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A Novel Surgical Navigation Concept for Closed Intramedullary Nailing of Femur Using 4-DOF Laser-Guiding Robot

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***Abstract*—Closed Intramedullary Nailing is a frequent orthopedic operation for fixing a long bone's fractures. This technique requires the surgeon to insert an intramedullary nail into the bone canal of the fractured long bone, such as, femur, tibia and humorous. After the insertion, the surgeon is required to drill and interlock the bone with the nail by inserted two screws at the proximal and distal locking positions, called proximal and distal locking process. The difficulty is to locate and identify the position and orientation of the locking position which must be matched with the holes on the intramedullary nail. Traditionally, surgeon is working on locking process by using a large number of X-Ray images from fluoroscopic system for guiding with skill and trail-and-error process.**

This paper presents a new concept for surgical guiding using a 4-DOF laser-guiding robot to help navigating the surgeon to perform their work easier with higher accuracy. The proposed system consists of; (1) Image processing unit (IPU) which requires a few fluoroscopic images to process with our surgical path-generation algorithm, (2) 4-DOF laser-guiding robot which is our novel human-machine interaction approach, (3) Optical tracking system (OTS) used to identify position and orientation of the system's component, and (4) Central control unit (CCU) which receives system components' pose information from OTS, accepts surgical path from IPU, and, then, command the robot to guide the surgeon to perform surgery.

Keywords-Closed Intramedullary Nailing; Surgical Robot; Surgical Navigation; Medical Robot; Orthopedics

I. INTRODUCTION

Orthopedic surgery is one of the largest and most important operations conducted in most hospitals. Closed intramedullary nailing (Closed Nailing) is one of a frequent orthopedic surgery for treating long bone's fractures, such as, femur, tibia and humorous. Closed nailing is a minimally invasive surgery. Traditionally, surgeon performs the operation based on fluoroscopic image guiding with highly skill and trial-and-error processes. In our particular study, we are considering the Closed Intramedullary Nailing of Femur. Closed nailing procedure can be separated into several processes which are: (1) *Bone fixing process* – Surgeon needs to re-form the fractures in their places by push/pull the fractured limb based on skill and fluoroscopic images. (2) *Guide-wire insertion process* – Surgeon is required to open up a small incision at the proximal femur site. Then, surgeon accesses the intramedullary canal through femoral head using a hard and sharp tool. A guide-wire is then inserted from proximal to distal parts of femur. (3) *Reaming process* – Surgeon uses a flexible long-tube-shape driller to ream the intramedullary canal for consistent diameter size from proximal to distal parts. (4) *Nail insertion process* – A proper intramedullary nail is inserted in the prepared canal through the proximal incision. In order to insert the nail, surgeon is required to force the nail in the canal with several tools, such as, pliers and hammer. This process creates the deformation in the nail. (5) *Locking process* – Surgeon is required to drill holes at the proximal and distal parts of femur to insert locking screws at both sites. The screws must be through the bone and pre-made holes on the nail guided by fluoroscopic images. Figure 1 shows the fluoroscopic images from locking process.

In the literature reviews, the radiation exposure time in distal locking hole is 31-51% of 3 min to 30 min [1] in the overall of radiation exposure time. Two major reasons cause the difficulty. First, the intramedullary nail is usually deformed by external force and toques during the Nail insertion process [2]. Therefore, an available external mechanical guide is unable to use. Second, both targets (holes) and tools (drilling equipment and screws) in locking process, are related to each other in *3-D Space*, while the surgeon is performing based on *2-D* fluoroscopic image. Therefore, a large number of X-ray exposures are required for collecting *2-D/3-D* misunderstanding in surgeon's decisions. Moreover, X-ray radiation can harm both patient and surgical team for their long-term health.

