

## 3D Navigation for Transsphenoidal Surgical Robotics System Based on CT - Images and Basic Geometric Approach

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**Abstract**— This paper presents the use of computed tomography image (CT) to generate a 3D workspace in the area of skull base. Our ultimate goal is to develop a surgical robotic system to aid in the endoscopic transsphenoidal surgery. The 3D workspace can benefit both aspects of robot design and intra operative navigation system. In our system, the 3D model of a skull base area is created by the 3DSlicer program and is exported as Stereo Lithography (STL) format which is composed of faces and vertices for the basic structure. For the intraoperative navigation system, the collision detection of tools and anatomical structures can be done by a geometrics approach.

**Keywords:** Surgical robotics, Navigation system, Collision Detection.

### I. INTRODUCTION

Currently, surgical robotic has become a major field of robotics research due to several benefits in terms of providing both safety and ease of work for the surgeons. The use of robotics systems in surgery can avoid damage to the surgical area which results due to human error such as hand tremor, fatigue, lack of depth information, and limitation of real-time information processing ability of human. Normally, pre-operative images for example, Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are commonly used for surgery planning at the pre-operative stage. However, during the intra-operative stage, the use of pre-operative information in the surgery without the aid of a computer-integrated system may not provide the best efficiency.

Robot-assisting systems have a number of advantages over human. They have the ability to process large amounts

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of data to obtain the best decision in the operation. These abilities are particularly important when working under the sensitive and fragile anatomical region, such as, the brain area, to avoid complications during and after the surgery [1-4].

One common disease found in the brain area is the brain tumor. Brain tumor is a mass that grows from the abnormal cell in the brain area, which is a life threatening disease and be able to cause serious problems to the function of the brain.

Pituitary is a gland that is located inside the skull above the nasal passage, lies behind the thin bone structure called sella above the sphenoid sinus (see Figure 1). The main role of the pituitary gland is to control the secretion of hormones from other glands and organs in the body by releasing hormones into the blood stream. The tumors involving the pituitary, called “pituitary tumor” or “pituitary adenomas,” can effect both hormone secretion of pituitary and can cause impairment of the vision field.

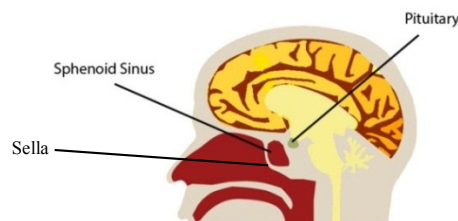


Fig 1. Structure of skull base area

Endoscopic transsphenoidal surgery is one of the most common treatments for removing a pituitary tumor. This surgery is considered to be a minimally invasive method which can be performed without disturbing other regions within the brain area. In the common procedure [5, 6], the surgeon depends on the pre-operative images (CT or MRI), and the images feedback from the endoscope. The standard medical instruments for transsphenoidal surgery comprise of dissector, medical bone drill and suction. These medical instruments are inserted through the nostril to remove a pituitary tumor (more details in the next section).

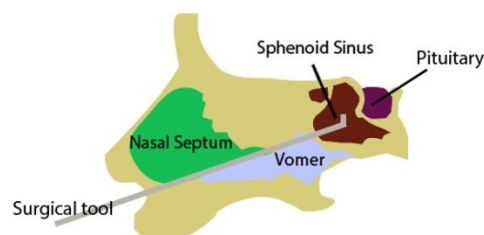


Fig 2. Common surgical path of endoscopic transsphenoidal surgery

From the problem stated above, our ultimate goal is to develop a surgical robotic system to aid in the endoscopic transsphenoidal surgery. The full surgical robotic system is a tele-operative system, and consists of pre-operative planning system, navigation system and robotic system to hold the medical tools. The pre-operative planning system is using pre-operative data, such as, CT or MRI to create the visual environment of the surgery. A 3D model of anatomical structure benefits surgeon by providing pre-operative assessment of patient's anatomy. A path of surgery is generated during the pre-operative stage. The plan is then executed during the surgery. An optical navigation system is used during the surgery to provide the position and orientation information of the medical instruments and tumor by using a 3D model from the pre-operative stage. The surgical robotic system is used to hold and carry the tools along the surgical path by a surgeon at the control station. The navigation system and robot will be able to provide stability along the surgical path, following and preventing the medical tools from going beyond the safe area in the surgery [7].

