Intramedullary Nail Distal Hole Axis Estimation using Blob Analysis and Hough Transform

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***Abstract*—In a closed intramedullary nailing of femoral surgery, one of the most difficult task for surgeons is to identify the position and orientation of the screwing holes at both ends of the intramedullary nail (IMN) after being inserted into a patient's femoral canal. The distal hole location may be shifted by external forces and torques applied to the IMN during the insertion procedure resulting in the IMN to deform. To recover the position and orientation (or "pose") of the screwing holes in the conventional operation, surgeons require high degree of experience, and a number of trial-and-error adjustments to correct the path for inserting the screws. Both surgeon and patient are also continuously exposed to a great amount of X-ray exposure from the fluoroscopic imaging system. This paper discusses a necessary part of a surgical navigation research for assisting orthopedic surgeons. This work addresses a problem of estimating the intramedullary nail (IMN) distal hole axis from a 2-D image taken from the fluoroscopic imaging system. The proposed approach is based on the geometric properties of the nail itself. The Hough transform and Blob analysis were employed as main image processing tools. The preliminary results show that the proposed method performed satisfactorily. However, there are several limitations associated with this approach. In particular, the proposed method cannot differentiate estimated distal hole angles in the first quadrant from the second quadrant.**

***Keywords*—Intramedullary, Closed Nailing, Orthopedics Surgery, Robot-Assisted Surgery, Computer-Integrated Surgery, Fluoroscopic Navigation.**

I. INTRODUCTION

Minimally invasive surgery (MIS) is currently popular because of its advantages especially the patient recovery period which can be reduced significantly. Computer-integrated surgery (CIS) has gained more interest from biomedical researchers [1-4], because it can reduce complexity in MIS procedures. A frequent orthopedic MIS case is the closed intramedullary nailing of femur (or Closed Nailing) as shown in Fig. 1 [5]. Similar to other MIS cases, this surgery requires accurate positioning and orientating of medical inserting devices (e.g. nail) with respect to the internal organs (e.g. femoral fractures). During the conventional Closed Nailing surgery, both surgeon and patient are continuously exposed to a great amount of X-ray exposure from the fluoroscopic imaging system. Long term X-ray exposure could harm both the surgeon and patient. Fig. 2 shows a scene in a Closed Nailing surgery where involved healthcare personals are exposed by X-ray.

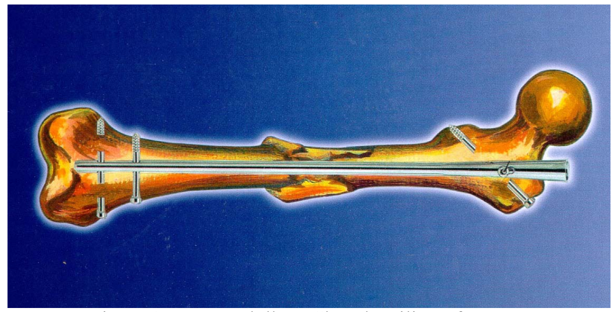

Figure 1. Intramedullary Closed Nailing of Femur.

Thus, a new approach was proposed by Suthakorn *et al.* [6] to aid surgeons in recovering the position and orientation of an intramedullary nail after being inserted into a patient's femoral canal. This approach utilizes both fluoroscopic and optical stereoscopic systems with a computer-integrated method. The method includes using a 3-D tracking system with markers, and mapping coordinate frames and axes received from fluoroscopic images into real-time optical-images on a computing system. A mathematical model and an algorithm are developed to generate a guiding path for the surgery guidance system. Zhu *et al.* presented a similar approach to derive the 3-D position and orientation of the distal hole axis using two radiation images [7].

Figure 2. Image shows a number of healthcare personals who are exposed to X-Ray during a Close Nailing Surgery.

