Abstract: Endoscopes have been in use for many procedures including limited surgery. A very common application of endoscopes been used in surgery is biopsy. However present Endoscopes has certain limitations such as restricted degrees of motion of tool leading to poor manipulation of tissues, limited visualization of surgical field, increased sensitivity to hand movement etc. Further reduced access reduces dexterity, limits perception, increases strain and likelihood of error in addition to increased procedural time. Biopsy of internal organ through natural openings involves two basic issues – insertion of biopsy tool and manipulation of tissues by tool. The proposed system will use one of the existing biopsy channels of the endoscopic tube for insertion of robotic arm. Endoscopic tube will be stationed at the end of the esophagus and robotic arm will be anchored in the leading face of the tube. The robotic arm will be actuated by servomotors kept outside the body through wires. The proposed robotic arm shall provide distinctly more degree of freedom and better maneuverability inside the stomach with respect to that of currently used biopsy tool. This will also enable the surgeon to access much greater area inside the stomach. The view of operating zone can also be improved by integrating vision system to the multiple arms of the manipulator. The robots used for surgery where the entire robot is placed inside the body are called as In Vivo Robot. Various configurations are being developed by the researchers around the globe and still the research is in infancy. The work presents bond graph model of a robot for taking a biopsy sample inside the stomach. To develop the bond graph model a kinematic analysis is carried out and various transformer modulli required for drawing of bond graph model are evaluated. The developed bond graph model can be used for trajectory or force control of in vivo robots.

Keywords: In-Vivo robot, Biopsy, dexterity, kinematic analysis, Bond graph modeling.

1. INTRODUCTION

It is quite evident that minimally invasive surgery has an edge upon conventional form of invasive techniques. The advantage of using robot assisted surgery is their precise localization on the point of biopsy (position and orientation), reduction of patient trauma and surgeon’s tremor. The application in which the entire robot is put inside the human body to perform the specified task is called In Vivo robot. Since last decade many Researcher have zeroed on this particular area. But dexterity, maneuverability and accuracy still are the main concerns to be dealt with. Zhang and Nelson have performed a kinematic analysis for surgical tool for obtaining optimized workspace which will avoid collision of the internal organs with the robot links and will increase dexterity. Modelling and analysis to obtain a better wheel design for a improved wireless mobile imaging robot has been performed by Rentschler et al. Keeping in mind very limited space for actuation and high performance in terms of torque and angular reach two different solutions for electrical actuation has been presented by Sars et al., where the 1st approach is to steer a 2 d.o.f structure by two pairs of antagonist shape memory alloy (SMA) wires. And the 2nd approach consists of a multi d.o.f structure. Giatagnas et al have focused on the kinematic analysis and the experimental evaluation of a prototype endoscopic robotic surgical tool with tendon driven actuation mechanism.

In order to obtain high dexterity and maneuverability this Hyper-redundant robots are preferred over conventional one. These types of robots are termed as hyper-redundant manipulators due to their number of actuatiable DOF being much higher than the DOF of their intended workspace. Chirkjian and Burdick proposed vast deal of theories that gave foundation for kinematics of hyper-redundant robots. The kinematic model for different continuum type robots has been presented by Hannan and Walker. Different approaches towards the constant curvature kinematics and decomposition of differential kinematics have been crystallized by Webster and Jones. In designing the continuum robot three cables were utilized (Hannan and Walker, Cieslak and Morecki, Jones and Walker, Immega, and Antonelli). The forward kinematics of a 3-cable driven single section continuum robot has been derived by Jones and Walker.

In this attempt a 4 DOF hyper-redundant In Vivo robot is proposed, which will be inserted in the existing tool channel of the endoscope to take biopsy from stomach. The present design will enhance dexterity and surgeon’s capacity to explore the internal cavity beyond duodenum with easiness due to the extra degrees of freedom apart from that of the In this attempt a 4 DOF hyper-redundant In Vivo robot is proposed, which will be inserted in the existing tool channel of the endoscope to take biopsy from stomach. The present
design will enhance dexterity and surgeon’s capacity to explore the internal cavity beyond duodenum with easiness due to the extra degrees of freedom apart from that of the endoscope. Unlike other designs the present design is actuated with two wires placed 180° apart.

