Design and Analysis of Minimally Invasive Surgical Robot

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Abstract. Minimally Invasive Surgical robots are commonly seen in medical centres for surgical purposes. However, the major challenges seen with such robotic systems are its heavy weight, costly and lack of capability to reconfigure according to the patient-specific needs. In this paper, a robot is proposed to overcome the difficulties with existing robotic systems. Six different concepts are proposed in this paper which are modelled in SolidWorks software. The best design has been selected using the concept scoring technique. Besides, the forward and inverse kinematics for the best concept is achieved using the Denavit-Hartenberg (D-H) modelling technique. Finally, results obtained from the analytical model has been verified using Peter Corke Toolbox in MATLAB. The trajectory planning of the selected concept has been done using the third-order polynomial equation and it is plotted using MATLAB.

1. Introduction
In recent years, Minimally Invasive Surgery (MIS) is extensively seen in practice for performing different medical procedures [1]. This is because of its several advantages compared to the other traditional open surgical procedures. In traditional open surgeries, the surgeon has to make larger incisions to have a clear view of the internal organ. These incisions can be a reason for the heavy blood loss in patients. This may lead to increased recovery time and infections for the patient. Unlike Open Surgery, MIS will require smaller incisions of less than 10mm. Following this, the surgeons have to insert visual devices along with the instrument from the incision to have a clear view of organ to be operated [1]. For some of the complicated surgeries, it is difficult to perform MIS due to some limitations like (1) restricted DOFs of the instrument, (2) surgeon fatigue, (3) hand-eye incoordination and (4) long learning curve.

In order to overcome the limitations with present surgical devices, robotic system has been introduced into the field of surgery. In 1985, Shao et al. used an industrial robot for performing a neurosurgical biopsy which was the first of its kind [2, 3]. Many further developments are done to design various surgical robots. Most of the surgical robots follow master-slave relationship in which surgeon operates master manipulator sitting at the work console and visualizing the operation on the video screen. In the surgical scene, there will be two human-robot interfaces established namely Surgeon-robot interface and Patient-robot interface [4]. The robot-assisted surgery has advantages like (1) instruments used are dexterous, (2) operation performed is more precise, (3) improved hand-eye coordination and (4) reduced surgeon fatigue.

The most effective way of improving the dexterity of MIS is to design instruments with additional DOFs. One kind of the dexterous surgical device is Da Vinci surgical system by Intuitive Surgical Inc. which is a 6 DOFs robot with intuitive control and is more useful for performing complicated and delicate operations. It is also the most successful and commercially available robot-assisted surgical system [5]. There are certain
drawbacks of this system like (1) lack of capability to reconfigure according to the different procedures, (2) requires large workspace and (3) high cost. Due to the above factors, robot-assisted MIS has limited patient base.

Recently many slave manipulators are designed suitable to satisfy the surgical needs and suitable master manipulator is being proposed ergonomically. Establishing the control between the master and slave manipulators is the most challenging part in surgical robots. The master-slave real-time control strategy for a novel surgical robot had been adopted for solving problems of intra-operative re-mapping and kinematic transformations using consistency principle [6]. An integrated MIS robotic system was proposed and a modular design for the control system was adopted. The kinematic relations were established between the master and slave manipulators and were tested using software [7]. A tele-matched surgical robot with tendon mechanism for precise force reflection and stable, intuitive operation had been developed. A torque estimation scheme instead of physical sensors was used to estimate the external forces [8].

Some surgical procedures require two or more surgeons and additional staff like nurses. The surgical robots with multi-arms have been introduced for supporting the collaborative operation of multiple surgeons. A system resembling the Raven IV system with two robotic arms had been developed. The manipulation dexterity and common workspace of each robotic arm was optimised [9]. A master-slave robotic system with two symmetric arms was developed. The kinematic computation, shape optimization algorithm and collision avoidance algorithm for the robotic arms were constructed [10].