In a closed nailing surgery, one of the most difficult tasks for surgeons is to identify the position and orientation of the screwing holes at both ends of the intramedullary nail after being inserted into a patient's femoral canal. The hole location may be shifted by external forces and torques applied to the IMN during the insertion procedure resulting in the deformation of the IMN. To recover the position and orientation (or "pose") of the screwing holes in the conventional operation, surgeons require a high degree of experience, and a number of trial-and-error adjustments to correct the path for inserting the screws. This can be done by gradually adjusting the shooting angle until the projection of the two screwing holes is seen to be as circular as possible on the X-ray image. The concept of the proposed approach is to utilize a hybrid system of a fluoroscopic system and an optical stereoscopic system to quickly recover the screwing holes on the IMN, and to reduce the number of trial-and-error adjustments.

The operation starts after the surgeon inserts an IMN into the femur canal and sets the fractured bone into the desired position [6]. Two markers are attached to the patient in the location that can be seen from both fluoroscopic and optical stereoscopic imaging systems. Fig. 3 shows experimental markers proposed by our research group. The attaching procedure is done by attaching each marker directly to the distal and proximal part of the fractured bone through the skin (one marker for each position.)

Figure 3. Experimental Active (Left) and Passive (Right) Marker.

Then, two X-ray images are taken by the fluoroscopic (C-Arm) system from different angles. The image processing and pattern recognition methods are used to generate (1) the frames attached to the markers, (2) the axis of the IMN and its perimeter, and (3) the screwing holes' location and orientation (pose) on the IMN. Note that in most cases, the shape of screwing holes viewed on X-ray images are elliptical as shown in Fig. 4, and a set of diagrams comparing between optical stereoscopic and fluoroscopic images is shown in Fig. 5.

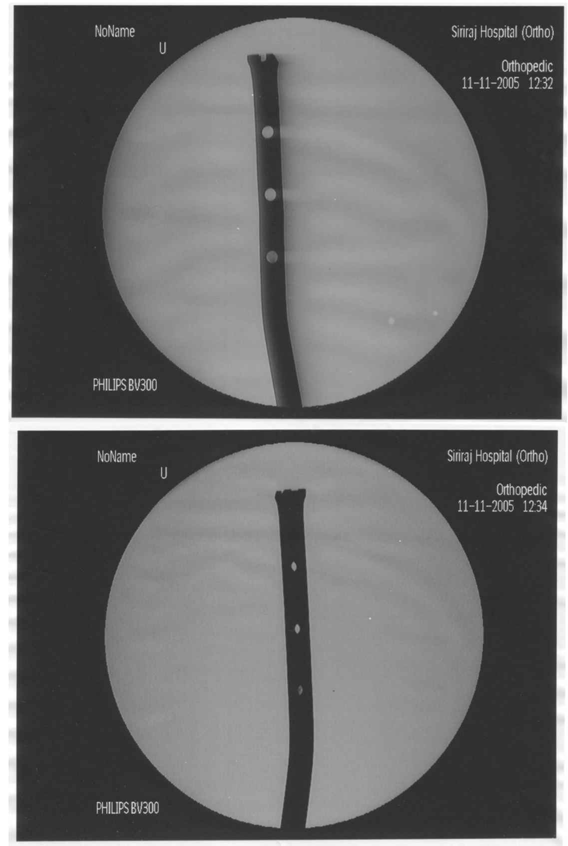

Figure 4. IMN distal holes are shown at different angles of view. Top image shows the distal holes while their axes are perpendicular to the Fluoroscopic image plane, and Bottom image shows the distal holes at a rotated angle.

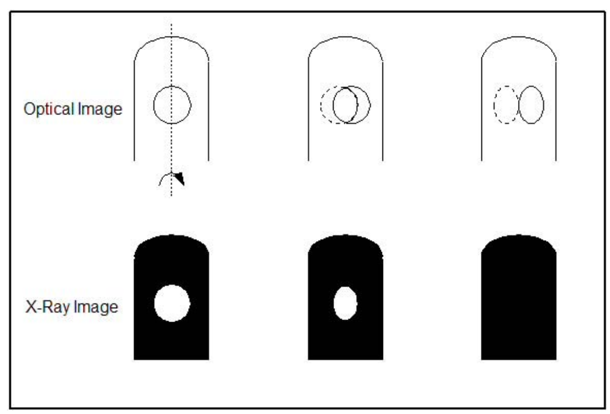

Figure 5. IMN diagram comparing images as seen from the optical stereoscopic (upper) and fluoroscopic (lower) systems.