To achieve the goal, we firstly create a visual environment of the surgery by using CT images. A 3D model of workspace is created from a set of CT images, and is used for the robot's path planning and navigating. The collision detection system is a part of the navigation system to constraint the movement of medical tools held by robot during the surgery (see Figure 3).

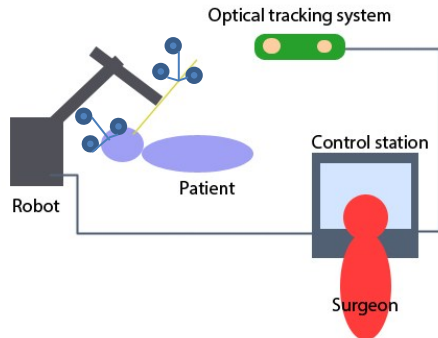


Fig 3. The diagram shows the components of robot aiding system for endoscopic transsphenoidal surgery

In robot aiding surgery, pre-operative planning is one of the most important parts of the system. A 3D model of the surgical workspace can be used to create the visual environment and benefits to surgeon in terms of providing the effective pre-operative assessment of patient anatomy. During the surgery, a 3D model of the workspace can be used with a tracking system to create a navigation system for the robotic system. Visual endoscopy [8] is a technique using a 3D model of human anatomy to create the visual depiction during the actual endoscopy. Visual endoscope can benefit the surgeon by providing the vision of obstructed landmark in the actual endoscope. The position information of obstructed anatomical landmark during the surgery can increase the accuracy and safety for the process of the surgery.

## II. COMMON PROCEDURE OF ENDOSCOPIC TRANSSPHEROIDAL SURGERY

In common transsphenoidal surgery, there are 5 main anatomical regions involved with the surgery, consisting of nostril, nasal septum, vomer bone, sphenoid sinus and sella.

The surgery begins with the pre-operative management. The visual information from MRI and CT images of the brain is obtained and some medications are given to the patient. During the surgery, patient is put into anesthesia and an intravenous is inserted into the arm. The patient is positioned supine. Torso will be elevated about 20 degree and head is position with forehead-chin line set horizontally. Head of the patient will be placed higher than the heart to reduce the cavernous sinus pressure to minimize venous bleeding. This position will also allow the surgeon to access the middle turbinate easily when the endoscope is inserted (see Figure 4).

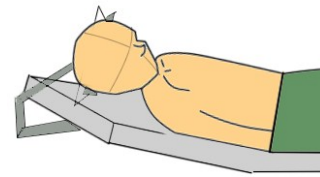


Fig 4. Patient positioning in the endoscopic transsphenoidal surgery

Once the patient is positioned, the nasal cavity, patient face and also the abdominal wall is prepared in aseptic manner. Then the nasal airway is explored to select which nostril will be used. Nostril with wider nasal airway will be used for the surgical approach. Endoscope is then inserted into nasal cavity, index finger and thumb of surgeon are used to steer the video camera to maintain the orientation of the video image. After passing the endoscope through the nostril to the back of nasal cavity. Small portion of nasal septum is removed using bone-biting instrument to expose bone region called vomer. After removing of the nasal septum, both of the nostrils are connected. At this point, medical instrument can be inserted through both of the nostrils.

The bony structure of vomer is removed using a bone drill. Behind the wall of the vomer bone is air-filled spaces called sphenoid sinus. At the back wall of the sphenoid sinus is the sella, which is the thin bone where the pituitary gland is overlying. The bone wall of sella is removed to expose the pituitary tumor. A small surgical instrument will be inserted through this path to remove the tumor along with the suction instrument. After the tumor is removed, the sella will be closed by using a small piece of fat obtained from the abdomen to fill the empty space. Then the cartilage graft will be placed to close the hole in sella using biological glue. Soft and flexible splint will be placed in the nose to control bleeding and swelling.

