On the Preliminary Design of a Portable Manipulation System for Commercial Robotic Surgery Forceps

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***Özetçe* — Robot manipülatörlerin cerrahi operasyonlarda kullanımı ve bu alandaki faydaları, bilimsel çalışmalar ve teknolojideki gelişmelerden dolayı günden güne artmaktadır. Arttırılmış hassasiyet, küçük kesilerden operasyonların yapılarak az iz kalması ve operasyon sonrası hızlı iyileşme süresi gibi avantajların; bu robotik sistemlerin birçok operasyonda kullanımını arttırdığı açıktır. Öte yandan yüksek yatırım maliyetleri ve operasyonların çeşitli masraflarından dolayı ameliyat robotları dünya çapında yaygınlaşamamıştır. Mekanik olarak cerrahi robot sistemlerinin verimliliği büyük robot manipülatörler tarafından sağlanan makro manipülasyona ve makro manipülatörün ucuna bağlanmış çok serbestlik derecesine sahip özel cerrahi forsepslerin kullanılmasıyla sağlanan mikro manipülasyon'a dayanmaktadır. Bu robotik sistemlerin yüksek maliyet nedeniyle karşılanamadığı veya gerek olduğunda büyük manipülatörlerin transfer edilmesinin veya temininin imkansız olduğu durumlarda; cerrahlar büyük manipülatörler yerine robotik cerrahi forsepslerini kullanabilirler ve böylece robotik cerrahi forsepslerinin avantajlarından da yararlanılarak ameliyatlar gerçekleştirilebilir. Bu bakış açısıyla, çalışma kapsamında ticari robotik cerrahi forsepslerin, cerrahlar tarafından klasik cerrahi forseps gibi kullanıldığı taşınabilir bir manipülasyon sistemi için konsept tasarım önerilerek alternatif bir çözüm sunulmaya çalışılmış bu sayede ise robotik ve klasik laparoskopinin harmanlanması planlanmıştır.**

Anahtar Kelimeler* — *Robotik, Cerrahi robotik, forseps, Laparoskopik cerrahi

***Abstract* — Utilization areas of robot manipulators in surgical operations and their effectiveness through scientific studies and technological advancements are increasing rapidly day by day. It is clear that advantages such as enhanced precision, small incision requirements, fast recovery rates and limited post operation problems in cases favors the usage of these robotic systems for various operations in many hospitals. On the other hand, due to their high investment costs and variable expenses of the operations, surgical robots can't become widespread in the world. Mechanically, effectiveness of many surgical robotic systems depends on the macro manipulation that is carried out by the large robot manipulator and the micro manipulation that is carried out by the utilization of specific multi degrees of freedom robotic surgery forceps that are attached to the end effector of the macro system. As these specific forceps are relatively cheap to manufacture, using surgeons in place of bulky macro manipulator can render some surgical operations to benefit from the advantages of robotic surgery forceps for the situations when it is not possible to transfer or supply the complete surgical system. From this point of view this study tries to introduce an alternative solution by proposing a conceptual design of a portable manipulation system for a commercial robotic surgery forceps that can be used as a classical surgery forceps by the surgeon. Thus it is aimed to blend the robotic and classical laparoscopic surgery together.**

Keywords – Robotics, Surgical robotics, forceps, laparoscopic surgery

I. INTRODUCTION

Minimally invasive surgery has become widespread since the late 1980's and nowadays there are lots of surgical operations that are performed by means of laparoscopic surgery. One of the most important things in laparoscopic surgery is the selection of instruments that will be used for the surgical tasks. In regular laparoscopic instruments there exist mostly two independent degrees of freedom (DoF) to actuate the end effector of the forceps. Although many surgical operations can be carried out with two degrees of freedom, it is not an easy task to perform surgeries in a limited workspace inside the patient while the remote center of motion stays at the incision point. In order negate these effects and increase dexterity, higher degrees of freedom forceps and actuated systems have been tried to be implemented to the area by the help of technological advances and researches. As a result robotic surgery systems have emerged in the related field. Being a great leap, increased dexterity in the systems has been able to eliminate the inherent limitations of the manual laparoscopic surgery.

