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Workspace Determination and Robot Design of A Prototyped Surgical Robotic System Based on A Cadaveric Study in Endonasal Transsphenoidal Surgery

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***Abstract*— The Endonasal endoscopic transsphenoidal surgical system will be presented in this study. The Endonasal transsphenoidal surgery (ETSS), a process to approach and remove pituitary tumor, is less invasive, and causes less pain and faster recovery than the old process (Craniotomy surgery). However, the optic nerves, cavernous sinuses and carotid arteries are intimately next to the pituitary gland. A slight deviation of tools from ETSS-pathway can lead to serious complications. Therefore, neurosurgeons should control their hands steadily and also concentrate on the operation at the same time. This study proposes to design and develop assisting robot for ETSS. This study is separated into 2 parts: the first is ETSS-workspace analysis and the second is robot design and implementation for surgical assisting. For the ETSS-workspace, optical tracking system is used to detects motion of surgical instruments while ETSS-procedure is performed in cadaveric case. Then, the workspace and range of motion of instruments are analyzed. For robot designing, the workspace of surgical tools was used to be constrain of robot's workspace. The robot consists of 6 DOF; 3 DOF for translation movements, 2 DOF for rotation movements and 1 DOF for tool insertion. DELTA parallel robot is applied for 3 DOF in translation movements. Precision and accuracy of this robot are evaluated by ETSS-phantom that known the position, orientation of a pituitary tumor and ETSS-pathway. This robot is a part of ETSS system to assist neurosurgeons to hold and control medical instruments in the operation. Furthermore, this system is able to be developed by applying with medical image; CT-SCAN and MRI to analyze optimal pathway of medical tools.**

KEYWORD- pituitary gland, Endonasal endoscopic transsphenoidal surgery, delta parallel robot

I. INTRODUCTION

The pituitary gland is a small bean-like organ that is located within the sella turcica. The sella is adjoins to vascular and neurologic structures, including the cavernous sinuses, cranial nerve III, cranial nerve IV, cranial nerve VI, optic chiasm and internal carotid arteries.

The statistic data from National institute of health (NIH) [1], USA, shows that about 1 in 10,000 people get pituitary tumor. Most pituitary tumors are benign, which do not invade to other parts of the body, but tumors can cause the pituitary gland to produce too many hormones that develop into endocrine diseases, such Cushing's disease and Acromegaly. Some pituitary tumors have their symptoms that are directly related to their growth in size, for example; headaches, vision problems and vomiting. Fortunately, pituitary tumor is usually curable. Surgery is one of common choices to remove tumors and can decrease symptoms from serious effect. There are two main techniques of surgery; the first is a traditional technique, craniotomy. Craniotomy, is operation which the skull, or cranium, is opened for accessing to the brain. But patients will get risk to have postoperative brain swelling or blood clot that takes more time to recovery. Thus, the second technique is developed to do less invasive, less pain and faster recovery time that is Endonasal transsphenoidal surgery [2].

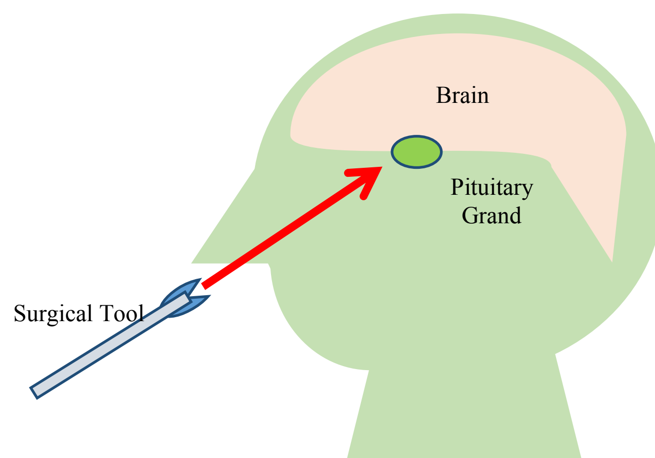

Fig. 1 Location of pituitary gland, Pathway of Endonasal Transsphenoidal Surgery

Then, a surgeon can access to the pituitary gland through the sphenoid sinus by using a microscope or an endoscope. This procedure relieves the necessity of fully opening the skull, which can diminish risks of neurological injury [3]. Nevertheless, Endoscopic transsphenoidal surgery (ETSS) also has limitations that surgeons have to operate on a narrow working area and have to be steady their hands.