Endoscopic transsphenoidal surgery has many challenging points that require both surgery skills and anatomical knowledge. The first one is that, the surgeon gets image feedback from the endoscope which can provide only 1 dimensional image. The lack of depth information is a difficult matter in surgery and requires intensive practice.

The position of the tools is also confusing sometimes because of the complexity of the anatomical region and lack of direct vision. Hand tremor, fatigue and stability of tools handling are the limitations of human which sometimes affect the surgery for example, the use of bone drill to open the vomer bone can be ricochet to the surrounding structure and injure the patient.

### III. PRE-OPERATIVE 3D MODELING AND PATH PLANNING

To assist the surgeon in endoscopic transsphenoidal surgery, we studied the creation of a pre-operative plan by using a CT image that represents the bone structure of the workspace area along with the standard procedure of endoscopic transsphenoidal surgery. The plan can be executed in intra-operation using a surgical robot and an optical navigation system to guide tools along the path and limit movement of tools for safety reasons.

#### A. 3D Volume modeling from CT Image using 3D Slicer

3DSlicer is an open source program for medical image visualization and analysis. The key feature of 3DSlicer is the use of DICOM image data from medical imaging systems to render and visualize the 3D volume of the image. 3dslicer comes with many functions that facilitate the procedure of image segmentation, image registration, medical path planning and image analysis. It also possesses the ability to connect to other software and hardware using pre-developed protocol which makes 3DSlicer very flexible for research purposes.

We used 3DSlicer to visualize and create a 3D polygon model of the pituitary transsphenoidal surgery workspace which includes the area of the nasal cavity, sphenoid sinus, sella turcica and pituitary. The 3D model of the workspace is created using pre-operative CT image of the patient's head. The CT image will be cropped at the area of the skull base to create the 3d model of the bone structure (Figure 5). The created 3D models will then be saved as Standard Tessellation Language (.stl) file format. The STL file format is a standard format for a CAD model which represents only the surface geometry of the 3D model. For the workspace creation, we used the threshold technique to separate the bone structure from the CT image. At the first stage of development, we will ignore the structure of soft tissue.

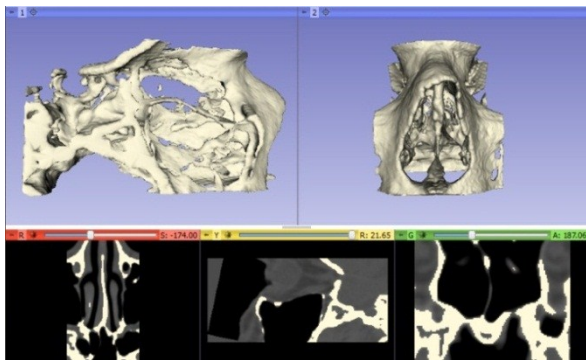


Fig 5. 3D model of bone in the skull based area from the side view and front view

#### B. Mesh model processing

For geometric approach of bone structure in the workspace area. We're using the STL format of the bone area which comprises of faces and vertices. The original model of the bone structure contains 513,506 face and 1,540,518 vertices. The mesh reduction algorithm is done to the original mesh in order to optimize the speed of calculation. We reduced the number of mesh to 10% to lower the computation time while preserving the structure of the bone (see Figure 6).

