Chapter 7

DESIGN AND DEVELOPMENT OF SOFTWARE FOR COMPUTER ASSISTED SURGERY

In this work, we propose a novel computer assisted method for accurate placement of pedicle screws for different spinal disorders. The location and orientation of the pedicle screws are clinically important in pedicle screw fixation. The point of insertion is determined using the image slices of diagnostic CT. The orientation of the pedicle screw is determined by processing the video streams captured online during the surgical process using two digital cameras. Mathematical morphology based techniques are employed for screw segmentation and Hough Transform for angle determination. This is a very less expensive system with a personal computer and two digital cameras, and can be assembled on demand very quickly. The system has proved to have clinical precision required for spine surgery and extremely useful in medical education field for surgery training.

7.1 INTRODUCTION

Spinal fusion and Pedicle screw fixation techniques are usually used in the case of vertebral fractures, dislocation, scoliosis, kyphosis, spinal tumor, failed previous fusion (pseudarthrosis) and for the severe back pain that doesn't respond to other therapies. The biggest challenge in the surgery is accurate placement of the pedicle screws.
The pedicle is surrounded by many sensitive structures and is not visible during pedicle screw insertion. Screw malposition is the primary cause of complications like pedicle wall perforation, nerve roots and cord impingement, and very rarely damage to vascular structures [1]. Nerve root and cord impingement alone occurs in 6.6% of all placements [2]. Therefore exact location of initial point of entry and screw orientation is of great importance.

Many computer-assisted techniques such as Robotic method [3], Fluoroscopic method [4], Virtual fluoroscopic method [6,7], Rapid prototyping [8] etc. have been developed in recent years to help doctors get the best possible alignment of pedicle screws. Even though these methods claim above 90-percentage accuracy, setting up of these instruments are very costly and have side effects like exposure to radiation. Even though radiation hazard is eliminated in imageless systems, they are very expensive.

A less expensive technique with minimal hardware is proposed here to locate the initial point of entry and to track the trajectory of the pedicle screw in real time with the help of Image processing and Computer graphics techniques.
7.2 METHODS AND MATERIALS

The proposed technique is based on online capturing and processing of the video of the surgical procedure. The setup is arranged by placing the cameras on their holders at a distance of approximately 2 m and at a height of 1.5 m from the vertebra of interest orthogonal to each other. The computer system is arranged with the monitor at a viewable distance from the surgeon. The entire setup does not cause any interference to the surgeon. The system provides a view of the video and the corresponding cylinders are drawn with the orientation of the pedicle screw marked as its axis. A sketch of the system is shown in Figure 88.

Pre-operative planning

The pre-operative planning stage involves a sequence of steps like identifying the vertebrae where pedicle screws need to be inserted, selection of appropriate representative image of the vertebra, marking land mark points, computing the parameters of the pedicle area visualized as a cylinder etc. This process needs to be done for each of the vertebrae involved in the procedure.

The axial CT image of a vertebra consists of at least eight or nine slices with a
The fourth or fifth slice of the candidate vertebra is the best representative image. From this image, the surgeon can determine any deviations from normal anatomy, and obtain a feel of pedicle dimensions and relationships to the transverse process and facet joint. The transverse image is used to determine the pedicle width, angle, relationship with other anatomical structures, and distance to important anterior vascular structures (e.g., aorta). Two vertical lines in the spinous process and one in the middle of the superior articular process are drawn in the image manually to aid the registration of the online captured video. Another two lines are drawn through the center of the pedicle area from the lamina to the vertebral body as the approximate path of the pedicle screw. This reference image is used for registration at the time of surgery. Such a reference image is shown in Figure 89.

Figure 88 - Sketch of surgical setup
Figure 89 - An example reference
Pedicle has a non-uniform cylindrical shape with varying diameter across its length. A sketch of the possible cylinder is shown in Figure 89. The diameter of the cylinder is approximated as the minimum diameter of the pedicle. The parameterization of the cylinder is carried out using a 3D model of the candidate vertebra constructed using the eight or nine slices of the CT image. We used '3D DOCTOR' [9] software package for the vertebra modeling, in which the region of interest (i.e., pedicle area) in each CT slice is marked and stacked together to obtain a 3D model. From the transverse and the sagittal view we could obtain the height and radius information of the cylinder. This cylinder is used for visualization of the trajectory of the pedicle screw at the time of surgery.
7.2.2 Image Registration and surgery

After surgical exposure of the spine, the registration of the reference image is carried out by overlaying it with online video captured by adjusting the focus of the camera so that the dimension of the objects present in both match. For this, two needles are placed in the spinous process and one in the middle of the superior articular process. The zoom of the camera is adjusted so that the needles in the captured video are exactly overlapped with the lines drawn on the planned image. After successful registration, the drill is placed on the pedicle area and its location is adjusted to coincide with the entry point marked in the reference image.