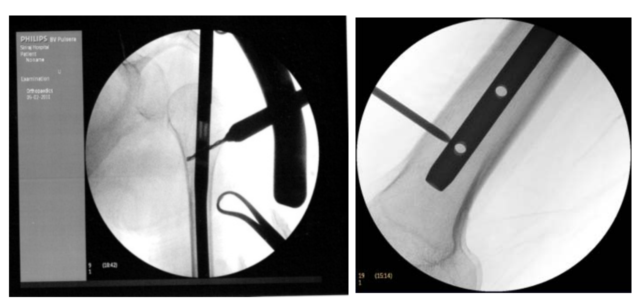


Figure 1. (a) Fluoroscopic image of proximal locking process using targeting device. (b) Fluorosocpic image of distal locking process based on fluoroscopic guidance.

Several devices and algorithms have been developed and applied to overcome these difficulties, such as, nail mounted targeting device, self locking nail system, stereo fluoroscopy and computer navigation system [3]. However, there are a number of problems which have not been solved, such as, long setup time and working space interference in employing complicated surgical robot, or problem on hand-eye coordination in applying a navigation system which demonstrates the surgical paths through display monitor.

Our study is to develop a robot-assisted surgical guidance system for distal locking process in Closed Intramedullary Nailing of Femur which overcomes the setup time, robot size and hand-eye coordination problems.

II. RELATED WORK

Yaniv and Joskowicz [4-5] developed a robot assisted guide positioning for distal locking intramedullary nail. This robot is a bone-mounted miniature robot fitted with a drill guide. The robot rigidly attached to the nail or bone. The system was automatically positioning a mechanical drilling guide which was mounted on a robot using a single fluoroscopic image for guiding the drilling path. The mean accuracy in vitro experiments is angular error of 1.3 degree and translation error of 3 mm.

In 2006, Neatpisarnvanit and Suthakorn [6] presented a method for distal hole detection. This method was based on geometry of intramedullary nail. The intramedullary nail outer diameter (dN) and distal hole diameter (dH) were required to estimate distal axis's orientation. Then, the dN was calculated using Hough transformation (Hough line). The Blob analysis was applied to measure distal hole opening height (dh). All of those information (dH, dh, dN) are used to estimate distal hole axis orientation.

Zhi-jiang *et al.* developed a system called "HIT-RAOS" [7], this system was developed by Du Zhi-jiang et al.The system goal of this system is to assist surgeons many process step on Close intramedullary nailing. Such as, to reposition broken bones, to guide the surgeon locking nail, to reduce the surgeon's working under c-arm by tele-operation system. The system consists of patient side, computer control system side and surgeon side. The operation table was developed for assisting a surgeon to adjust a patient in different pose on any fracture position. The fluoroscopy was modified for tele-operation. So, surgeon can control a position of fluoroscopy far away from c-arm that avoid from x-ray radiation. In the registration algorithm, the maker box was attached at the end of the guiding robot. The guiding robot is a commercial robot (SV3X serial robot) made in Motorman Company. The position was calibrated by the position on the maker box. Which relate to the robot coordinate O(x, y, z). Then, the position of balls in marker can be acquired in coordinate O(x, y, z).

The approach for recovery a position and orientation of distal hole axis was previously proposed by our researchers in the BART LAB, at Mahidol University [8-9]. The key of the algorithm used only the area of distal hole's projected image to recover the nail's rotation angle. The algorithm was separated into 2 parts. The first part is a data collection part which is done in pre-operative. The distal locking hole image data was taken in different rotating angles. The image processing technique was applied to determine area of distal holes in each a rotating angle of distal holes image. The area of distal holes and angle were plotted on graph. A fitting curve technique was applied to find the best fit of a data. That curve called "Tool Curve" was used to reversely determine rotating angle of intramedully nail. The second part is an intra-operative part. The image was acquired from fluoroscopic. Then, the matching process of a real-time area data to the tool curve is reversely recovering the rotational angle of intramedullary nail.