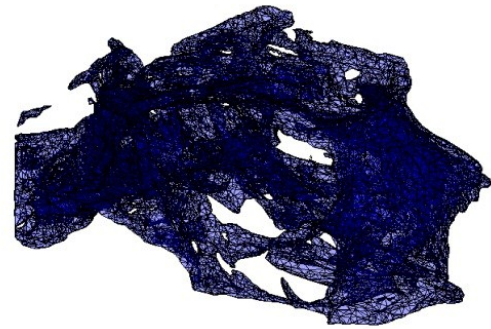


Fig 6. The reduced mesh model of the bone

#### C. Surgical path planning

For the surgical path planning. The fiducial points are placed along the surgical path passing through the region of the nostril, nasal septum, vomer and sphenoid sinus (Figure 7). The fiducial points placing method is done in 3DSlicer manually

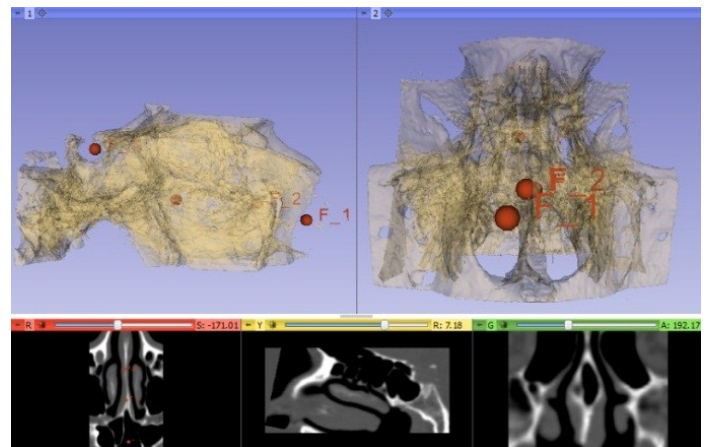


Fig 7. Fiducial points are placed along the path of the surgery.

The fiducial points that are placed at the mentioned region not only indicates the path of the medical tools, but also the points of the bone structure that needs to be drilled or removed during the surgical approach.

After the fiducial placing method for path planning is done. The surgical path is interpolated using cubic spline interpolation to create the set of points along the path (Figure 8).



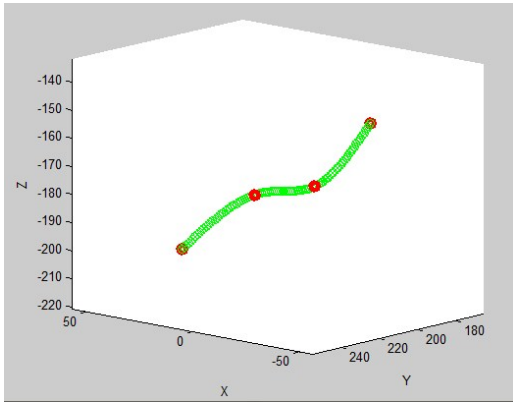


Fig 8. The set of point represent the path of the tools in Cartesian coordinates system.

Once the surgical path is planned. Another set of fiducial points are placed around the entrance of the nasal bone in a quadrangle shape (Figure 9). This area indicates the constraint entrance of the tools at the nostril area. The reason that we use another constraint at the entrance of the nostril is to reduce the risk of soft tissue and cartilage bone injury.

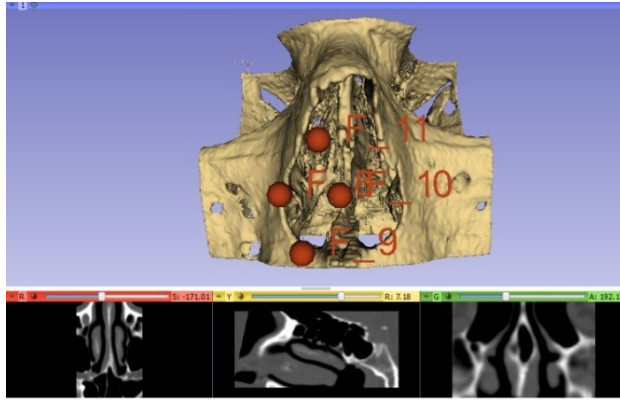


Fig 9. Fiducial points for entrance constraint

This set of fiducial points is then used to create 2 triangles that represent the entrance area of tool (Figure 10).

