On the Design and Experiments of a Fluoro-Robotic Navigation System for Closed Intramedullary Nailing of Femur

Sakol Nakdhamabhorn and Jackrit Suthakorn

Abstract. Closed Intramedullary Nailing of Femur is a frequent orthopedic surgical operation. Traditionally, surgeons are performing the procedure based real-time on fluoroscopic images. Therefore, a great amount of X-Ray is exposed to both patient and surgeon. One of the most difficult tasks is the distal locking process which requires trail-and-error and skill for understanding 2D images generated from 3D objects. This paper describes the overall design and experimental sections of our research series on developing a surgical navigation system using a robot guiding device based on fluoroscopic images. Two approaches with and without employing optical tracking to generate relationship among tools, patient, and imaging system are presented. Moreover, a new technique to interface between surgeon and system is proposed to reduce the problem of hand-eye coordination on most surgical navigation system. This work is built on our previous work on path generation for distal locking process. Our experiment results show a promising solution for guiding the surgeon during the distal locking process in Closed Intramedullary Nailing of Femur.

Keywords: Fluoroscopic Navigation, Surgical Navigation, Robot-Assisted Surgery, Computer-Integrated Surgery, Intramedullary Nailing.

1 Introduction

1.1 Motivation

Closed Intramedullary Nailing or "Closed Nail" is a frequent orthopedic surgical procedure for fixing a long bone, such as, femur or humerus bones. The closed

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nailing procedure starts with bone fixing, guide-wire inserting, bone canal reaming, nailing inserting and screw locking. Traditionally, surgeon is performing the procedure based on the real-time fluoroscopic images. Therefore, both patient and surgeon are exposed with a large amount of X-Ray exposures [1]. One of the most difficult tasks is the locking process, especially, the distal locking process. This requires a number of trials and errors with high skill to realize the 3D object from the 2D fluoroscopic images. This skill is required for realizing the position and orientation of screw locking path.

This paper describes the overall design and experimental sections of our research series on developing a surgical navigation system using a robotic guiding device based on fluoroscopic images.

1.2 Related Works

Numerous computer-integrated surgical systems [2-3] have been released to assist surgeons in various operations. The goal is to reduce the difficulties in process, to reduce time consuming and to use less of X-ray exposure. Yaniv and Joskowicz [4-5] developed a precise robot to guide in positioning the distal locking intramedullary nail. The system is automatic positioning a mechanical drill guide mounted on a miniature sized robot using a fluoroscopic image. The mean accuracy in vitro experiment is angular error of 1.3 degree and translation error of 3 mm.

HIT-RAOS" [6] is another system developed by Du Zhi-jiang *et al.* The system aims to assist surgeons in several steps on close nailing procedure. Such as, to reposition bone fractures, to guide the surgeon in locking process, to reduce the surgeon's working under C-arm by a tele-operation system. The system consists of patient station, computer control system and surgeon station. At patient site, a repositioning robot was developed. The operation table could adjust its position for locating the patient at different pose. The fluoroscope was modified for teleoperation so the surgeon can control the fluoroscope's position from remote position. In the registration algorithm, a pre-calibrated maker box is attached at the end of guiding robot. The system interacted with user through graphic interface.

An approach for recovery the position and orientation of distal hole's axis was previously proposed by our corresponding author [7-9]. The proposed algorithm required only the area of distal hole's projected image to recover the nail's rotation angle based on hole's area and characteristics of hole's axes. The brief description of the algorithm is explained in section 2.3.

2 Fluoro-Robotic Navigation System

This section covers overall of our navigation system, kinematic analysis and relationships, two navigation approaches with and without optical tracking, a brief description of our path generation algorithm, and guiding system.