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Reminding that the pituitary gland is surrounded by cavernous sinus, internal carotid arteries and optic chiasm, thus a slight deviation from ETSS pathway can lead to serious complications. Surgical assisting robot is applied to assist the neurosurgeon steady and control the surgical tools during the operation. Then, the surgeon can concentrate on the operation obviously.

II. ETSS Procedure

In currently, Endonasal Transsphenoidal Surgery (ETSS) is widespread in the world for approaching pituitary gland and other organs nearby. ETSS procedure is easier than craniotomy procedure.

1) Preparation

Patient is prepared in a supine position and also locked position of head by Mayfield head clamp. A surgical exposure is cleaned by antiseptic solution.

2) Insertion

Surgeon inserts tools into nostrils. Normally, there are 2 kinds of tools; an endoscope for capture image inside and another one is a surgical tool, which usually is dissector, forceps and maybe driller. So, the surgeon has to control 2 devices by their hands, one device for one hand and one nostril.

3) Connection

A surgeon passes a long instrument into distal end of nasal septum, then connected left and right nasal cavities together. So, the surgeon can operates their surgery comfortably.

4) Sphenoidotomy

After connected left and right nasal cavity, surgeon use bone-biting instruments (Milling or Kerrison [4]) to create an opening of sphenoid bone into the inner layer where the pituitary gland is located within the sella turcica.

5) Dissection

A surgeon removes all visible tumors by using a dissector.

6) Closing

The hole in the sphenoid bone is replaced by PMMA (polymethyl-methacrylate) [5], the biocompatible material. This glue can heal and prevent a leakage of cerebrospinal fluid from the brain into nasal cavities.

III. Workspace Determination on Cadaveric Study

An ETSS experiment on a cadaveric case is observed, Optical tracking system has used to detect and record the position and orientation of surgical tools during ETSS operation. As the result has shown in figure 2.

There are 2 groups of points in figure 2, the upper one (pink) is passive marker-origin points and the lower one (blue) is tip-points of surgical tool which operate inside cadaveric body. For ETSS workspace analysis, only the surgical tool tip-points are considered.

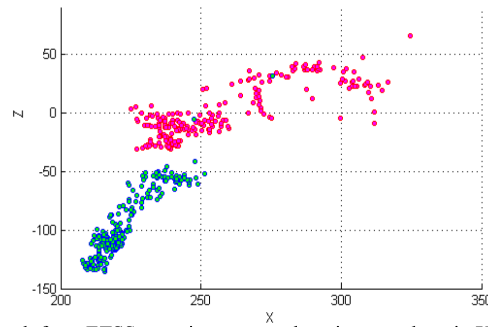


Fig. 2 Result from ETSS experiment on cadaveric case, show in XZ-plane with millimetre unit.

Then, these cloud points (blue points) translated into to origin frame and define the boundary of these cloud point. The limitation of our robot workspace will be considered from the boundary. The boundary of tool tip cloud points have conceded in a simple geometrical shape, cylindrical. The cylinder can cover the clouds point and use for limitation of our prototyped robot, which the cylindrical is 24.2 mm for diameter and 100.6 mm for length. The cylindrical shape has shown in figure 3.