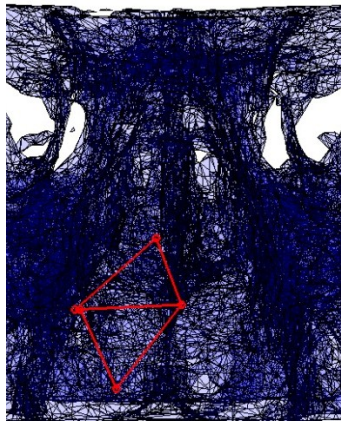


Fig 10. Two triangles represent the entrance area of tool

#### IV. COLLISION DETECTION ALGORITHM

Our basic idea for the collision detection algorithm is using the structure of face and vertices to find the intersection point between a tool that is represented in vector and the basic structure of bone model which is represented in triangles. At the first stage of the development, we will not be concerned with the shape and diameter of tools. We determine the intersection point of the vector and triangle by projecting a vector into the triangular plane. If a projected point is inside the triangle, the vector is passing through the triangle and the collision occurs.

A line that represents a tool has the length of 20 cm which is the length of a medical dissector. We define 2 points which represent the origin and the tip of the tools respectively as

$$P_{origin} = (x1, y1, z1) \quad \text{and} \quad P_{tip} = (x2, y2, z2)$$

. The parametric equation of a 3D line is given by

$$x = x1 + (x2 - x1)t \quad (1)$$

$$y = y1 + (y2 - y1)t \quad (2)$$

$$z = z1 + (z2 - z1)t \quad (3)$$

When  $t$  is the symbolic parameter

To find a plane equation, first we calculate the face normal of triangle by finding the cross product of two edges of the triangle. The points of the triangle can be written as

$$P_1 = (x1, y1, z1)$$

$$P_2 = (x2, y2, z2)$$

$$P_3 = (x3, y3, z3)$$

And the vectors that represent the edge of the triangle are

$$\overrightarrow{P_1P_2} = (x2 - x1, y2 - y1, z2 - z1) \quad \text{and}$$

$$\overrightarrow{P_1P_3} = (x3 - x1, y3 - y1, z3 - z1)$$

The normal of the triangle can be calculated with the cross product of two vectors.

$$\vec{n} = \overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3} = \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} =$$

$$\begin{bmatrix} (y2 - y1)(z3 - z1) - (z2 - z1)(y3 - y1) \\ (z3 - z1)(x2 - x1) - (x2 - x1)(z3 - z1) \\ (x2 - x1)(y3 - y1) - (y2 - y1)(x3 - x1) \end{bmatrix}$$

With point  $P_1$  and normal vector  $\vec{n}$  of a plane, we can find the equation of the plane by using vector equation of the plane. Given  $P$  any point in the plane.

$$P = (x, y, z)$$

The vector equation of the plane is

$$\vec{n} \cdot (P - P_1) = 0$$

And the vector equation of the normal plane equation is

$$\begin{aligned} & ((y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_3 - y_1))x + \\ & + ((z_3 - z_1)(x_2 - x_1) - (x_2 - x_1)(z_3 - z_1))y + \\ & + ((x_2 - x_1)(y_3 - y_1) - (y_2 - y_1)(x_3 - x_1))z + \\ & - \left( \begin{array}{l} (x_1 + (x_2 - x_1)t)x_1 + ((z_3 - z_1)(x_2 - x_1) + \\ -(x_2 - x_1)(z_3 - z_1))y_1 + ((x_2 - x_1)(y_3 - y_1) + \\ -(y_2 - y_1)(x_3 - x_1))z_1 \end{array} \right) \\ & = 0 \end{aligned} \quad (4)$$