2. THE PHYSICAL SYSTEM

The conceptualized In-Vivo robot set-up sown in Fig. 1 consists of In-Vivo robot, stomach model a flexible tube with provision of camera, light source, suction pump etc. The proposed miniaturised 4-DOF In-Vivo robot consists of three links and a clipper. The links are connected to the flexible shaft with the help of a coupler. The robot arm will be fitted to the existing tool channel of the endoscope. A clipper is attached to the tip to collect the biopsy in the simulated stomach environment. The CAD model of the In-Vivo robot manipulator with different parts is as shown in Figure 2. The 4 scaled model was fabricated using both conventional and advanced manufacturing processes like wire cut EDM and the fabricated model is as shown in Fig. 3. The fabricated model inside the foam based stomach is as shown in Fig. 4.

3. KINEMATIC ANALYSIS

The frame assignment to the In-vivo robot is as shown in the Fig.5. The Inertial frame is attached to the Bush and the subsequent frames are attached to the wire, coupler, and the links and to the clipper joint. The D-H Parameters for the assigned frame as per the standard D-H conventions (Denavit and Hartenberg) are given as shown in Table1.
Table 1. D-H Parameters of the In Vivo Robotic Manipulator

<table>
<thead>
<tr>
<th>i</th>
<th>$a_{i-1}$</th>
<th>$d_i$</th>
<th>$\theta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>$\phi$</td>
</tr>
<tr>
<td>3</td>
<td>-90°</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>$L_1$</td>
<td>$\phi$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>$L_2$</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>$L_3$</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>$L_4$</td>
<td>0</td>
</tr>
</tbody>
</table>

The general form of Homogenous Transformation matrix (by Denavit and Hartenberg) is

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

The transformation matrices based on the D-H parameters as follows:

$^{0}_1T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$^{1}_2T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$^{2}_3T = \begin{bmatrix} c_2 & -s_2 & 0 & L_1 \\ s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$^{3}_4T = \begin{bmatrix} c_3 & -s_3 & 0 & L_2 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

$^{4}_5T = \begin{bmatrix} 1 & 0 & 0 & L_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

P.M. Pathak described the kinematic analysis of a three link ground Robot, according to which the manipulator is a chain of bodies with each one of them capable of having a motion relative to their neighbour link. The velocity of link $i + 1$ will be equal to the velocity of link $i$, plus new velocity component added by joint $i + 1$. The angular velocity of link $i + 1$ is equal to the angular velocity of link $i$ plus a new component caused by rotational velocity of joint $i + 1$. So the angular and linear velocity of link $i + 1$ with respect to inertial frame $\{0\}$ can be calculated from the following relations:

$^{i+1}_i(\omega_{i+1}) = ^{i+1}_i(\omega_i) + ^{i+1}_i(\omega_{i+1}) \quad \text{(For rotational joint)}$

$^{i+1}_i(V_{i+1}) = ^{i+1}_i(V_i) + ^{i+1}_i(\dot{P}_{i+1}) \quad \text{(For prismatic joint)}$

The velocities of centre of mass of the links and the clipper joint are as given in Equation (9):

$^{i+1}_i(V_{G_i}) = ^{i+1}_i(V_i) + ^{i+1}_i(V_{G_i})$

where $\dot{P}_{i+1}$ represents the position of origin of frame $\{i+1\}$ with respect to frame $\{i\}$ in the $i^{th}$ frame. Likewise the linear velocity $^{i+1}_i(V_{i+1})$ represents the velocity of frame $\{i+1\}$ with respect to inertial frame $\{0\}$ while looking from the $\{i+1\}$ frame.