Simultaneously, the optical stereoscopic imaging system is capturing and generating the frames attached to the same markers. A computer algorithm registers generated frames from both systems thus producing an insertion path which aids surgeon to navigate during the screw inserting procedure. Because the marker is fixed rigidly to the bone and visible on the optical stereoscopic images, the computer software uses this information to construct and track the insertion path, regardless of the patient's movement.

During the screw insertion procedure, the proposed system requires only real-time images from the optical stereoscopic system which can be taken continuously and without risk of radiation exposure. The pre-registered insertion path generated from the algorithm is mapped onto the real-time optical images. The real-time images are shown on the monitors from two different views and angles so that the surgeon can use this guiding path to aid the surgical navigation.

II. Surgical Navigation Research at Mahidol University

Research in development of surgical navigation system for orthopedic surgery at Mahidol University can be described in stages as follow:

A. Medical Information Retrieval Stage

The first stage is to collect medical information and physician's requirements. This also includes a series of surgery observations. The stage results create a set of constraints and directions in conducting the following research.

B. Methods and Algorithm Development Stage

This stage consists of fluoroscopic image processing, mathematical modeling and information processing, surgical planning, image mapping and monitoring. Fluoroscopic image processing is to extract distal hole figures from an X-ray image. The mathematical modeling and information processing are to retrieve distal hole position and orientation using information from X-ray images. Surgical planning is to generate a guiding path for physician to follow. Image mapping is to map generated guiding path and other information from X-ray images onto optical images from an optical stereoscopic system. Monitoring is to display and interface between navigation system and surgeon. Each subsystem is to be developed separately and integrated in the next stage.

C. Instrumentation Development Stage

This stage is to utilize all knowledge and subsystems from previous stages to develop a prototype set of navigation system. This is to prepare for physical and clinical trials in the next stages.

D. Stage of Physical Experiment in Lab Set up

This experiment stage is to test and improve the system which will be performed in a laboratory environment. The end of this stage is to systemically test the proposed system in artificial bones or cadavers.

E. Clinical Trial Stage

This stage will not be started until physicians and the ethics board would give us a permission to perform the clinical trials. This stage is to demonstrate and micro-adjust a prototyped surgical navigation system. A full surgical navigation system is depicted in Fig. 6.

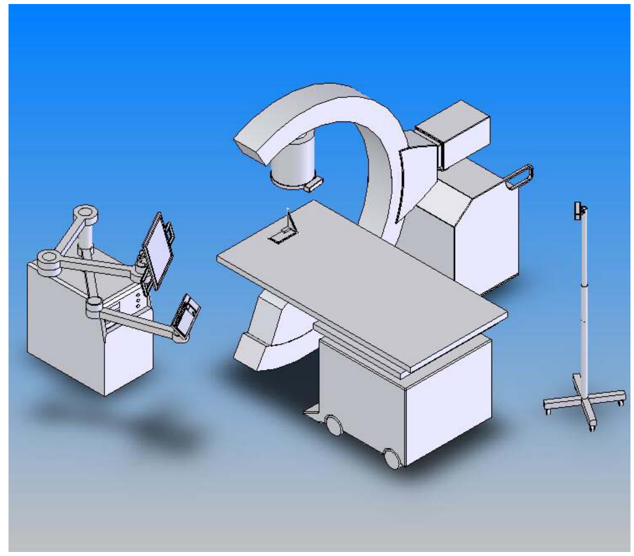

Figure 6. Image depicts a full surgical navigation system in navigation research at Mahidol University.