III. THE NOVEL CONCEPT IN CLOSED NAILING NAVIGATION

A. Overall system

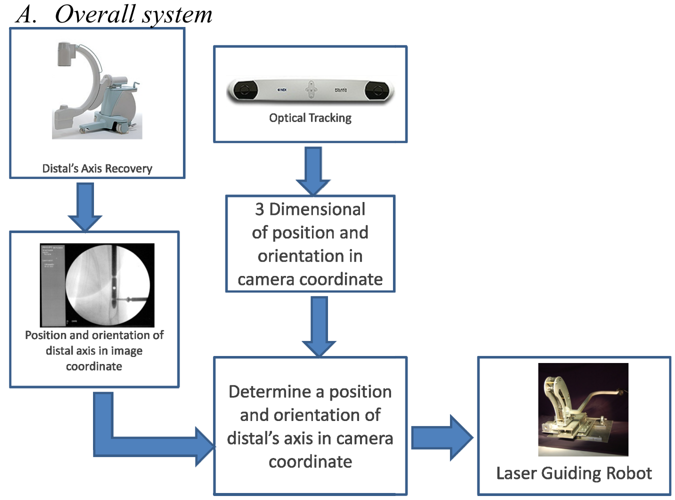


Figure 2. Diagram of overall system.

Our navigation system can be separated into three main subsystems. The first subsystem is a system for recovery a distal locking holes. This subsystem determines a position and orientation in the fluoroscopic image which uses only a few fluoroscopic images. The second subsystem is an optical tracking system. The position and orientation of each object in the system can be determined in this system. Those position and orientation are used to map fluoroscopic coordinate, surgical guiding robot's coordinate into real-time working coordinate. The last subsystem is a guidance system which is an important system to interact with a user. In this surgical guidance system we propose a robot-assisted guidance for guiding a surgeon to operate a distal locking hole drilling. Those three subsystems are integrated into a complete surgical navigation system. Figure 2 shows a diagram of overall system.

IV. Detailed Subsystem

A. Distal's Axis Recovery

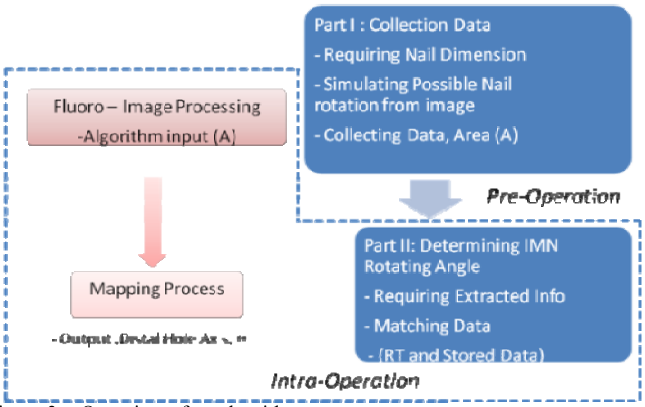


Figure 3. Overview of an algorithm.

In order to recover a distal holes axis, the recovery algorithm requires a few images to locate a distal locking holes axis (see Figure 3). The algorithm is separated into two parts. The first part is applied from our previous research for finding a rotation angle of distal hold axis in X-Y-Z axis. This part uses basic information of intramedullary nail. This information consists of a nail radius and an area of distal locking holes of a nail. The data information simulated from a image of nail rotation in all possible projection. Then, all of simulated images are extracted an area of distal locking holes. So, the area of distal locking holes in each rotation angle is stored together with an X-Y-Z rotation angle in a database. This part is done in pre–operative. The second part is a segmentation part for extraction an area of distal locking holes. The edge detection technique and fitting ellipse [10] are applied to find a location and an area of distal locking holes. That area of distal locking is calculated for real-time matching process to recover a distal locking hole. The quadratic curve fitting is applies to find the best fit to the data in database. The curve is called "tool curve". The tool curve is used to reversely recover the rotational angle of distal locking hole. This step is operated in intra-operative. Figure 4 shows an example result display for the system.