So the position vectors for different values of $i$ are as follows:

$^{0}_1P = [0 \ 0 \ d]^T \quad ^1_2P = [0 \ 0 \ L_1]^T \quad ^2_3P = [L_1 \ 0 \ 0]^T \quad ^3_4P = [L_2 \ 0 \ 0]^T \quad ^4_5P = [L_3 \ 0 \ 0]^T$

And the angular velocities for different values of $i$ are as follows:

$^{i+1}_i(\dot{\omega}_i) = [0 \ 0 \ 0]^T \quad ^2_3(\dot{\omega}_2) = [0 \ 0 \ \phi]^T$

The velocities of centre of mass of the links and the clipper joint are as given in Equation (9):
And the tip velocity with respect to the inertial frame \( \{ 0 \} \) i.e \( \dot{V}_{t} \) is as given in Eq. (7).

To check the validity of model first we check the model without wire actuation. The 1st Joint was rotated while all other joints were locked at zero degree initial value. We obtained a circle of 0.176 m radius (sum of four planar link lengths) as shown in Fig. 7. Then to further validate the model tip trajectory by rotating second joint with all other joints locked at zero degree initial value was traced. Tip trajectory obtained is as plotted in Fig. 8. This is with initial tip position at \( x_{tip}=0.176m \) and \( z_{tip} \) at 0.044m.

4. BONDGRAPH MODELING

Based upon the equations obtained the bondgraph modelling of the In Vivo Robot was performed. Various transformer moduli were found from the kinematic relationships. The parameters taken for the simulation are as enlisted in Table 2.

Table 2. Simulation Parameters

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Link Length</td>
<td>0.044 m</td>
</tr>
<tr>
<td>2</td>
<td>Link mass</td>
<td>0.001 kg</td>
</tr>
<tr>
<td>3</td>
<td>Torque Applied</td>
<td>2 N·m</td>
</tr>
<tr>
<td>4</td>
<td>Joint Inertia</td>
<td>0.01 kg m²</td>
</tr>
<tr>
<td>5</td>
<td>Joint Resistance</td>
<td>( R_i=0.001 ) Nm(rad/s),</td>
</tr>
</tbody>
</table>

Bond graph model of In Vivo robot is shown in Fig. 6.

5. RESULTS AND DISCUSSIONS

To check the validity of model first we check the model without wire actuation. The 1st Joint was rotated while all other joints were locked at zero degree initial value. We obtained a circle of 0.176 m radius (sum of four planar link lengths) as shown in Fig. 7. Then to further validate the model tip trajectory by rotating second joint with all other joints locked at zero degree initial value was traced. Tip trajectory obtained is as plotted in Fig. 8. This is with initial tip position at \( x_{tip}=0.176 \) m and \( z_{tip} \) at 0.044 m.
Then the wire actuation for obtaining the 3rd degree of freedom was simulated by activating the upward and downward wire actuation and the tip trajectory obtained are as plotted in Fig. 9 and in Fig. 10. This is as per the expected result. When string is moved in one direction tip moves up (Fig.9), while when the string is moved in other direction tip moves down(Fig.10).

6. CONCLUSIONS
Kinematic analysis of the 4 scaled In-Vivo robot was performed. The bondgraph model of the same was simulated by giving the parameters. The simulation results of the tip trajectory were obtained by rotating the 1st joint and a perfect circle was obtained which satisfies the model. The second joint was then activated and rotated which gave a perfect circle. Also the left and right wire actuations were activated individually to move the tip to the desired position and the results were found to be quite satisfactory.

7. ACKNOWLEGEMENT
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REFERENCES


Fig. 7: Tip trajectory of In-Vivo robot by rotating first joint with all other joints locked at zero degree initial value

Fig. 8: Tip trajectory by rotating second joint with all other joints locked at zero degree initial value

Fig. 9: Tip Trajectory by actuating wire with tip moving in upward direction

Fig. 10: Tip Trajectory by actuating wire with tip moving in downward direction