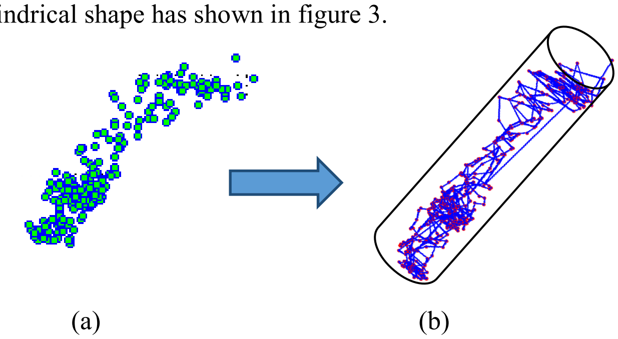
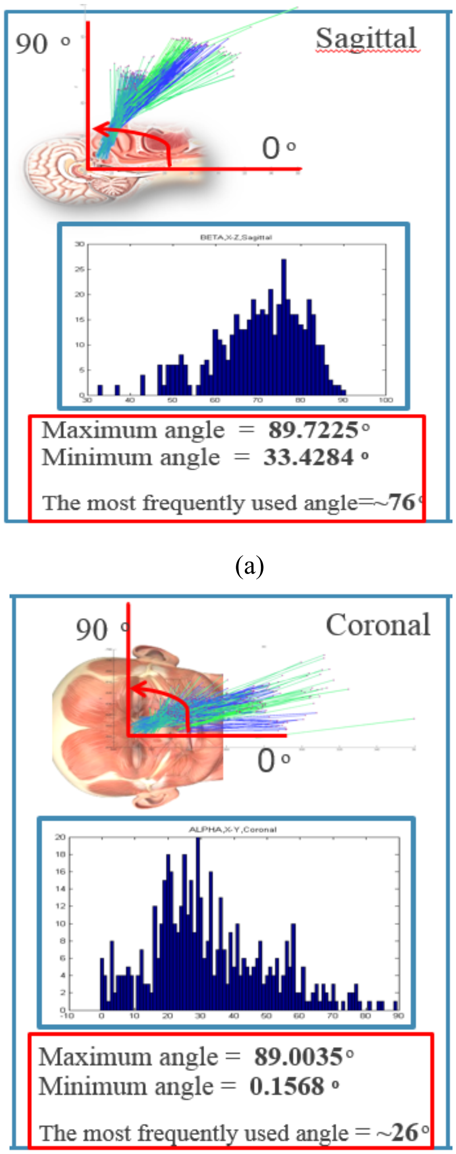


Fig. 3 a) Cloud point of tool tip, b) Boundary of ETSS workspace

Moreover, range of motion of our prototype robot is analyzed from the surgical tool movement data. The data had separated in 3-plane of anatomy, Sagittal, Coronal and Transverse plane. Two points of each data had set in Euclidean's distance equation. The Euclidean's distance equation had used to define shape and orientation of surgical tool. Then the line had used to solve the angle of surgical tool represent on X-axis of each plane. All data from ETSS-experiment had been applied, then histograms of all angle had plotted. The histograms show character of tool movement that are able to get 2 interesting information, the minimum and maximum angle of surgical tools and the most frequently used angle of each plane.

That are max = 89.7225 degrees, min = 33.4284 degrees and about 76 degrees for the most frequently used angle in Sagittal plane, max = 89.0035 degrees, min = 0.1568 degrees and about 26 degrees for the most frequently used angle in Coronal plane and max = 89.9166 degrees, min = 45.7785 degrees and about 83 degrees for the most frequently used angle in Transverse plane or you can see in figure 4.



(a)

(b)

Fig. 4 Histograms of surgical tool's angle in 2 plane of anatomy, a)sagittal plane and b)coronal plane. X-axis for numbers of data and Y-axis for angle in degree unit.

IV. Robot Design and Development

A. *Design Analysis*

To design the prototyped robot, degree of freedom and range of motion of robot are constrained of robot design. The range of motion had been proposed in previous chapter and DOF will be solved in this chapter.

Normally, DOFs of medical robots are consist of 2 parts; initial pose setup and intra-operative movement. Initial pose setup is a part that used to set the position and orientation of robot before the operation, which there is 6 DOFs; 3DOFs for XYZ-translation motion and 3DOFs for XYZ-rotation motion. For intra-operative movement, you can see that in previous chapter. ETSS-pathway which starts at nostril until the end distal of nasal cavity is always straight. After that is a sphenoidotomy process that driller is able to perform it. Therefore, intra-operative movement has only 1DOF for surgical tool insertion and a little bit translations in lateral planes. Accordingly, our robot consists of 2 movement-parts; the first is 6 passive-DOFs; 3DOF for translations and 3DOF for rotations. These 6 passive-DOF to setup the initial pose of surgical tool before the operation and the last is 4 active-DOF; 3DOF for translations and 1DOF for surgical tool insertion.