Throughout the literature many scientific researches have been executed on the field of robotic laparoscopic surgery and many robotic surgery systems have been proposed to the medical literature. Although their origins goes back to two decades from now, the most famous and known surgical platforms can be listed such as da Vinci, AESOP and ZEUS surgical robotic systems [1-2]. AESOP robotic surgery system is mainly composed of a single robotic arm that is used to hold an endoscope. The arm can be controlled via voice commands of the surgeon in order to increase the stability of the image provided from the endoscope. The main idea behind the developed system is having a third arm in the operation room that supports surgeon during the procedure. Similar to the AESOP, structure of the ZEUS surgery system also includes a

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robotic arm for the endoscope. Additionally the system comes with dual four degrees of freedom arms that can carry surgical tools as their end effectors. During the surgical operation, surgeon controls those arms remotely via systems control center. During its experimental studies it was revealed that the system is able to cancel undesired tremors at a certain levels and increase the overall dexterity during the operations. In order to mimic human arm and increase the dexterity further, da Vinci surgical system has implemented three seven degrees of freedom robotic arms that will be used for translations rotations and grasping. Similar to the ZEUS, the system has a control center for the surgeon and its forceps can mimic the human wrist motion thanks to their four degrees of freedom structure. Although mentioned systems create the foundations of robotic laparoscopy history, there also exist various new designs and studies in the current literature [3-8].

In their experimental studies, Dakin et al. [9] revealed that task performance of the basic laparoscopic surgeries when the standard laparoscopy equipment are used is faster when compared with the operations carried by ZEUS and da Vinci surgical systems. On the other hand authors concluded that precision vise robotic systems have the advantage over basic laparoscopic surgeries. In a classic laparoscopic surgery, it is clear that surgeon should carry out repetitive and precise movements during the operation in a limited workspace inside the patient [10]. From this point of view in order to enhance the dexterity and precision of the operation, the surgeon and the laparoscopic equipment that s/he holds should be considered at the same time. That is, usage of insufficient degrees of freedom forceps with respect to the task and inadequate handle designs will mostly decrease the overall dexterity of the most capable surgeon during the laparoscopic surgery [11-12]. In order to get rid of the disadvantages between this interconnection and improve it as the minimally invasive techniques are applied to the vide variety of tasks, actuators and control systems (robotization) have been proposed to be located between the surgeon and the equipment [13-14].

In light of these, current study focuses on the conceptual design of a portable manipulation system with four degrees of freedom and laparoscopic surgery tool for the surgeon that allows the utilization of a commercial robotic surgery forceps. As mentioned earlier, the main motivation of the study comes from removing the dependency of macro manipulator part of the robotic laparoscopy systems to utilize their precise micro manipulation end effector forceps to increase surgeon dexterity for certain environments such as hospitals with low budget, secluded rural areas and small operation rooms. It is known that multi degrees of freedom specific forceps designed for surgical robotic systems have potential to give better results when compared with classical laparoscopic instruments due to their advantage in terms of increased dexterity and precision. During the study, for preliminary conceptual design, daVinci forceps bases were targeted. Proposed manipulation system was designed in such a way that it allows for the selected da Vinci robotic surgery forceps to be mounted on it. Thus the resulted assembly forms compact and actuated laparoscopic equipment that will be used by the surgeons manually and benefit from some of the advantages of the sole robotic surgery. Although proposed manipulation systems macro movements will be actuated by the surgeons arm as a macro manipulation, actuation of the forceps will be performed by smart actuators with respect to the control input received from the joystick controllers on the handle.

II. STRUCTURAL DESIGN

Main objective of this study is to design a manipulation system that uses commercial forceps as laparoscopy instruments. In light of this da Vinci Maryland Bipolar Forceps were used as a target commercial robotic surgery forcep. As seen in Figure 1a, the forcep has three rotational degrees of freedom with wrist like structure and a single grasping actuation. Although the motions are coupled due to the tendon driven transmission, all of the motions are controlled via the four knobs located at its base (Figure 1b).

