$) | $\theta_1$ |
| 2 | 90° | 0 | $d_2$ ($L_2$) | $\theta_2$ |
| 3 | 90° | $a_2$ ($L_3$) | 0 | $\theta_3$ |
| 4 | 0° | $a_3$($L_4$) | 0 | $\theta_4$ |

Where,

$\theta_1$ = rotation angle about roll axis (or rolling tube).

$\theta_2$= rotation angle about 1st axis (or pitch axis) of universal joint.

$\theta_3$= rotation angle about 2nd axis (or yaw axis) of universal joint.

$\theta_4$ = angle made by gripper with respect to base frame.

$d_1$ ($L_1$ = offset between frame 0 and 1) =21 mm.

$d_2$ ($L_2$ = offset between frame 1 and 2) =201 mm.

$a_2$ ($L_3$ = link length of universal joint) =5 mm.

$a_3$ ($L_4$ = link length from yaw axis to gripper) =37 mm.

Using DH parameters defined in Table II and the general form of transformation matrix as mentioned before, the forward kinematics was solved as described below to obtain the position (X, Y, Z) of the gripper.

$$^0T_1 = \begin{pmatrix} C_1 & -S_1 & 0 & 0 \\ 0 & 0 & -1 & -L_1 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$^1T_2 = \begin{pmatrix} C_2 & -S_2 & 0 & 0 \\ 0 & 0 & -1 & -L_2 \\ S_2 & C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$^2T_3 = \begin{pmatrix} C_3 & -S_3 & 0 & L_3 \\ 0 & 0 & -1 & -L_2 \\ S_3 & C_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$
{}^{3}T_{4} = \begin{pmatrix} C_4 & -S_4 & 0 & L_4 \\ S_4 & C_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}
$$

Once the frame transformations were obtained, these are concatenated to get a single transformation that relates the gripper's frame to the base frame. The Cartesian coordinates of the gripper w.r.t. the base frame were extracted from the transformation matrix to give the forward kinematics of the STM. The forward kinematics equations obtained are,

$$X = 37C_1C_2C_3+37S_1S_3+5C_1C_2-201S_1$$

$$Y = -37S_2C_3-5S_2-21$$

$$Z = 37S_1C_2C_3-37C_1S_3+5S_1C_2-201C_1$$

Based on these forward kinematic equations, the workspace of the STM was calculated and is shown in Fig. 3. For the calculation of workspace, the roll, pitch and yaw angles values of 180° are considered.

The position (X, Y, Z) of STM gripper calculated through ADAMS software is shown in the Fig. 4. The corresponding velocity and acceleration plots are shown in Fig. 5.

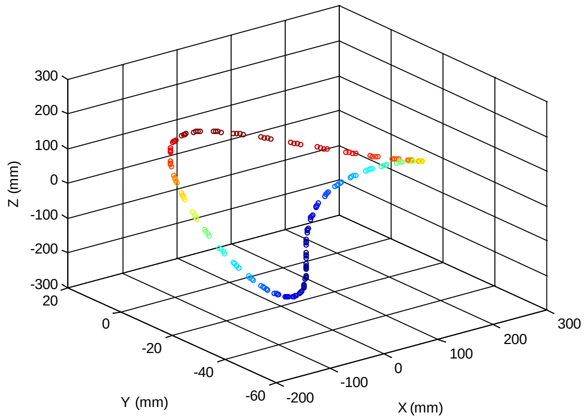


Fig. 3. Workspace of the STM gripper.

*Dynamic Analysis:*

The dynamic analysis is carried out using ADAMS software. The friction at the joints is neglected at the present but the results incorporating this will be available at the time of oral presentation. Also, the motor/actuator mass and its dynamics were not applicable for this configuration as all the motors are located at the one end away from the joints. Fig. 6 shows the plot of torque required at the roll, pitch and yaw joints of STM for a given trajectory.