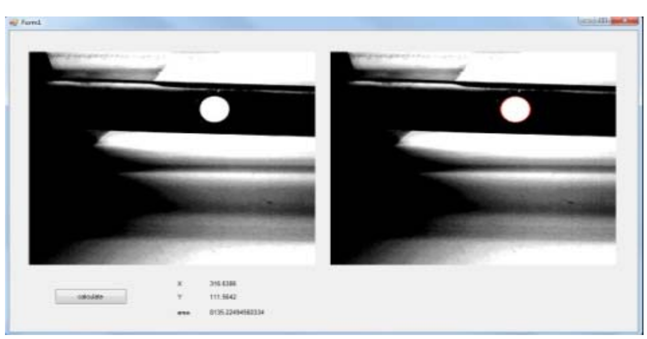


Figure 4. The image after applied an aglorithm.

B. Optical tracking System

Optical Tracking system is a system for measurement a position and orientation in 3 dimensional of active or passive marker. The active marker made from infrared light-emitting and wireless passive marker made from reflective sphere. Therefore, the stereo camera received light from marker reflection or marker emission. The stereo camera can identify and recognize markers by the different pattern shape of markers. Thus, the objects are attached with markers that can determine a three-dimensional position and orientation of those objects relative to stereo camera.

In our system we produce our own optical tracking system using Bumblebee stereo vision camera. The marker is created by an infrared light emitting diode (IR-LED). There are three different patterns of our marker which are T-pattern, L-pattern and 7-pattern as shown in Figure 5.

Figure 5. (a) a Bumblebee stereo camera. (b) an optical marker in different pattern.

In this system, the optical markers are attached with C-arm, patient bone, guiding robot. Then, the optical tracking system provided three-dimensional position and orientation of those three objects related to the optical tracking coordinate.

C. Fluoroscopic Image Calibration

The position and orientation of distal locking hols in Distal's Axis recovery system is based on pixel image coordinate (two-dimensional). Unfortunately, the drilling trajectory is three-dimensional coordinate (optical tracking coordinate). Then, the fluoroscopic image calibration is applied to find three-dimensional position in two-dimensional position on image.

The main idea of camera calibration is to find a projection matrix that project a three-dimensional position object into a two-dimensional pixel point. The equation of camera projection is shown in equation (1).

$$x = K[R|t]X \qquad (1)$$

Which, x is u,v image point.

K is intrinsic parameters or camera matrix.

[R|t] is extrinsic parameters or the pose of camera coordinate.

The equation (1) can be written in matrix from as shown in equation (1.1).

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} fx & 0 & cx \\ 0 & fy & cy \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r11 & r12 & r13 & t1 \\ r21 & r22 & r23 & t2 \\ r31 & r32 & r33 & t3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (1.1)$$

The intrinsic matrix and extrinsic matrix are combined into a projection matrix P.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \cong \begin{bmatrix} P11 & P12 & P13 & P14 \\ P21 & P22 & P23 & P24 \\ P31 & P32 & P33 & P34 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (2)$$

So, the projection matrix P is estimated by using the direct linear transformation (DLT) algorithm. The equation (2) can be arrange as

$$u = \frac{P11X+P12Y+P13Z+P14}{P31X+P32Y+P33Z+P34} \quad (2.1)$$

$$v = \frac{P21X+P22Y+P23Z+P24}{P31X+P32Y+P33Z+P34} \quad (2.2)$$

Then, the equation (2.1), (2.1) are represented in Matrix form

$$\begin{bmatrix} X & Y & Z & 1 & 0 & 0 & 0 & 0 & -uX & -uY & -uZ & -u \\ 0 & 0 & 0 & 0 & X & Y & Z & 1 & -vX & -uY & -uZ & -v \end{bmatrix} \begin{bmatrix} P11 \\ P12 \\ \cdot \\ \cdot \\ \cdot \\ P34 \end{bmatrix} = 0 \quad (3)$$

Shortly,

$$AP = 0 \quad (4)$$

The equation (3) is an equation of one point of projection. Then, the n corresponding point between two-dimensional image (u, v) and three-dimensional (X, Y, Z) were collected. So, the vector P can be determined from singular value decomposition. After, the matrix P was calculated the intrinsic and extrinsic matrix can be determined. In our system, the optical maker was attached with image generator. The transformation diagram in each frame coordinate is shown in Figure 6.