Robot is confided to apply parallel robot mechanism for 3 DOF in intra-operative surgery because the parallel robot has advantages that fit with ETSS-operation more than serial robot in term of precision, accuracy, stiffness and also load / weight ratio [6]. The parallel robot can classified in 3 classes [7]; translation manipulation (Delta parallel robot), orientation manipulation (Stewart platform) and mixed-DOF manipulation. Meanwhile, ETSS is looking for a translation mechanism

B. *Investigation on Parallel Mechanism*

The study of delta parallel robot said that delta parallel robot consists of 4 opponents; base plate (fixed plate), mobile plate and 2 links connecting to each other with universal plate. Moreover, to study behavior of delta parallel robot and also control delta parallel robot, inverse kinematics are studied [8, 9].

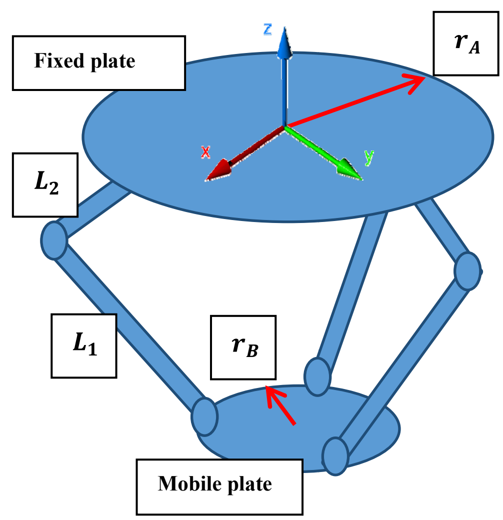


Fig. 5 Components of delta parallel robot with origin frame.

r_A = radius of fixed plate (distance between center and L_2-link)
r_B = radius of mobile plate (distance between center and L_1-link)
L_1 = length of link attaching with mobile plate
L_2 = length of link attaching with fixed plate
θ_j = angle of each L_2 representing on X-axis (j=1, 2, 3)
φ_{1j} = angle of L_2 representing on fixed plate plane
φ_{2j} = angle of L_1 representing on L_2
φ_{3j} = slip angle of L_1in lateral plane

1) Inverse kinematics

Inverse kinematics is defined by geometrical method, where the end effector, point P = $[X_P, Y_P, Z_P]$, is given. The unknowns are joint angles φ_{1j}, φ_{2j}, φ_{3j} (j=1, 2, 3) [8, 9]

$$\left(2rL_2 - 2L_2X_P\cos\theta_j - 2L_2\sin\theta_j\right)\cos\varphi_{1j} - 2rX_P\cos\theta_j + 2L_2Z_P\sin\varphi_{1j} - 2rY_P\sin\theta_j + {X_P}^2 + r^2 + {L_2}^2 + {Z_P}^2 + {Y_P}^2 - {L_1}^2 = 0 \quad (1)$$

2) Workspace of Delta parallel robot

Workspace of delta parallel robot is defined as a region of the three-dimension Cartesian space. Referring to inverse kinematics equation (1), which is able to write as [8, 9]

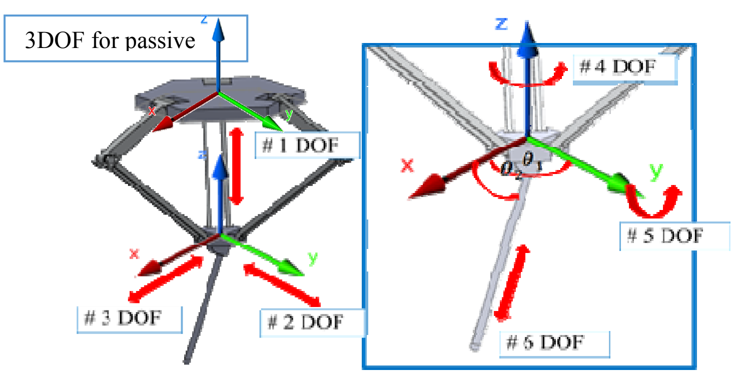
$$h_j(X_P, Y_P, Z_P) = ((X_P\cos\theta_j + Y_P\sin\theta_j - r)^2 + ((XPsin\theta j-YPcos\theta j)2+ZP2+L22-L12)2-4L22(XPcos\theta j+YPsin\theta j-r2+ZP2) \quad (2)$$