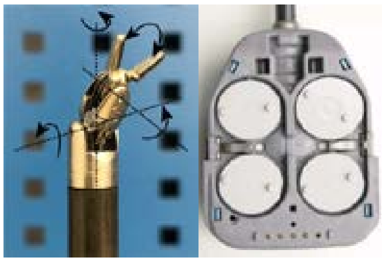

Figure 1. a) daVinci Maryland Bipolar Forceps b) Four knobs at the base platform of the forcep

In order to verify the feasibility of the preliminary conceptual design, without concerning the overall size of the system first, four Dynamixel MX-64 smart actuators that were available at the medical robotics laboratory were used as the actuators of the manipulation system. Due to the locations of the knobs the body of the system was designed as compact as possible with respect to the actuators selected and direct transmission couplings between the actuator horns and the forceps knobs. At the end of the 3D modelling and assembly verification, assembly parts were manufactured by using a rapid prototyper. Overall design and preliminary prototype with assembled actuators can be seen in Figure 2.

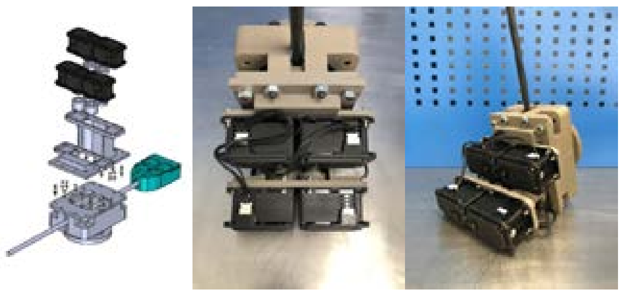

Figure 2. 4 DoF Manipulation system with an attached da Vinci robotic surgery forceps

III. KINEMATIC ANALYSIS

Due to the fact that actuators of the proposed system are planned to be controlled by the surgeon via the attached joystick handle, forward kinematic analysis of the forceps should be carried out. As seen in Figure 1a grasping motion occurs at the further end of the forcep by the dual gripper jaws. However prior to the analysis an important point should be noted. Thanks to the structural design of the da Vinci robotic surgery forceps, both of the jaws has independent actuation. Thus, the grasping and gripper tip rotation occurs by the coupled rotations of two actuators.

In order to represent this structure in kinematic representation, kinematics of the system was considered as two open serial kinematic chains as 01234 and 0123'4' respectively as seen in Figure 3. As it can clearly be seen P and P' points represents the distinct tip points of the jaws while i represents an imaginary point that is located at the mid segment of the arc between P and P' points with a radius d centered at the origin of the 3 and 3' axis.

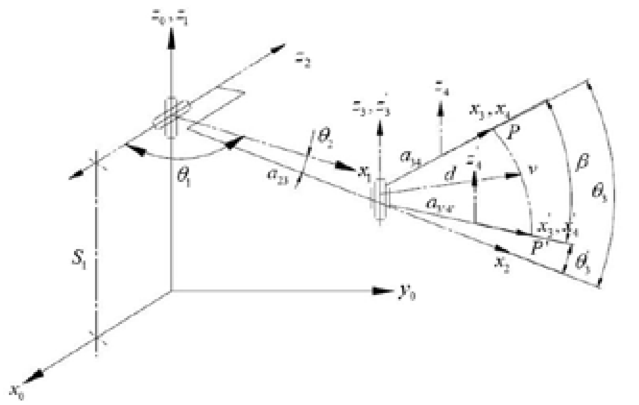

Figure 3. Kinematic representation of the forceps with Denavit-Hartenberg parameters.

After labeling kinematic representation of the system with Denavit-Hartenberg parameters, Denavit-Hartenberg table can be constructed to continue forward analysis (Table 1).