The surgical tools used should be more dexterous to perform the operation precisely and cost effective so that they can be available easily. A reconfigurable, partially disposable and tendon-driven robotic arm was designed for providing assistance in laparoscopic surgery [11]. A small MIS robot had been designed with disposable components to reduce the cost. Modularity for the link geometry were considered to increase the flexibility to adapt the patient-specific needs [12]. A novel and dexterous robotic surgical tool for trans-gastric natural orifice surgery was designed using 3D valve, hydraulic artificial muscles and multi-segmented flexible manipulator arms [13]. A novel miniaturized cable-actuated multi-steerable tip was developed which navigates through the complex curves. Bending stiffness and the ability of the tip to form complex shapes was also tested [14]. Nevertheless, all surgical robots are not tele-operated. A modular hand-held and dexterous surgical robot with interchangeable instruments was developed. Connection between the handle and instrument was established and tested [15].

Therefore, it is necessary to have an adaptive and inexpensive design for MIS which can overcome the inherent shortcomings of presently available robotic systems. The design of a robot for MIS with reduced cost and increase flexibility to adapt different procedures and patient specific needs has been presented in this paper. This paper discusses about the design of the surgical robot for minimally invasive surgery, kinematic modelling with forward kinematics using D-H parameters and inverse kinematics of the robot in the following sections.

2. Conceptual Designs for Surgical Robot

This section explains six different conceptual designs whose CAD models were developed in SolidWorks software. All the proposed concepts have six DOFs with three DOFs for positioning and three active joints for operation. The active joints are designed to have the roll, pitch and yaw (RPY) motions. Fig. 1 shows the first conceptual design. It has two prismatic and one revolute joints for positioning. Fig. 2 depicts the second conceptual design. It is basically a Cartesian robot with three prismatic joints. Fig. 3 displays the third conceptual design which comprises of two prismatic and one revolute joints. Fig. 4 presents the fourth conceptual design which has two prismatic and one revolute joints with a different arrangement compared to the first concept. Fig. 5 displays the fifth conceptual design, which also has three prismatic joints configured differently compared to second concept. Similarly, fig. 6 shows the last conceptual design with two prismatic and one revolute joints.
Figure 1. Conceptual Design 1

Figure 2. Conceptual Design 2

Figure 3. Conceptual Design 3
3. Concept Scoring
This section explains the conceptual scoring for all the designs shown in the previous section by considering the important characteristics necessary for medical robots. The scoring has been done depending upon the importance of the characteristics and the corresponding rating of the design. The
desired characteristics weightage is expressed in percentage and the corresponding rating of each
design is scored out of five, as shown in table 1.

| Characteristics     | Weightage | Design 1 | Design 2 | Design 3 | Design 4 | Design 5 | Design 6 |
|---------------------|-----------|----------|----------|----------|----------|----------|----------|
|                     |           | R | S | R | S | R | S | R | S | R | S | R | S |
| Precision           | 20%       | 3 | 0.6 | 5 | 1 | 4 | 0.8 | 3 | 0.6 | 3 | 0.6 | 5 | 1 |
| Cost                | 20%       | 4 | 0.8 | 5 | 1 | 5 | 1 | 4 | 0.8 | 4 | 0.8 | 5 | 1 |
| Manufacturability   | 25%       | 3 | 0.75 | 4 | 1 | 5 | 1.25 | 3 | 0.75 | 3 | 0.75 | 5 | 1.25 |
| Weight              | 10%       | 3 | 0.3 | 5 | 0.5 | 5 | 0.5 | 3 | 0.3 | 3 | 0.3 | 4 | 0.4 |
| Reach               | 5%        | 5 | 0.25 | 4 | 0.2 | 4 | 0.2 | 5 | 0.25 | 5 | 0.25 | 5 | 0.25 |
| DOF                 | 10%       | 5 | 0.5 | 5 | 0.5 | 5 | 0.5 | 5 | 0.5 | 5 | 0.5 | 5 | 0.5 |
| Ease of control     | 5%        | 5 | 0.25 | 4 | 0.2 | 5 | 0.25 | 5 | 0.25 | 4 | 0.2 | 5 | 0.25 |
| Ease of use         | 5%        | 4 | 0.2 | 3 | 0.15 | 4 | 0.2 | 4 | 0.2 | 4 | 0.2 | 4 | 0.2 |
| **TOTAL**           |           | 3.65 | 4.55 | 4.7 | 3.65 | 3.6 | 4.85 |
| **RANK**            |           | 4  | 3  | 2  | 4  | 6  | 1  |

Where R is rating and S is weighted score.