The next step is the correction of orientation of pedicle screws in two planes so that it correctly enters the canal of the pedicle and the vertebral body. The pedicle screw will not be visible in the video, but the orientation of the drill guide and screw inserter, which is clearly visible, can be taken as that of the screw. The drill guide and the screw inserter have clearly distinguishable structural properties and appearance, in comparison with other objects present in the video. By making use of this, a mathematical morphology based technique is employed for segmentation and automatic estimation of the orientation of the drill guide. Binary mathematical morphology is an algebraic system based on set theory that provides two basic operations: dilation and erosion [10,11]. Images are considered as sets of points on which set operations can be performed. The Dilation operation grows or thickens
objects in a binary image based on the shape referred to as a structuring element. Erosion shrinks objects in a binary image. As in the case of dilation, the manner and extent of shrinking is controlled by a structuring element.

The online video stream captured during surgery is processed by extracting frames one by one. Each grabbed RGB image from the stream is first converted into gray scale image and histogram equalization is performed to enhance the contrast between the drill and the surrounding regions. The histogram equalized image is then high pass filtered using a Canny’s edge detector to boost the edges. The Canny’s edge detector finds edges by looking for local maxima of the gradient, which is calculated using the derivative of a guassian filter.

\[ I(x,y) = \left[ (\partial f/\partial x)^2 + (\partial f/\partial y)^2 \right]^{1/2} \]  \text{Where I is edge detected binary image}

Now, mathematical morphology is applied on this edge boosted image to segment the drill guide. The edge-boosted image is then dilated using a line shaped structuring element of length 5. The dilation of binary image I by Se, is defined as \( I = I \oplus S_e = \{ z | (\hat{1})_z \cap S_e \neq \emptyset \} \); Where \( \emptyset \) is the empty set and \( S_e \) is the flat line shaped structuring element having a length of 4. The dilated image is filled with background pixels surrounded by foreground pixels, according to the neighborhood defined by 8-connectivity.
\[ l_2 = X_k = (X_{k-1} \oplus S_{e_2}) \cap l_1^c; \ k = 1, 2, 3, \ldots \]

where \( X_k \) is the region filled with 1's in \( k \)th iterative step, \( S_{e_2} \) is the flat symmetric structuring element with radius 1 and \( l_1^c \) is the complement of the dilated image. This image is then eroded with a 2-Dimensional flat structuring element \( S_{e_3} \), which is 'disk' shaped in the Euclidean metric and centered at the origin and its radius is chosen as 2. The erosion of \( l_2 \) by \( S_{e_3} \), can be represented as:

\[ l_3 \ominus (S_{e_4}) = l_3 - (l_3 \odot (S_{e_4})); \]

where \( \{S_{e_4}\} = \{S_{e_4}^1, S_{e_4}^2, S_{e_4}^3\} \). \( S_{e_4} \) is the line shaped structuring element sequence with a length of 1 pixel from the origin, \( S_{e_4}^2 \) is the rotated version of \( S_{e_4}^1 \). The resultant image is one with the drill guide as the prominent object present with its side as two long straight lines.

\[ l_3 = l_2 \ominus S_{e_3} = \{z \mid (S_{e_3}) z \subseteq l_2 \} \]

Any parasitic elements present after erosion are removed by repeated thinning operation based on morphological hit or miss transform specifying that length of the parasitic component does not exceed a specified number of pixels.

The orientation of the drill guide is computed by locating the strongest line in the segmented image using Hough transform \([10, 11]\), which is a mapping from image plane to parameter space. The computed angle \( \theta \) of the drill
guide is the orientation of the pedicle screw in that plane. The flow chart shown in Figure 90 shows the steps involved for extracting the drill guide and the detection of screw mal position.

7.2.3 Experimental setup and Results

The new technique was evaluated by inserting pedicle screws on lumbar vertebra of artificial spine. An axial CT was taken of the spine for pre-operative planning. Three Lumbar vertebrae (L1, L3, and L5) were considered for experiment and their respective reference image was prepared by marking spinous and articular processes. All the three vertebrae were 3D modeled using '3D Doctor' software and the dimensions of the cylinders were measured. The process involved insertion of six pedicle screws. The position of the sidewise camera was adjusted based on the vertebra where the screw was inserted. The position of the camera on the anterior view does not change with the change in vertebra.

The image registration27 was carried out by adjusting the focus of both the cameras to match the respective reference image. The drill guide was successfully segmented and its orientation was computed. The possible track
of the pedicle screw was refreshed as a marker on the cylinder displayed on
the view provided by the system. The orientation of the drill guide was
adjusted in both planes in such a way that, the marker, passes the bottom
surface area of the cylinder. A post operation axial CT was taken to validate
the accuracy of the pedicle screw insertion carried out. The result was very
promising. Two frames were processed per minute from each video stream
with Pentium '4, 1.8 GHz machine. The small delay in refreshing the pedicle
screw path does not adversely affect the procedure. This can be corrected
by further fine-tuning the segmentation and line detection module of the
software system.

7.2.4 Conclusion

A CT-based image guided less expensive method using image processing
and computer graphics techniques for accurate placement of pedicle
screws during spine surgery\textsuperscript{31} is discussed in this chapter. The approximate
path of the pedicle screw in two planes is displayed online during surgery,
aiding the surgeon to correctly insert the screw into the vertebral body. The
system developed is a less expensive one with two removable digital cameras
and a personal computer. This method is extremely useful in medical
education as a tool in spine surgery training.
REFERENCES


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