Table 1: Denavit-Hartenberg table

<table>
<tr><th colspan="2">i</th><th>ai-1,i</th><th colspan="2">▪ i-1,i</th><th colspan="2">Si</th><th colspan="2">▪ i</th></tr>
<tr><td colspan="2">1</td><td>0</td><td colspan="2">0</td><td colspan="2">S1</td><td colspan="2">▪ 1</td></tr>
<tr><td colspan="2">2</td><td>0</td><td colspan="2">-▪/2</td><td colspan="2">0</td><td colspan="2">▪ 2</td></tr>
<tr><td>3</td><td>3'</td><td>a23</td><td>▪/2</td><td>▪/2</td><td>0</td><td>0</td><td>▪ 3</td><td>▪ 3'</td></tr>
<tr><td>4</td><td>4'</td><td>a34=a3'4'=d</td><td colspan="2">0</td><td colspan="2">0</td><td colspan="2">0</td></tr>
</table>

Transformation between the i-1 and i coordinates, ${}^{i-1}_{i}\mathbf{T}$ can be reached by a translation along x_{i-1} axis by $a_{i-1,i}$, rotation around x_{i-1} axis by ▪ $_{i-1,i}$, translation along z_i axis by S_i and rotation around z_i axis by θ_i that can be represented as,

$$ {}^{i-1}_{i}\mathbf{T} = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1,i} \\ c\alpha_{i-1,i}s\theta_i & c\alpha_{i-1,i}c\theta_i & -s\alpha_{i-1,i} & -s\alpha_{i-1,i}S_i \\ s\alpha_{i-1,i}s\theta_i & s\alpha_{i-1,i}c\theta_i & c\alpha_{i-1,i} & c\alpha_{i-1,i}S_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

where c and s represents cos and sin of the related angles respectively.

After the given inputs, in order to find the orientation of the coordinate frame 4 in a rotation matrix form ${}^{0}_{4}\mathbf{R}$ and the position of P point with respect to the base frame 0, successive multiplications of the related transformation matrices should be carried out as,

$$ {}^{0}_{4}\mathbf{T} = {}^{0}_{1}\mathbf{T}\,{}^{1}_{2}\mathbf{T}\,{}^{2}_{3}\mathbf{T}\,{}^{3}_{4}\mathbf{T} $$

$$ {}^{0}_{4}\mathbf{T} = \begin{bmatrix} & {}^{0}_{4}\mathbf{R} & & P \\ & & & \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

where in Equation 2,

$$ r_{11} = c\theta_1 c\theta_2 c\theta_3 - s\theta_1 s\theta_3 ,\; r_{12} = -c\theta_3 s\theta_1 - c\theta_1 cs\theta_3 , $$
$$ r_{13} = c\theta_1 s\theta_2 ,\; r_{21} = c\theta_2 c\theta_3 s\theta_1 + c\theta_1 s\theta_3 , $$
$$ r_{22} = c\theta_1 c\theta_3 - c\theta_2 s\theta_1 s\theta_3 ,\; r_{23} = s\theta_1 s\theta_2 ,\; r_{31} = -c\theta_3 s\theta_2 , $$
$$ r_{32} = s\theta_2 s\theta_3 ,\; r_{33} = c\theta_2 , $$
$$ p_x = c\theta_1 c\theta_2 a_{23} + (c\theta_1 c\theta_2 c\theta_3 - s\theta_1 s\theta_3) d , $$
$$ p_y = c\theta_2 s\theta_1 a_{23} + (c\theta_2 c\theta_3 s\theta_1 + c\theta_1 s\theta_3) d , $$
$$ p_z = -s\theta_2 (a_2 + c\theta_3 a_3) + S_1 $$