Fig. 1, fig. 4 and fig. 5 resemble the model of a SCARA robot. The main disadvantage of these
models are reduced precision and high deflection since it acts more like a cantilever beam. Due to
these reasons, the concepts 1, 4 and 5 scores less compared to concepts 2, 3 and 6. However, the major
drawback with concepts 2 and 3 designs is its manufacturing difficulty as they need to be welded to
the patient bed. Therefore, sixth concept qualifies to be the best of the six concepts considered in this
paper. This can be confirmed from the maximum score of the concept 6 compared to the other
concepts as is evident from table 1. As shown in the fig. 6, the prismatic joint attached to the frame
allows to have reach all over the patient bed. The frame is designed in such a way that the patient bed
can be moved flexibly. Each link is connected using cables and the motion of every joint is given by
using servomotors.

4. Kinematic Modelling

4.1. Forward Kinematics

The kinematic model has been developed for the considered six DOFs mechanism based on the
Denavit-Hartenberg approach. Fig. 7 shows the frame assignment corresponding to the D-H
convention. Following this, the D-H parameter table is filled as stated by the D-H convention as shown in table 2.

![Figure 7. Frame assignment of the robot](image-url)
Table 2. D-H parameters of robot

| Link | \( \theta \) | \( d \) | \( a \) | \( \alpha \) |
|------|-------------|--------|------|--------|
| 1    | 0           | \( d_1 \) | -155 | 0      |
| 2    | \( \theta_2 + \pi/2 \) | 0 | -50  | \( \pi/2 \) |
| 3    | 0           | -(\( d_3 + 262 \)) | 25   | \(-\pi/2\) |
| 4    | \( \theta_4 \) | 0 | 0    | \( \pi/2 \) |
| 5    | \( \theta_5 + \pi/2 \) | 0 | 0    | \( \pi/2 \) |
| 6    | \( \theta_6 \) | 0 | 0    | 0      |

Then the D-H transformation matrices are filled for all the links as depicted in eq. 1, 2, 3, 4, 5 and 6.

For first link,

\[
T_1^0 = \begin{bmatrix}
1 & 0 & 0 & -a_1 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & d_1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (1)

For second link,

\[
T_2^1 = \begin{bmatrix}
-\sin \theta_2 & 0 & \cos \theta_2 & a_2 \sin \theta_2 \\
\cos \theta_2 & 0 & \sin \theta_2 & -a_2 \cos \theta_2 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (2)

For third link,

\[
T_3^2 = \begin{bmatrix}
1 & 0 & 0 & a_3 \\
0 & 1 & 0 & 0 \\
0 & -1 & 0 & -d_3 - a_3 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (3)

For fourth link,

\[
T_4^3 = \begin{bmatrix}
\cos \theta_4 & 0 & -\sin \theta_4 & 0 \\
\sin \theta_4 & 0 & \cos \theta_4 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (4)

For fifth link,

\[
T_5^4 = \begin{bmatrix}
-\sin \theta_5 & 0 & \cos \theta_5 & 0 \\
\cos \theta_5 & 0 & \sin \theta_5 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5)

For sixth link,

\[
T_6^5 = \begin{bmatrix}
\cos \theta_6 & -\sin \theta_6 & 0 & 0 \\
\sin \theta_6 & \cos \theta_6 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (6)

Where \( a_1 = 155, a_2 = 50, a_3 = 262, a_4 = 25 \)
The final transformation matrix for the robot is obtained from the eq. 7.
\[ T_6 = T_1 T_2 T_3 T_4 T_5 T_6 \]  

(7)

The movements of the robot are analysed in MATLAB corresponding to the D-H parameters mentioned above. The motion of the robot can be analysed by specifying the values of the parameters with code ‘teach’. Fig. 8 displays the posture of the robot for given end effector pose.