Set of point P generates h_j, which h_j can state point P:
if $h_j(P)$<0 for j=1,2,3 then P is inside the workspace.
if $h_j(P) \leq 0$ for j=1,2,3 and $h_j(P)$=0 for j=1 or j=2 or j=3 then P is on the boundary of workspace.
if $h_j(p)$>0 for j=1 or j=2 or j=3 then P is outside the workspace.

After that, delta parallel robot simulation had developed in MATLAB programming. Delta parallel robot's workspace and behavior are studied from the simulation. Study of delta parallel robot told that workspace of this robot is depend on 4 parameters; radius of upper plate (fixed plate), radius of lower plate (end-effector plate), length of L1 link and length of L2 link. Then dimension of robot is able to define from size of robot's workspace.

C. Robot Workspace Development

After the study of delta parallel robot in previous chapter, then the final version of prototyped robot is already. The conceptual design of final robot will be explained



(a) (b)

Fig.6 Concept of prototyped robot, a) 3DOF for translation motion in intra-operative movement and also 3DOF translation for passive joints. b) 2DOF for rotation and 1DOF insertion.

For intra-operative movement, delta parallel robot will be used for 3DOF in translations motion and also linear actuator for 1DOF to insert surgical tool. Moreover, 2DOF for rotations motion will be added at the mobile plate (end-effector plate) and 3DOF for translations will be added at fixed plate. These 5DOFs are used for setup the position and orientation of surgical tool parallel with surgical pathway as shown in figure 6.

The workspace of delta parallel robot had designed to fit with the cylindrical shape of ETSS boundary. The dimension of delta parallel robot (4 parameters) are depend on size of robot workspace. Dimension had solved by developed MATLAB programming. Then, the insertion motion of surgical tool will increase robot workspace along the length of cylindrical shape, as figure 7. Therefore, if initial position of delta parallel robot is set to perpendicular with ETSS boundary including to the initial orientation of surgical tool also set to parallel with ETSS boundary, then surgical tool is unable to damage any tissue outside ETSS boundary.

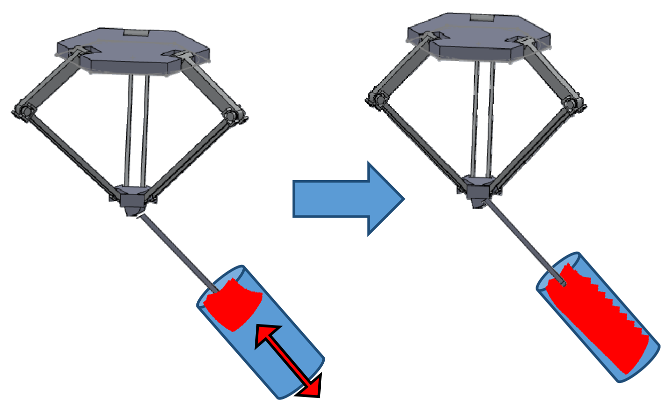


Fig. 7 Conceptual design of robot-workspace and ETSS-workspace.

D. Robot Implementation

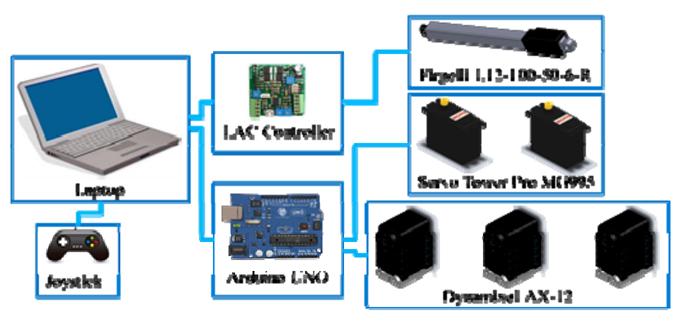


Fig. 8 Robot control architecture

The final version of robot prototype had improved in CAD programming. Moreover, controlling system of robot prototype has been designed. Microcontroller, has been used for control actuators, which are 3 actuators for delta parallel robot, 2 actuators for surgical tool rotation and 1 actuator for surgical tool insertion. The controller system is also connected with laptop for the high-level controller in

MATLAB programming. In MATLAB programming inverse kinematics equation used to solve the angle parameters then order to microcontroller.