2.1 Overall System

Our Fluoro-Robotic Navigation System can be separated into 3 major subsystems. The first subsystem is a distal locking hole recovery subsystem. This subsystem acquires a few X-Ray images from the fluoroscope to recover an axis of distal locking hole's position and orientation which are used to calculate for the path generation. The second subsystem is the mapping 2D X-Ray coordinates into the real 3D world environment coordinates. The third subsystem is the guidance system which is an important system to interact with the surgeon. In this surgical guidance system, we propose a robot-assisting guidance technique to navigate the surgeon to perform drilling the distal locking hole. Figure 1 illustrates the overall navigation system.

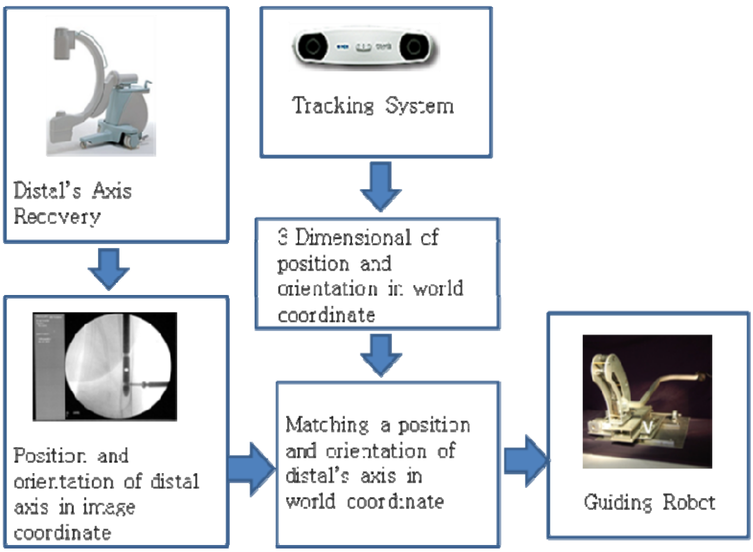


Fig. 1 The diagram of overall system.

2.2 Kinematic Relationships

An important part of the navigation system is the tracking system. This system is to determine the position and orientation of each related object in the procedure. The relationship between each object, such as, drilling tool, patient, imaging system, can be determined with the kinematic relationship. The position and orientation relationships are used in the matching process to register positions of pixels in 2D X-Ray image coordinates into the 3D world coordinates. The two approaches, which are ones with and without optical tracking, are proposed here.

2.2.1 The Approach I: With the Optical Tracking System

An optical tracking system is employed in the first approach to generate a cycle of kinematic relationships between objects. A number of optical markers are attached to; fluoroscopic imaging system, patient bone, and guiding robot. The optical tracking system provides positions and orientations in 3D-space of those three objects related to the optical tracking coordinate.

In order to generate a trajectory path for distal locking process, matching coordinates from different objects are required. The fluoroscopic calibration process is also required to register the position of each pixel in 2D X-Ray images into the position in 3D world coordinates. Therefore, the position and orientation of distal locking hold axis in the real 3D world coordinates can be determined. The homogenous transformations to demonstrate the kinematic relationships among objects are shown in Figure 2.

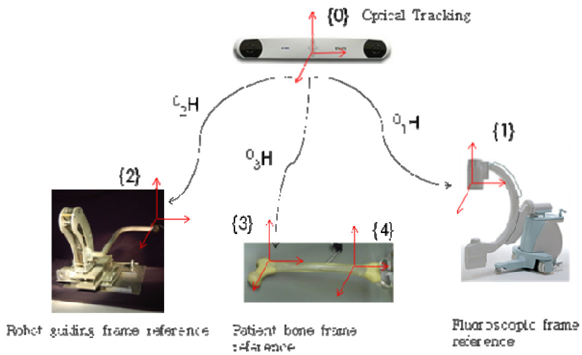


Fig. 2 Transformation diagram of this system

2.2.2 The Approach II: Without the Optical Tracking System

The second approach is employed an X-Ray marker to be attached on robotic guiding device. The shape of an X-Ray marker is designed in a circular shape which is similar to the distal locking hole's shape. The marker is attached to the end-effecter of guiding robot which to be appeared in the view of fluoroscopic image. Therefore, the position and orientation relationships between distal locking hole and the guiding robot can be calculated by comparing the rotation angle of the X-Ray marker with the angle of distal locking hole.