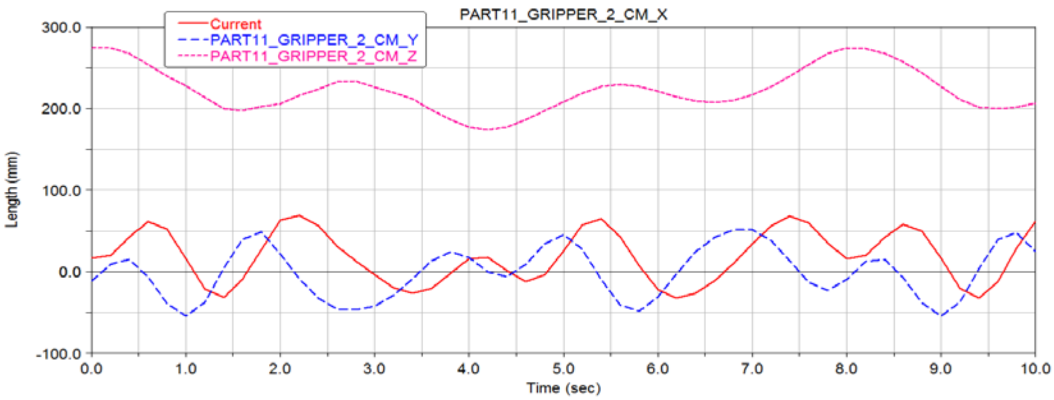


Fig. 4. The position of center of mass of the gripper obtained through ADAMS software.

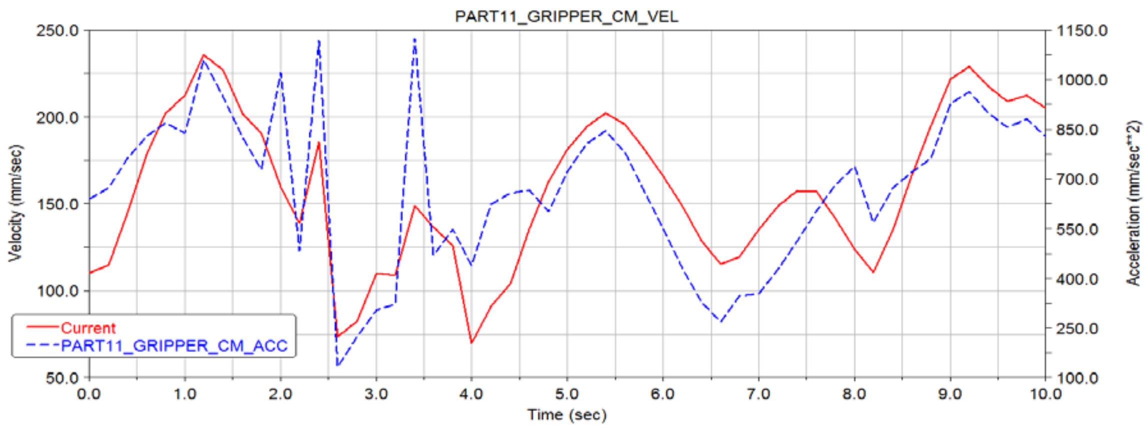


Fig. 5. The velocity and acceleration of center of mass of the STM gripper.

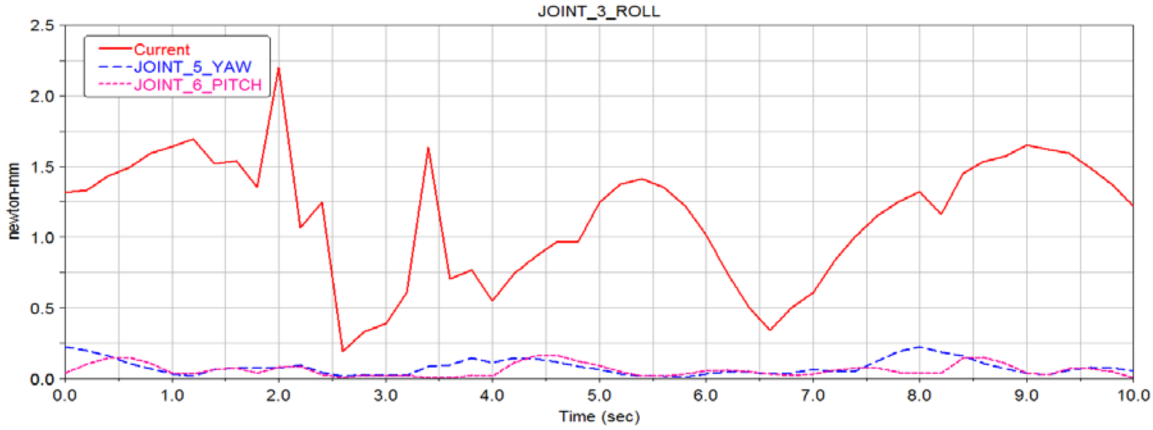


Fig. 6. Torque required at the roll, pitch and yaw joints of STM for a given trajectory.

## V. CONCLUSIONS

A surgical tool manipulator with 3 DOF is proposed and its 3D model was developed. The kinematic and dynamic analysis is carried out using ADAMS software. The position and orientation of gripper (end effector) is also calculated analytically using D-H parameters and transformation matrix. The workspace of STM is also analyzed.

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