The final prototype had implemented for proving the hypothesis of this project's problem.

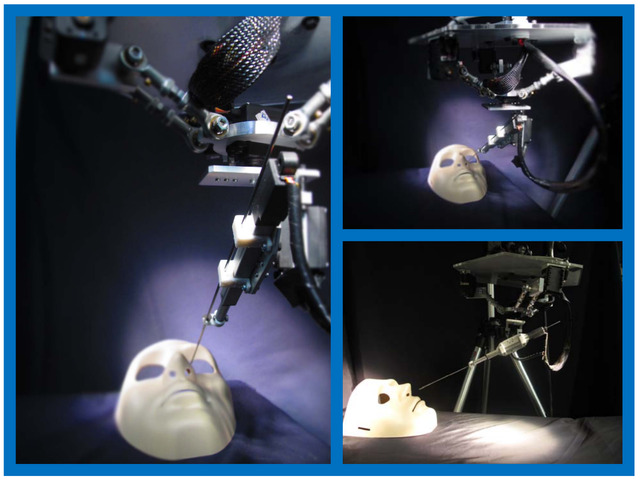


Fig.9 The prototyped robot for ETSS surgical robotic system

V. ROBOT DEMONSTRATION

Computer integrated surgery (CIS) is able to use in modern surgical system and also this chapter. ETSS system with prototyped robot is combined with preoperative system to plane the operations. In intraoperative system, dimension and orientation of ETSS pathway are required. They are generated from patient's medical image in preoperative system. Intraoperative system consists of 5 steps which are:

1). Initial orientation setup

To setup orientation of surgical tool parallel with the orientation of ETSS-pathway by joint 5 and joint 6 and then locked.

2). Initial position setup

To setup position of surgical tool to initial position of ETSS-operation by 3 passive joints and then locked.

3). Surgical tool insertion

To insert surgical tool, which parallels to ETSS pathway, along nasal cavity until end distal by insertion joint.

4). Sphenoidotomy

To open hole at sphenoid bone and also remove pituitary tumor by 3DOF translation of delta parallel robot. Workspace of delta parallel robot is always kept surgical tool inside ETSS boundary.

5). Closing and Surgical tool removal

To close the hole at sphenoid bone with bio-glue (PMMA) and finally remove the surgical tool.

Delta parallel robot is a major mechanism to control surgical tool's movement during ETSS operation. Other joints are used to keep delta parallel robot in optimize position and orientation.

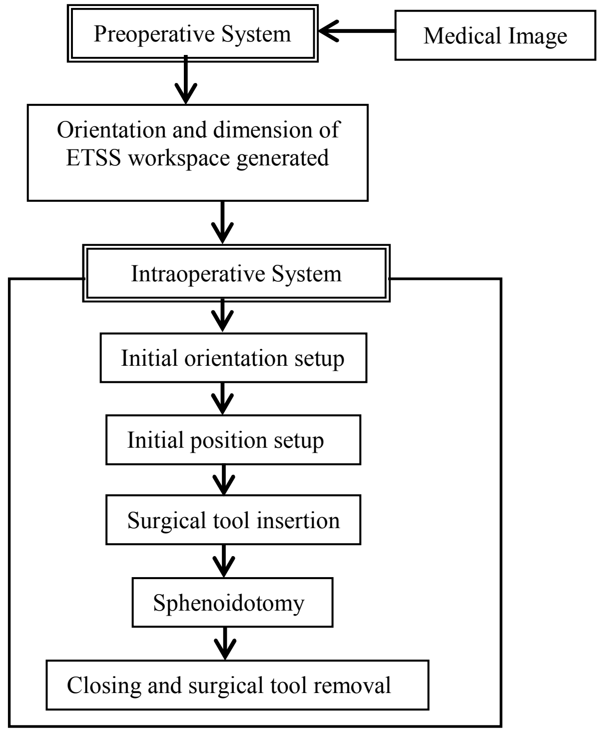


Fig. 10 Procedure's diagram of ETSS system with prototyped robot, including of preoperative and intraoperative system

VI. RESULT AND DISCUSSION

A. System evaluation

To evaluate the performance of developed robot the experiment is separated in 2 parts; robot evaluations in term of range of motion and workspace of delta robot, and demonstration of ETSS surgical robotic system in developed phantom.

