Design and Development of System Integration for Fluoroscopic Navigation Using Surgical-Guiding Robot

Sakol Nakdhamabhorn[1,2], Jackrit Suthakorn[1,2,*], *Member, IEEE,*
[1]Department of Biomedical Engineering, [2]Center for Biomedical and Robotic Technology,
Faculty of Engineering, Mahidol university, Sayala, Nakorn Pathom, Thailand
[*]Corresponding Author: egjst@mahidol.ac.th

***Abstract*—Fluoroscopic x-ray is an essential tool for orthopedic surgery, especially, Close Intramedullary Nailing Operation. Close intramedullary nailing is a very efficiency technique for treatment the long bone fracture. In this technique, surgeon is required to insert an intramedullary nail into the medullary canal to stabilize the fractured bone. The most difficult task for the surgeon is to identify two screwing holes at the distal location of the nail. In conventional method, surgeon requires a lot of fluoroscopic exposures to recover distal interlocking holes. Therefore, both of surgeon and patient continually absorb an irradiation that is harmful for their long term health.**

This paper presents a system for fluoroscopic navigation in close intramedullary nailing. The systems are integrated with three sub-systems: 1) A recovery of distal interlocking holes system for locating distal interlocking holes. 2) An optical tracking system for registering an x-ray image coordinate into the world coordinate. 3) A surgical guiding robot system for guiding a position and orientation of distal interlocking holes using robot guidance.

Keywords-Intramedullary nailing; Fluoroscopic Navigation; Navigation System; Robot-Assisted Surgery; Computer-Intergrated Surgery;

I. INTRODUCTION

Engineering and healthcare have been an important part of human life. Recently, engineering has paid more influence to several healthcare procedures. Computer-Integrated Surgery (CIS) and Robot-Assisted Surgery (RAS) play important roles in numerous medical operations. An important section of CIS/RAS is "medical navigation" which involves surgical planning and guiding in pre- and intra-operative procedures.

Orthopedic surgery is one of the most common operations in hospitals. Closed intramedullary nailing (Closed Nailing) is a frequent orthopedic treatment 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 bone-fixing process. The intramedullary nail is used as an internal structure to hold the fractures together in their proper shapes. Closed Nailing is a minimally invasive surgery (MIS) which requires only a few small incisions during its process. That can prevent an infection at wound area and a bone can be healed by conventional healing process. Since surgeon inserted a nail into a bone completely. Surgeon proceeds to the interlocking process. This process Surgeon needs to drill a bone and interlock by insert two screws into proximal and distal holes of intramedullary nail. At the proximal interlocking hole is easy to locate because a surgeon can use a mechanical mounted targeting device to aim that proximal hole. However, the most difficult task of this process is to locate position and orientation of distal interlocking holes. The two major causes of the difficulty of distal locking are: 1) C-arm image is two-dimensional image but the bone drilling trajectory needs to guide in three-dimensions. Therefore, a large number of C-arm images are required to target a bone drilling trajectory. That requires many time and x-ray radiation in the operation. 2) Intramedullary nail is deformed by external force and toques [1] during the insertion that changes a shape and position of distal holes in nail. Then an external mechanical guide cannot be used to target a drilling trajectory. In conventional method surgeon uses Fluoroscopic X-ray (C-arm) images to locate and identify the position and orientation of a distal locking hole of intramedullary nail. A surgeon uses trial and error to adjust C-arm into right position that is perpendicular with distal holes axis and makes distal holes appear perfectly circular shape on the screen. Therefore, a large number of X-ray images are required. The effect of X-ray radiation harms to both of surgeon and patient in long term health. The overall of radiation exposure time in close intramedullary nailing operation varies from 3 minute to 30 minute with 31%-51% of the overall radiation being from distal locking only depend on the patient anatomy and the surgeon's skill [2].

Many devices and techniques [3] have been developed to overcome these difficulties. For example, nail mounted targeting device, image intensifier mounted targeting device, self locking nailing system, stereo fluoroscopy and computer navigation system. However, these devices and techniques have several disadvantages. For example, these devices are lack of versatility and user-interface. These are also not easy to use.