III. Problem Statement And Formulation

Due to the complexity of current research problems, this paper focuses on how to determine the axis of the IMN and its perimeter, and the screwing holes' locations (using a 2-D fluoroscopic image) without trying to relate the IMN axes and IMN hole pose to the frames of reference generated using the markers.

Also, to further simplify the problem, it is assumed that the IMN translational movement is allowed in the X and Y directions (as shown in Fig. 7), whereas the IMN rotational movement is allowed in the X axis.

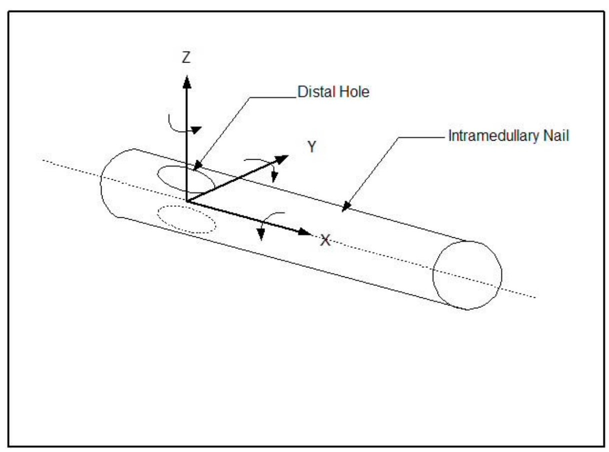

Figure 7. Distal hole axes.

IV. Method

The estimation of IMN distal hole axis can be divided in to a number of tasks. Fig. 8 illustrates the entire procedure. The proposed method is based entirely on the geometry of the IMN. It requires that the IMN outer diameter, *dN*, and IMN distal hole's diameter, *dH*, are known in order to properly estimate the IMN distal axis's orientation (or the ratio of *dH/dN*). Based on this information, the distal hole axis (angle) can be estimated by measuring the opening size of the distal hole and IMN outer diameter from the fluoroscopic image.

The first task is to convert black-and-white images of the IMN to binary images using the basic auto-threshold procedure. Then, the edge detection algorithm (in this case the Sobel method) is applied to the binary images. The IMN outer diameter can be estimated using the well known Hough transformation [8]. The Hough transform is designed to find lines (edges) in images. This transform is based on a simple idea. Suppose (*x, y*) is a point in the binary image. A single line or multiple lines can be detected if all pairs (*a,* b) satisfying a straight line equation $y=ax+b$ are considered by plotting them into an accumulator array, whereas the (*a, b*) array is the transform array. Possible candidates of straight lines in the image under analysis can be found from the accumulator array. The first two prominent Hough lines in the accumulator array indicate the perimeter of the IMN. The *dN* can be approximated by using these two Hough lines.

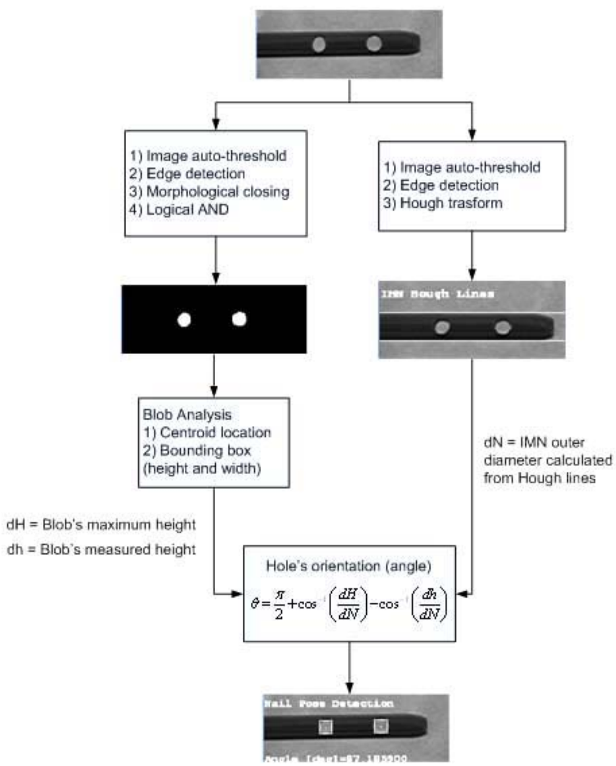

Figure 8. IMN distal hole orientation (with respect to the X axis, Fig. 7) estimation procedures.