4.2. Inverse Kinematics

Inverse kinematics determines the joint variables for a given pose of end effector. Assuming a generalised equation for the end effector pose as given in eq. 8.

\[
X = \begin{bmatrix}
x_n & o_x & a_x & p_x \\
y_n & o_y & a_y & p_y \\
z_n & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(8)

The final transformation matrix defined in eq. 7 is equated with the matrix in eq. 8.

\[
X * T_6^{-1} = T_1 T_2 T_3 T_4 T_5 T_6 \]  

(9)

Therefore, by solving the above equation we can compute all the parameters i.e., \( d_1, \theta_2, d_3, \theta_4, \theta_5, \theta_6 \) as given in eq. 10, 11, 12, 13, 14 and 15.

\[
d_1 = p_z
\]  

(10)

\[
\theta_2 = \tan^{-1}\left[\frac{25p_x + 3875 + (p_x)(\pm a)}{-155 - (p_x)(\pm a) - (25p_y)}\right]
\]  

(11)

Where \( a = \sqrt{(p_x + 155)^2 + p_y^2 - 625)} \)

\[
d_3 = -262 \pm \sqrt{(p_x + 155)^2 + p_y^2 - 625}
\]  

(12)

\[
\theta_4 = \tan^{-1}\left[\frac{-a_x}{a_y}\right] - \theta_2
\]  

(13)

\[
\theta_5 = \tan^{-1}\left[\frac{a_z}{a_x^2 + a_y^2}\right]
\]  

(14)
\[ \theta_6 = \tan^{-1}\left(\frac{-\alpha_2}{n_2}\right) \]  

(15)

5. Trajectory Planning

The series of displacements in the robot with respect to time are analysed using trajectories. It is mainly the trace of the path followed by the end effector. Trajectories of joint variables are defined using the polynomial equation as shown in eq. 16.

\[ \theta(t) = c_0 + c_1 t + c_2 t^2 + \cdots + c_{n-1} t^{n-1} + c_n t^n \]  

(16)

Here \( t \) is the time, \( \theta(t) \) is the joint variable with reference to time, \( c_n \) are the coefficients of \( n \)-order polynomial. In this paper, a cubic polynomial equation is used to determine the trajectory of the end effector as defined in eq. 17. Eq. 18 and eq. 19 defines the velocity and acceleration equations of the joint variables respectively.

\[ \dot{\theta}(t) = c_1 + 2c_2 t + 3c_3 t^2 \]  

(17)

\[ \ddot{\theta}(t) = 2c_2 + 6c_3 t \]  

(18)

\[ \dddot{\theta}(t) = 6c_3 \]  

Using inverse kinematic equations and initial positions and orientations of the robot, the desired final positions and orientations are calculated. The movements of each joint in the robot must be considered separately as a function of time. By considering the necessary conditions, the eq. 17, 18 and 19 can be solved to obtain the constant values. Therefore, the joint positions are computed at different intervals of time. All the joint variable trajectory equations are used together to get the trajectory plot of the end effector. The Cartesian co-ordinates of the end effector are calculated with the help of joint position values and forward kinematic equations. The co-ordinate values obtained are plotted using MATLAB software as shown in fig. 9.

![Figure 9. Trajectory planning](image)

6. Conclusion

This paper focuses on proposing different conceptual designs for the robot-assisted minimally invasive surgery which can be altered according to the patient specific needs. Six different concepts are shown which were modelled using the SolidWorks software. The best concept was chosen based on eight important characteristics that are required for surgical robots using the technique of concept scoring. The forward and inverse kinematics of the selected conceptual design is done using Denavit-Hartenberg modelling technique and the results are finally verified using Peter Corke toolbox in MATLAB software. The trajectory planning of the end effector has been plotted by using third-order polynomial equation. The Cartesian co-ordinate values of the end effector are calculated and plotted using MATLAB software. The scope for future work includes the development of dynamic model for
proposed mechanism, fabrication, implementation of suitable controller and finally performance evaluation.

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