The concept of the proposed approach is to integrate systems including image processing system to locate position and orientation of distal interlocking holes, tracking and matching coordinate system and guidance system. The integrated system used for generating a navigation trajectory path of distal locking holes drilling axis.

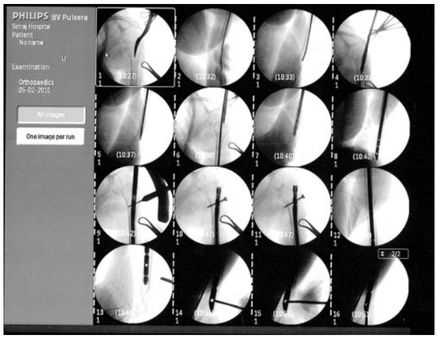

Figure 1. The series of Fluoroscopic X-ray that use in close intramedullary nailing operation.

II. RELATED WORK

Many Computer Integrated Surgery Systems [4] have been proposed to assist operation especially in distal interlocking holes targeting. The main goal is to reduce the difficulties in process, reduce time consuming and use a small number of X-ray exposure. Thierry Leloup et al, [5-6] developed a technique to recover a distal locking hole which used only two fluoroscopic images and not need to take at the axis of hole. Both of two images are used to determine a contour image of a nail and distal interlocking hole. The both contour images acquired in different projection plane. The three dimensional model of nail and distal interlocking hole is constructed with the intersection of two projection cones of nail. That model can be visualized in perspective on the computer screen. In vivo experiments the accuracy is approximate 1.5 mm in translation and 1 degree in rotation.

Guoyan Zheng et al, [7] developed an automatic recovery of distal interlocking hole. This work based on two calibrated and registered fluoroscopic images. They defined the recovery problem into a sequential two-stage model-base optimal fitting process. The first stage nail axis determination stage is used iteratively fitting a cylindrical model to the image to estimate the axis of the distal interlocking holes. Then, next stage for resolving the translation and orientation of the distal interlocking holes around the estimated axis from first stage by using iteratively fitting the geometrical models of the distal interlocking holes. In vitro experiments were shown an average angular error of 0.48 degree and translational error of 0.09 mm.

Another approach proposed a system which used robot to guide distal interlocking holes. Yaniv and Joskowicz [8-9] developed a precise 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. Therefore, the system was not serious about leg immobilization. The system automatic positioning a mechanical drill guide that mounted on a robot using single fluoroscopic image. The system is used 3-D Hough transform to locate the nail contour. The mean accuracy in vitro experiment is angular error of 1.3 degree and translation error of 3 mm.

III. DESIGN AND DEVELOPMENT

A. Overall system

This system consists of three major systems. The first system is a part for recovery distal locking holes axis with a few X-ray images. The second is a tracking system for tracking and matching a spatial X-ray coordinate (2-dimensional) into world environment coordinate (3-dimensional) using optical tracking system. Hence, the position and orientation of distal interlocking nail can be determined in world environment coordinate. The last system is a laser robot guidance system to generate a navigation trajectory path using information from second part. This robot is attached with a laser at the end of end-effecter that can be point and guide a bone drilling trajectory. All of these systems use a computer to integrate three systems into a navigation system for distal locking of close intramedullary nail as shown in Figure 2.

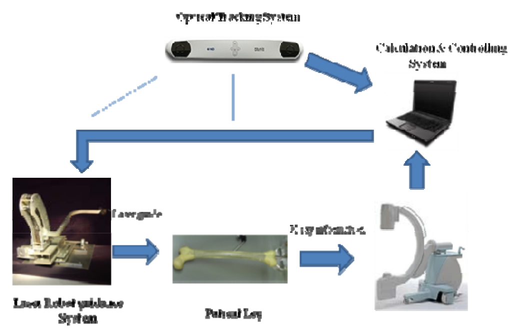

Figure 2. A diagram of overall system.

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. The detail in each system will describe in next topic below.

B. Recovery Distal Interlocking Hole System

In preliminary stage this paper simulated a fluoroscopic image in different angle of distal interlocking holes. First step image is converted in to black and white image (binary image). Then, binary image is contoured by canny edge detection algorithm. The fitting ellipse [10-11] algorithm applied to find a location of distal interlocking holes. This algorithm provided a position, and a length of major and minor axis of distal interlocking holes. All of information in each different angle image of distal interlocking holes are stored in pre-operation phase.