In order to measure the distal hole opening (indicated by white pixels surrounded by black pixels) three additional tasks were performed. First, the one-pixel edge of the distal hole opening was closed by applying the morphological closing operation. This morphologically closed image was, then, subtracted from the edged image to separate the distal hole opening. Next, the logical AND operation between the edge image and the subtracted image was performed to get rid of the excessive boundary pixels, due to the image subtraction in the previous step, as shown in Fig. 8.

The distal hole opening is measured by applying the Blob analysis [9]. The Blob analysis is an image processing algorithm for a group of pixels organized into a structure, in this case the distal hole opening. For example, the pixels making up each cell in an image of red blood cells can be thought of as blobs. Blob analysis can be used to calculate statistics for labeled regions in a binary image, such as the boundary and the centroid of a group of binary connected pixels, as values that represent spatial coordinate locations. The measured distal hole opening height is represented by *dh* variable.

Furthermore, the IMN outer diameter, *dN*, and the measured distal hole opening, *dh*, are used to calculate the IMN distal hole axis orientation (or angle, θ) – See Fig. 9. By applying basic geometry, the angle θ can be written in terms of *dh*, *dH*, and *dN*. If the ratio of the IMN distal hole diameter and the IMN outer diameter is known, then

$$\beta = \cos^{-1}\left(\frac{dH}{dN}\right) \tag{1}$$

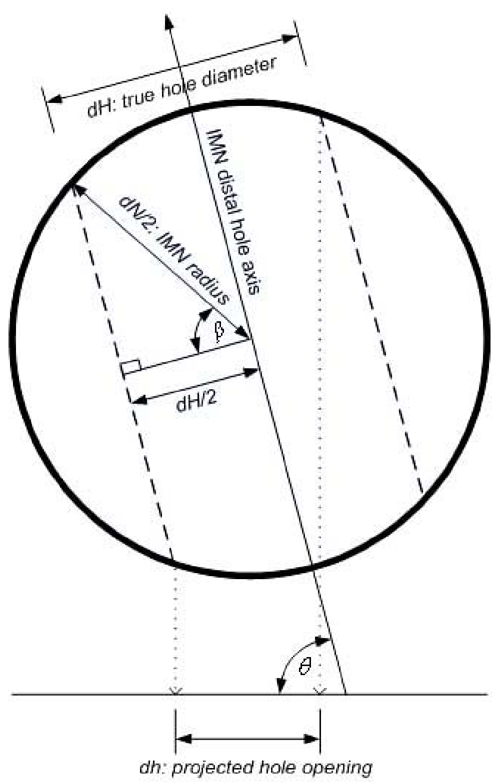

Figure 9. Lines represent the distal hole.

Using this fact, it can be shown that

$$\theta = \frac{\pi}{2} + \beta - \cos^{-1}\left(\frac{dh}{dN}\right) \tag{2}$$

The distal hole axis orientation (angle) is a function of the distal hole opening height. The proposed method was implemented within the MATLAB/SIMULINK environment [10].

V. TEST IMAGES AND ESTIMATION RESULTS

The test images were generated using a CCD camera. An IMN was arranged so that it can be rotated around the X-axis. The test images were taken on a white and illuminated background to mimic a fluoroscopic image. The IMN was rotated (around the X-axis) in steps of 10 degrees from 60 to 90 degrees. There is no need for a complete rotation of the IMN because the solutions of θ using Eq. (2) are the same in the first and second quadrants. Furthermore, the distal hole opening disappears when the IMN is rotated more than β degrees, due to the fact that

$$\theta = \frac{\pi}{2} + \beta - \cos^{-1}(0) = \beta \qquad (3)$$

Fig. 10 shows the detected Hough lines outlining the IMN perimeter. The effect of discretization in the accumulator array is visible in the lower panel of this figure. Figs. 11 – 13 show the resulting distal hole axis orientation at different angles. It is clear that the proposed approach can estimate the IMN orientation, properly.