2.3 Recovery of Distal Locking Hole on Intramedullary Nail

The algorithm of the recovery system is based on our previous studies in [7-10]. In this algorithm, only a few images are required to realize the distal locking hole's axis. The algorithm utilizes characteristic information of the intramedullary nail, such as, nail radius, major and minor axes of distal locking hole, and the area of distal locking hole. The algorithm is separated into two iterations. The first iteration is the simulation process. In this process, the nail is rotated at all possible projection.

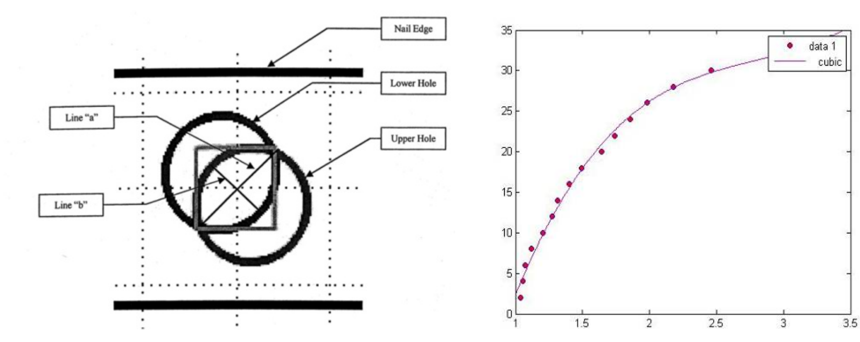
Then, the entire of simulated nail images are extracted a ratio between major and minor axes of distal locking hole. So, the ratio between major and minor axes in each rotation angle is stored together with an *X-Y-Z* Euler rotational angle in a database. This part has done in pre–operative process. The second iteration is for extracting information from the real-time distal locking hole images. The edge detection and fitting ellipse techniques are applied to find the location and other similar information from distal locking hole. The ratio between major and minor of distal locking hole is then calculated in real-time matching process to recover a distal locking hole's orientation. The cubic curve fitting is applied to find the best fit to the data in database. The curve is called "tool curve" as shown figure 3. The tool curve is used to reversely recover the rotational angle of distal locking hole's axis. This step is operated in intra-operative process. The simple cubic curve fitting equation is shown as equation 1.

$$y = ax^3+bx^2+cx+d \quad (1)$$

Where, y is the result of rotation angle in degree, a, b, c and d is a constant
x is the ratio between major and minor of distal locking hole.

2.4 Robotic Guiding System

The robotic guiding system is a significant proposed part in our surgical navigation system. This system interacts with the surgeon by automatically showing the generated surgical path. Most of navigation systems are usually displayed the guiding information through a monitor by demonstrating animation graphic on the screen. However, in the real situation, the surgeon would prefer to pay more attention on a surgical site more than the screen. Our approach removes the hand-eye coordination problem. The robotic guiding system is a 4 degree-of-freedom robot as shown in figure 4. The robot is placed at the side of the operation table. After the navigation system generates the trajectory path, the robot is then pointing the laser beam to the entry location while path orientation is also given by comparing the drilling tool axis and the laser beam axis.



(a) (b)

Fig. 3 (a) A picture show an information of distal locking hole (b) a tool curve [7-9]

In another robot guiding approach, the robot's end-effector is attached with an X-Ray marker. The robot can be designed in a smaller size than the first approach. The robot is imitated the movement of fluoroscopic system as shown in figure 5. The first joint of the robot is use to rotate about *Y*-axis of nail. The second joint is used to rotate about *X*-axis along with a nail. The guidance system starts when a fluoroscopic image is captured. The image consists of the X-Ray marker's shape, and the distal locking hole. Then, the distal locking hole axis is recovered at the same time as the recovery of robot's position and orientation. The degree of the rotation between x-ray marker and distal locking hole is determined. So, the robot is then controlled to move to the guiding position and orientation.