To find the point of intersection we substitute equation (1), (2) and (3) for (4) and get

$$\begin{aligned} & \left( \begin{array}{l} (y_2 - y_1)(z_3 - z_1) + \\ -(z_2 - z_1)(y_3 - y_1) \end{array} \right) (x_1 + (x_2 - x_1)t) + \\ & + \left( \begin{array}{l} (z_3 - z_1)(x_2 - x_1) + \\ -(x_2 - x_1)(z_3 - z_1) \end{array} \right) (y_1 + (y_2 - y_1)t) + \\ & + \left( \begin{array}{l} (z_3 - z_1)(x_2 - x_1) + \\ -(x_2 - x_1)(z_3 - z_1) \end{array} \right) (z_1 + (z_2 - z_1)t) + \\ & - \left( \begin{array}{l} ((y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_3 - y_1))x_1 + \\ ((z_3 - z_1)(x_2 - x_1) - (x_2 - x_1)(z_3 - z_1))y_1 + \\ ((z_3 - z_1)(x_2 - x_1) - (x_2 - x_1)(z_3 - z_1))z_1 \end{array} \right) = 0 \end{aligned} \quad (5)$$

Then we solve the equation (5) for t and substitute the result in equation (1), (2) and (3) to get the intersection point of the plane and vector.

$$P_{intersect} = (x_i, y_i, z_i) \quad (6)$$

After we get the point of intersection, we have to find out if the point of intersection is inside the triangle or not. To obtain the result, we used the property of Barycentric coordinate system. Given that point  $P_{intersect}$  is a point on the plane and  $P_1, P_2,$  and  $P_3$  are the vertices of the triangle. We can write the equation in Barycentric coordinate system as

$$P_{intersect} = \alpha P_1 + \beta P_2 + \gamma P_3 \quad (7)$$

Where  $\alpha, \beta$  and  $\gamma$  are the area coordinate of point  $P_{intersect}$  in Barycentric coordinate and

$$\alpha + \beta + \gamma = 1 \quad (8)$$

From the equation (7) we can express the coordinates as

$$\begin{aligned} x_i &= \alpha x_1 + \beta x_2 + \gamma x_3 \\ y_i &= \alpha y_1 + \beta y_2 + \gamma y_3 \\ z_i &= \alpha z_1 + \beta z_2 + \gamma z_3 \end{aligned}$$

and write in matrix form as

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \cdot \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}$$

Rearrange to

$$\begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} = \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \end{bmatrix}^{-1} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \quad (9)$$

By using matrix properties, we can solve (9) and obtain  $\alpha, \beta, \gamma$

To determine the point location, we can use the basic properties of Barycentric coordinates. If the intersection point lies in the triangle, the Barycentric coordinates of the point should be between 0 and 1.

The calculation of the intersection points between a vector and bone structure model which consists of large amounts of triangles will be very long, so we reduce the computation time by using the threshold of Euclidean distance between the tool position and the mesh vertices. The threshold method is applied to all vertices point of a triangle. We apply the intersection calculation between the line and triangle if Euclidean distance from every vertex point of a triangle to a line is less than threshold.

From our model the calculation of a full triangle in a mesh model of 51,350 faces is reduced to around 7,000 faces per calculation. The minimum Euclidean distance for the threshold method is extracted from the longest edge of triangles in our model to ensure that every intersected triangle is in the set of calculation.

## V. SIMULATION

We create the simulation of the system in MATLAB program. The position and orientation of the tool can be adjusted by using homogeneous transformation. The rotation point of a tool is located at the tool tip.

Homogeneous transformation from origin point (0, 0, 0) to tool tip ( $x_t, y_t, z_t$ ) can be described as below

$${}_{origin}^{tip}H = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma & x_t \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma & y_t \\ -s\beta & c\beta s\gamma & c\beta c\gamma & z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where  $c\alpha = \cos(\alpha)$ ,  $s\alpha = \sin(\alpha)$  and so on.

And the Homogeneous transformation from tool tip to the end of tool handle is

$${}_{end}^{tip}H = \begin{bmatrix} 1 & 0 & 0 & x_t + L \\ 0 & 1 & 0 & y_t \\ 0 & 0 & 1 & z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where L is the length of the tool.