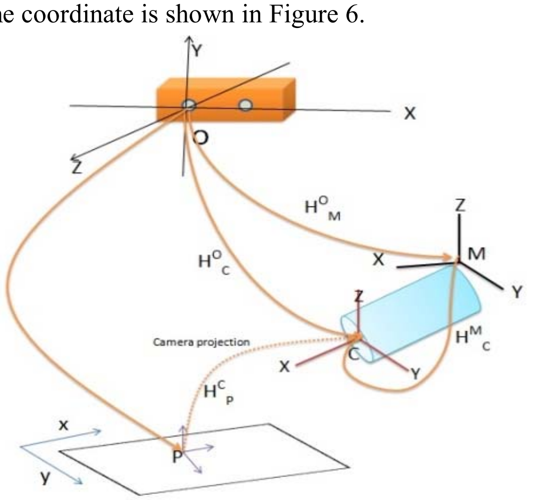


Figure 6. Transformation diagram of calibration.

After the calibration done, the intrinsic and extrinsic matrix was calculated. The extrinsic matrix is a transformation of the image coordinate relate to optical tracking coordinate. So, the transformation ${}^{O}_{C}H$ is an extrinsic matrix. Then, transformation between marker (M) to image coordinate (${}^{M}_{C}H$) was determined by this equation.

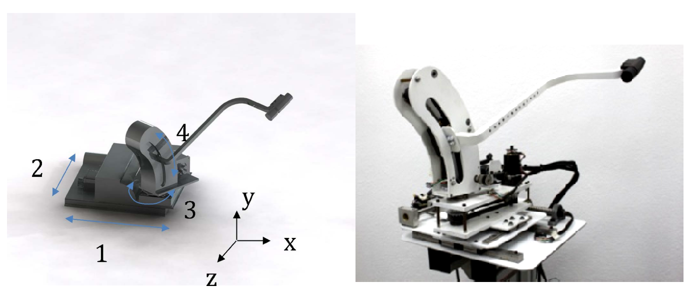
$${}^{M}_{C}H = {}^{O}_{M}H^{-1}\,{}^{O}_{C}H \quad (5)$$

Therefore, if image generator is moving in real-time process the new extrinsic matrix can be calculated a by equation (6). Then, the camera projection equation (1) can be updated with a new extrinsic matrix. So, the system can caculate a three-dimensional point in two-dimensional image point.

$${}^{O}_{C}H = {}^{O}_{M}H\,{}^{M}_{C}H \quad (6)$$

D. Laser-Guiding Robot

The guiding system is a very significant system in the surgical navigation system. This system interacts with a user to show a path of surgical or to receive a command from user. Many of navigation system usually use a monitor to display graphic information on screen. However, in the real situation a surgeon concentrates on a surgical area. If surgeon concentrates on the screen, surgeon will be loss a concentration in surgical operation. This paper presented a new method for guidance system by using a 4 DOF of laser-Guiding Robot. At the end of a robot is attached with a laser for pointing a trajectory path of distal locking holes drilling. Then, surgeons can drill a distal locking hole easily by drilling follow with laser beam. Therefore, surgeon can concentrate only in the surgical area. The robot consists of 4 Degree of freedom as shown in Figure 7. The first joint is used to translate a robot parallel with distal locking hole. The second is a translation joint that move robot perpendicular with distal locking hole. The third joint is a rotation joint to rotate when intramedullary nails tilt left or right. The last joint is used to move an end of effecter in curve shape to point a laser beam on a distal locking hole. The robot is placed down at the side of operation table. Hence, the robot does not concern about a sterilize process.



(a) (b)

Figure 7. (a) a design of guiding robot. (b) a prototype of guiding robot.