(a) (b)

Fig. 4 (a) A design of guiding robot. (b) a prototype of guiding robot[10]

(a) (b)

Fig. 5 (a) A simulate image of distal locking hole and a x-ray marker (b) a model of the second approach.

3 Experiment Setup and Results

3.1 System Simplification and Experimental Set Up

A phantom model and the simulated fluoroscopic imaging system are set up as shown in figure 6. The mimic of fluoroscopic system is created by attaching a small camera on a robotic manipulator driven by servo motor system to imitate the motion of fluoroscopic system. The robot guiding, which is attached with a simulate X-Ray marker, also moves in the similar way as the fluoroscopic system.

The simulated images were captured at 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 degrees of rotation to make a "Tool curve". In the experiment, simulate fluoroscope is rotated about *X*-axis of distal locking hole, while captures at 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 degrees of rotation. In addition, the images of a shape of marker are captured at 2, 4, 6, 8, 10 and 12 degree to make another "Tool curve".

In the experiment, the expected result is that the robot manipulator should move to the same axis of distal locking hole. Then, the robot can demonstrate the guiding of the trajectory path to perform the distal locking process.

The graphic user interface program shows the results of the detection and extraction information of distal locking hole as shown in figure 7. The experiment results to recover the distal locking hole's axis is shown in table 1 (a). The average error of the predicted angle is about 0.82 degree. The results of the marker rotation angle are shown in table 1 (b). The average error of the predicted angle is about 0.85 degree.

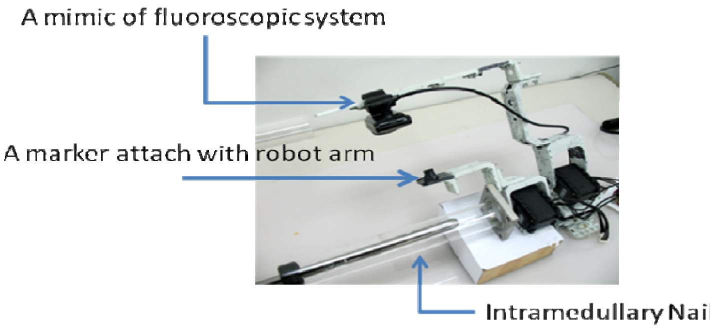


Fig. 6 The component of the experimental set up.

3.2 *Experimental Results and Analysis*

Fig. 7 A program show the recovery of the distal locking hole axis

4 Conclusion and Discussion

This paper has described an overall project on developing an orthopedic surgical navigation system for closed intramedullary nailing of femur. Kinematic based discussion on two proposed approaches with and without optical tracking have been presented briefly. A new concept of robotic guiding device to reduce the hand-eye coordination problem has also proposed. The system has built on our previous work on the algorithm to generate the surgical trajectory based on fluoroscopic images. An experimental set up and results to demonstrate the proposed concept have been demonstrated. The results have shown our method to be a promising solution with a reasonable error less than 0.85 degrees in rotational angle of nail which can be accepted by the orthopedic surgeon who specialize in this case. [This project is supported by the National Metal and Materials Technology Center (MTEC) of Thailand under the Project No. MT-B-50-BMD-14-125-G.]

Table 1 (a) The results of distal locking hole axis' recovery. (b) The results of a prediction angle of the X-Ray marker

(a)

The rotation angle of distal locking hole	The prediction angle
2	3.24
4	3.54
6	4.96
8	7.21
10	9.63
12	11.91
14	14.17
16	16.62
18	19.58
20	22.1

(b)

The rotation angle of a marker	The prediction angle
2	1.50
4	3.48
6	5.47
8	7.43
10	9.18
12	9.82

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