The same analogy can also be applied to find the orientation of the coordinate frame 4' in a rotation matrix form ${}^{0}_{4'}\mathbf{R}$ and the position of P' point with respect to the base frame 0 by replacing θ_3 variable with $\theta_3{}'$ in Equation 2. It should also be noted that for the ease of control virtual frame v can be taken as the tip point of the forceps. In this case position of the imaginary point P_v and the orientation of frame v with respect to the reference frame 0 could be found by replacing θ_3 variable with φ in Equation 2, where

$$ \varphi = \frac{\theta_3^{'} + \theta_3}{2} = \theta_3^{'} + \frac{\beta}{2} \quad (3) $$

and β is the angle of gripper opening. As revealed from Equation 3, if the gripper is desired to be actuated in its closed form ($\theta_3^{'} = \theta_3$, β =0) all of the tip points P, P', and P_v become coincident.

IV. MANIPULATION HANDLE

Following the structural design of the manipulation system and the forward kinematic analysis of the four degrees of freedom robotic surgery forceps, a basic handle conceptual design was decided to be implemented to the system. Proposed handle design would ensure that the surgeon can both hold the manipulation system confortably and control the movement of the forceps. Due to the fact that all of the motions will be controlled by the surgeon, the handle should have sufficient remote degrees of freedom.

As seen in Figure 4 all of the four variable rotations can be controlled via the single degree of freedom rotational (R) knob for the index finger and three degrees of freedom RRP joystick for the thumb. In this configuration grasping angle β is controlled by the prismatic movement (P).

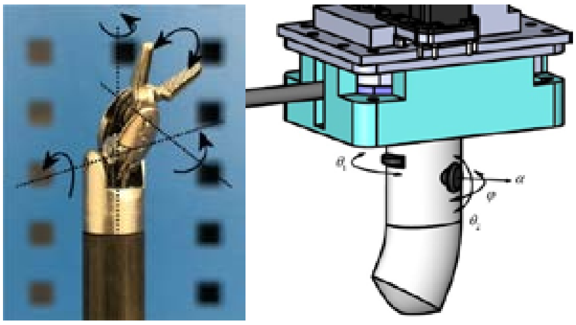

Figure 4. a) Illustration of the actuated movements of the forceps b) Conceptual handle design.

V. CONCLUSIONS AND FUTURE WORKS

Throughout the study, design of a four degrees of freedom portable manipulation system for a commertial robotic surgery forceps was proposed along with necessary kinematics and joystick handle concept. Preliminary prototype of the manipulation part was manufactured by utilizing rapid prototyper. After the assembly of actuators to the system was carried out, forceps manipulability was verified for the suitability of the motion transmission components in the proposed system (Figure 5).

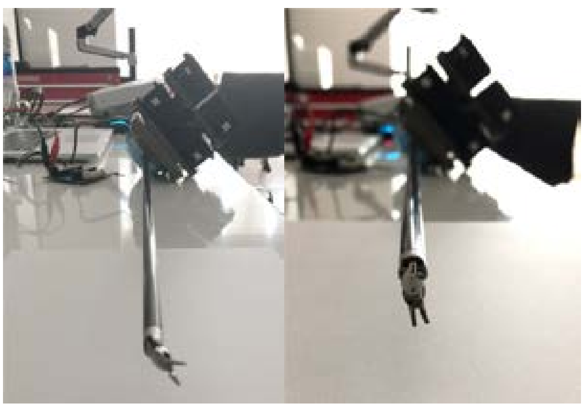

Figure 5. Forceps manipulation via assembled actuators

At the end of the preliminary study, promising results have been acquired that show the enhancement and applicability potential of the design with respect to the motivation of the study. As future studies, manipulation system will be designed in a more compact form by selecting optimal actuators with small form factor and finalization of the handle design will be carried out with respect to the feedbacks taken from the surgeons. It should be noted that throughout this study only the basic kinematics of the forceps structure was given. On the otherhand as mentioned earlier the forceps has a tendon driven structure that couples the motion between the forceps rotations and the base knob rotations. Thus in order to control the system forward kinematic analysis between the base knobs and the end effector is crucial. In light of this first clinical trials on mockups will be carried out after the implementation of the additional kinemtics to the system.

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