In addition, the guiding robot pointed a laser beam on a patient leg that show a position of distal locking hole as a dot point. But the drilling trajectory required orientation information as shown in Figure 8. Then, the system indicated the orientation of drilling trajectory by modifying a drilling tool. The sensor is attached at the rare of drilling tool as shown in figure8.The laser will hit a sensor if the drilling tool drilled in the right position and orientation.

(a) (b)

Figure 8. (a) picture show the wrong orientation of drilling trajecotry. (b) a sensor attechted to a drilling tool.

V. System Intergration

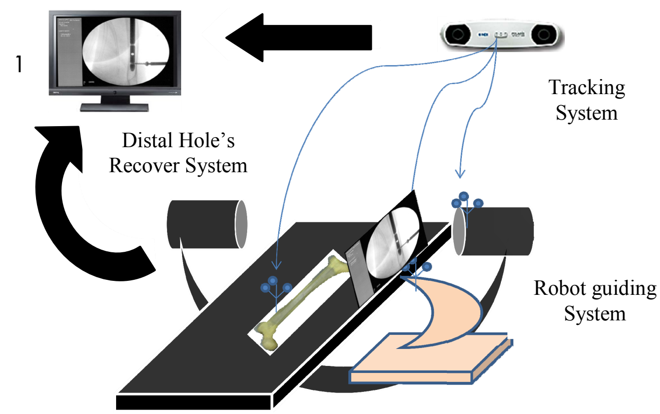


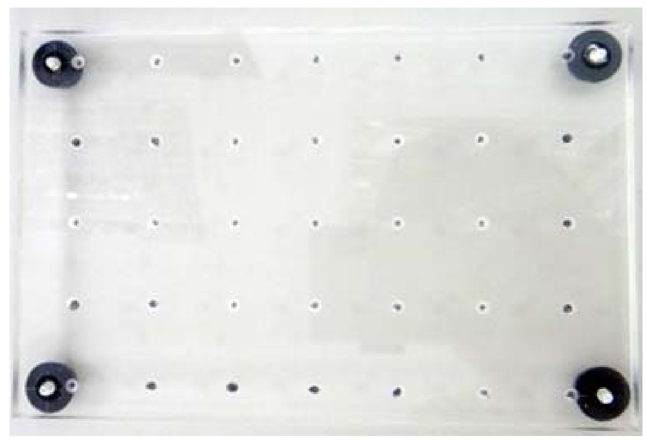
Figure 9. The overall of system intergration.

All of systems are integrated into a complete navigation system. The process of this system start from C-arm acquires an image then sends into computer to calculate a position and orientation of distal interlocking holes. Simultaneously an optical tracking system also sends information of position and orientation in each object to computer. The computer receives all of information to calculate a position and orientation of distal interlocking holes axes in world environment coordinate and sends that position to control guiding robot for guiding a surgeon by pointing a laser beam. Figure 6 presents the overall of system integration.

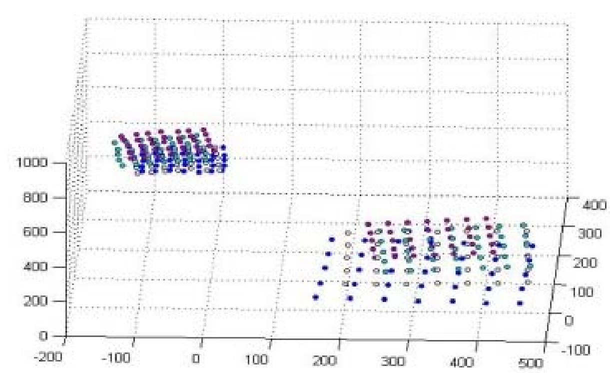
VI. Preliminary Experiment and Result

A. *Fluoroscopic calibration*

In calibration experiment, the calibration plate is created as shown in Figure 10. The corresponding control point is collected with 200 points in 8 different positions and orientation of calibration plate. The projection matrix is estimated by using those control points.