So we can find the Homogeneous transformation from origin point to the end of tool handle

$${}_{end}^{origin}H = {}_{tip}^{origin}H {}_{end}^{tip}H$$

In the simulation, the user can freely move a tool by using the slide bar in MATLAB GUI to move the tool into a bone structure of the skull base area. The tool has to pass through the entrance area of a nostril indicated by a red quadrangle (Figure 11). If the tool is going outside the entrance area or colliding with the bone model, a red circle will appear at the area of collision and prevent the tool from moving further (Figure 12).

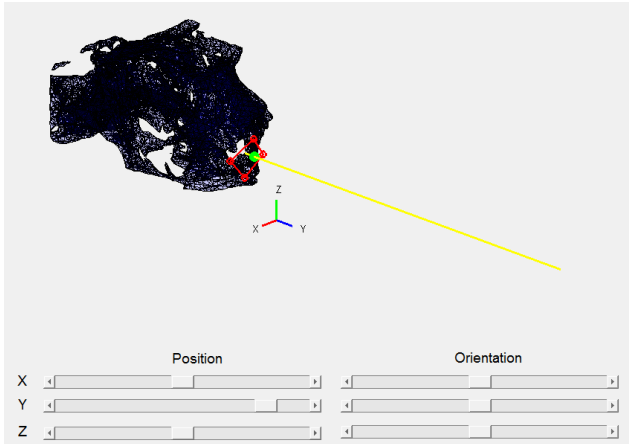


Fig 11. The simulation show bone model (in blue color), entrance area (in red color) and tool (in yellow color) along with the user interface to control position and orientation of the tool.

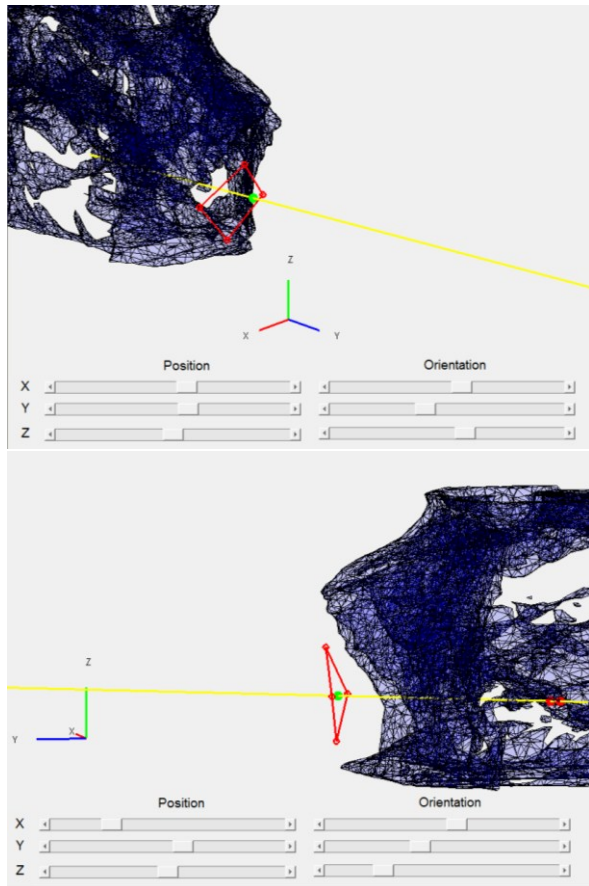


Fig 12. When the collision is occurred between tool and bone model, the red circle is appear at the area of collision.

## VI. CONCLUSION

This paper presents the development of a navigation system for surgical robotic system to aid in the endoscopic transsphenoidal surgery. The navigation system is based on a 3D model of skull base workspace which is created from CT images. Fiducial points are used to generate a path of the surgery inside the skull base workspace.

For the collision detection of tools and anatomical structure, a geometry approach for solving the collision detection is presented. This algorithm is preliminary implemented which the full implementation requires large amount of computation for each loop of detection. Therefore, a computational method to reduce the computational time will be added to speed up the collision detection. Example algorithms, such as, Broad phase and narrow phase algorithms, which are normally used in game physics, are planned for future implementation.

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