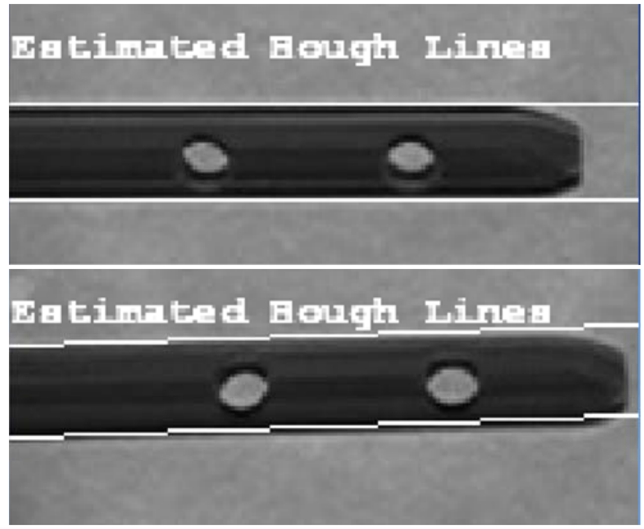

Figure 10. IMN outer perimeters outlined by two Hough lines.

Figure 11. Estimated angle of the IMN distal hole (true θ= 70 degrees).

Figure 12. Estimated angle of the IMN distal hole (true θ= 80 degrees).

Figure 13. Estimated angle of the IMN distal hole (true θ= 90 degrees).

VI. DISCUSSIONS

According to Fig. 10, the rotation around the Y-axis can distort the detection of IMN outer diameter. The Hough transform may not be able to recover correct IMN perimeters due to the discretization in the accumulator array. In addition, this rotation can interfere with the estimation of the distal hole orientation (angle). Figs. 11 – 13 show that the estimated angles are within an acceptable range in spite of the existence of the Y-axis rotation. This statement may be misleading because the rotation is too small. The Blob analysis provides additional information about centroid locations of the distal hole opening blobs (shown as white dots in Figs. 11 – 13). This information can be adjusted to represent the reference point of origin for the distal hole axis. A mathematical transformation based on the distal hole orientation is required to properly adjust these locations. Another disadvantage associated with this approach is that it is unable to differentiate axis angles calculated from the first and second quadrants. This is due to the fact that only one 2-D image was considered per session, in this work. If two images of the same IMN (but taken from different points of views) were used, then this problem would be solved.

VII. CONCLUSION AND FUTURE WORKS

An approach based on geometric properties of the IMN was described in this paper. This approach utilizes both the Hough transform and the Blob analysis as tools to recover the IMN distal hole axis from a 2-D fluoroscopic image.

The preliminary results show that this approach performed satisfactorily. However, it was unable to differentiate axis angles within the different quadrants. This work is a part of necessary sequential research toward development of surgical navigation system for orthopedic surgery.

The future works are to incorporate the image processing of two fluoroscopic images to the proposed method and include the frames of reference generated from the attached markers thus producing the insertion path to be used by the surgical guidance system. Furthermore, the accuracy of the proposed method is not thoroughly studied. It will be carried out in the near future.

ACKNOWLEDGMENT

This work was supported in part by the National Electronics and Computer Technology (NECTEC) of Thailand. The authors wish to thank Prof. Dr. Banchong Mahaisavariya of Siriraj Hospital School of Medicine, Mahidol University, for his invaluable help. The authors also would like to thank all researchers in Biomedical and Robotics Lab (BART Lab), Mahidol University for assistance and suggestions.

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