(a)



(b)

Figure 10. (a) a calibration plate. (b) the data set of Calibration point.

In order to prove an algorithm, the calculated projection matrix reprojects into a control point. The result of re-projecting point in each position and orientation of calibration plate are plotted as shown in Figure 11. The average of Euclidian distance error in all point is about 4 pixels.

B. *Distal's Axis recvoery*

In preliminary experiment, the phantom model was created by mimic a fluoroscopic system as shown in Figure 12. The simulated image was captured at 0, 5, 10, 15, and 20 degrees of rotation for creating a "tool curve".

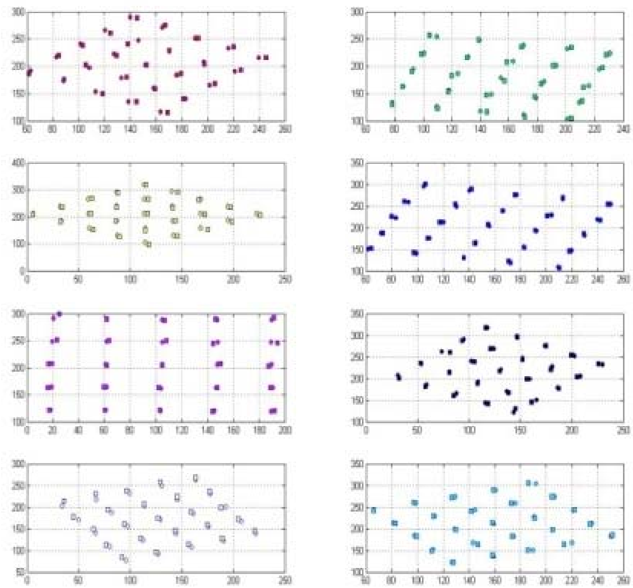


Figure 11. The result of re-projection point in each position and orientation.

Figure 12. A phantom model and the mimic of fluoroscopic system.

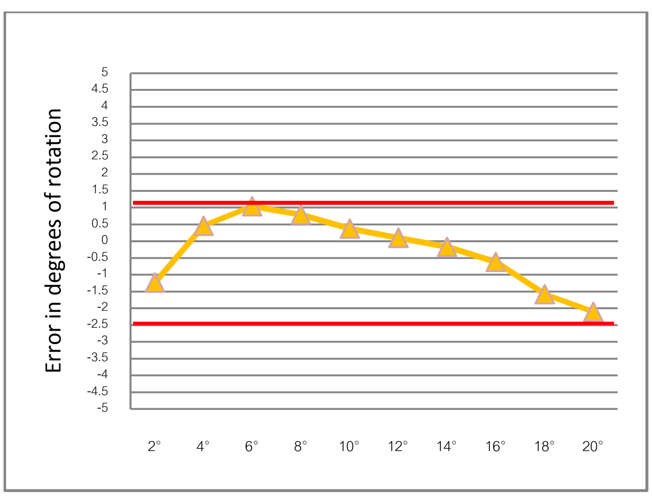


Figure 13. The graph shows an efficiency of Distal's Axis recovery algorithm.

The experimental images were captured in different angle of distal locking hole axis at 2, 4, 6, 8, 10, 12, 14, 16, 18, 20 degrees of rotation. The result of average error of a predicted angle is about 1 degree of rotation. The error in each degrees of rotation is shown in Figure 13. The efficiency of our algorithm can be accepted in the operation.

VII. Conclusion And Discussion

This paper presented a surgical navigation system for close intramedullary nailing of femur. The system required a few fluoroscopic images to calculate a drilling trajectory of distal locking hole. In preliminary experiment, the result of a recovery algorithm and calibration had shown an expected result. Then, those algorithms can apply in a real fluoroscopic system. The paper also presented a novel guidance system for guiding a drilling trajectory using a guiding robot. Therefore, surgeon can use this system easily and did not reduce hand-eye coordinate when they do the operation.

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