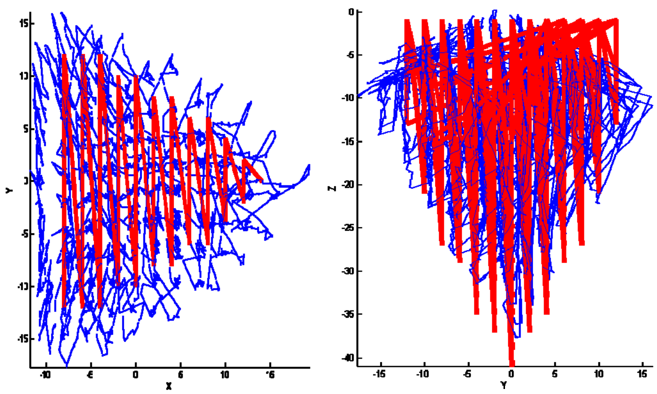
For the first experiment, optical tracking system has used to detect range of motion of each joint. By the way joint 1 is surgical tool insertion, joint 2 is pitch motion and joint 3 is yaw motion of surgical tool.

Table 1
Result from range of motion evaluation, result show maximum movement of each joint.

Joint	Range of Motion
Joint 1 (Insertion)	0-12 cm
Joint 2 (Rotation)	0-90 degree
Joint 3 (Rotation)	0-180 degree

The result had shown in table 1. Table 1 show that all joints of prototyped robot can cover on range of motion of surgical tool from chapter of "Workspace Determination on Cadaveric Study".

The experiment of delta parallel robot workspace had evaluation. Optical tracking system used to detect the movement of robot's end effector while experiment, then result from optical tracking were compared with workspace that was generated by MATLAB programming as shown in figure 11. In the comparison, you can see that workspace from experiment are a little bit wider than it supposed to be (computerized workspace), but in term of height, it shorter than computerized workspace.



(a) (b)

Fig. 11 Robot's workspace comparison between real (Thin line) and simulation (Thick line), a) is a comparison image in top view and b) is a comparison image in side view, X and Y axis show dimension of workspace in millimeters scale

The comparison of delta robot workspace in figure 11 shows that, size of workspace from experiment have error in X-axis is 28.4936%, Y-axis is 28.6722% and Z-axis is 7.2024%.

Furthermore, ETSS surgical robotic system was evaluates by demonstrate in developed phantom. In this part ETSS-operation was demonstrated in developed phantom which the position and orientation of ETSS phantom are adjustable. Follow the procedures of ETSS system in chapter of "Robot Demonstration", the result show that, prototyped robot is able to complete the demonstration of ETSS-operation well.

VII. Conclusion

This paper show road of this project, start from the experiment in cadaveric case for ETSS workspace and path analysis, then the ETSS workspace and range of surgical tool motion are applied for the constrain of prototyped robot. In robot design, delta parallel robot is proposed for 3DOF in translation and 2DOF for rotation and 1DOF for surgical tool insertion have added on the mobile plate of delta parallel robot. The simulation of delta parallel robot in MATLAB programming used to solve the dimension of delta parallel robot that can provide the workspace fit on ETSS workspace. The implemented prototyped robot had evaluated, experiment to solve the hypothesis consist of 2 parts; robot experiment which is range of motion and delta parallel robot's workspace and also demonstration of ETSS-operation. The result show that the prototyped robot has the range of motion correctly and a little bit error of robot's workspace, which improvement is expected with control system in future work. The prototyped robot is also able to complete the demonstration of ETSS system. In the future work, prototyped robot is expected to continuous develop robot prototype and the experiment in cadaveric case.

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