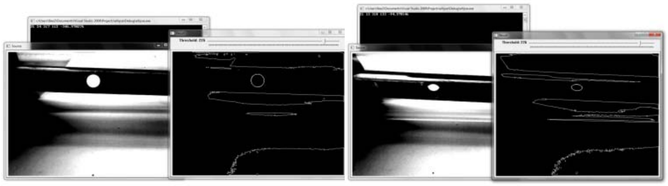

Figure 3. The images after applied canny edge dection and fit ellipse algorithm .

In intra-operation required two images in different angle. Those two images are processed to find a position, a length of major and minor axis. Afterward, the real-time matching process compared a data from pre-operation to predict an angular rotation of distal interlocking holes. The algorithm is based on our previous studies in[12-14].

C. Tracking System

Optical tracking system is used to measure a position and orientation in 3 dimensional of active or passive marker. The active marker is made from infrared light-emitting and wireless passive marker is made from reflective sphere. Therefore, the stereo camera receives light from marker reflection or marker emission. The different pattern shape of each marker helps an optical stereo camera to separate and detect a three-dimensional position and orientation. Thus, the objects that attach with markers can determine a three-dimensional position and orientation in same coordinate relative to stereo camera.

In this paper is used a commercial optical tracking "Polaris Vicra" from Northern Digital Inc. The passive markers attach with C-arm, patient bone, Robot guidance. So, the optical tracking system can determine three-dimensional position and orientation in each these three objects. That position and orientation of these three objects is used to register an X-ray image coordinate (spatial coordinate) into world coordinate (three-dimensional coordinate). So, the real position and orientation of distal locking hold axes in world coordinate can be determined.

The homogenous transformations in each frame are shown in Figure 4. The optical tracking system is provided a transformation in each frame coordinate then we can find the transformation relationship between each frame.

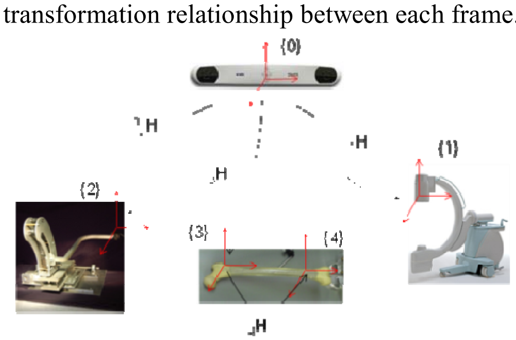

Figure 4. Transformation diagram of this system

The relationship between C-ram and bone is shown in this formula below.

$$ {}^{1}_{3}H = {}^{0}_{1}H^{-1}\,{}^{0}_{3}H \qquad (1) $$

The relationship between robot guidance and bone is shown in this formula below.

$$ {}^{2}_{3}H = {}^{0}_{2}H^{-1}\,{}^{0}_{3}H \qquad (2) $$

The relationship between robot guidance and C-arm is shown in this formula below.

$$ {}^{2}_{1}H = {}^{0}_{2}H^{-1}\,{}^{0}_{1}H \qquad (3) $$

The relationship between stereo camera and an axis of distal hole is shown in this formula below.

$$ {}^{0}_{4}H = {}^{0}_{3}H\,{}^{3}_{4}H \qquad (4) $$

The relationship between C-arm and an axis of distal hole is shown in this formula below.

$$ {}^{1}_{4}H = {}^{0}_{1}H^{-1}\,{}^{0}_{3}H\,{}^{3}_{4}H \qquad (5) $$

The relationship between Robot guidance and an axis of distal hole is shown in this formula below.

$$ {}^{2}_{4}H = {}^{0}_{2}H^{-1}\,{}^{0}_{3}H\,{}^{3}_{4}H \qquad (6) $$

D. Guidance System

The user interface is a very important part in the computer navigation system. The main goal of user interface system is to make user easy to use and does not interfere a user in common operation. Many systems usually use a monitor to display graphic information that shows information of drilling tool model, bone model and drilling path trajectory. Hence, surgeon keep his eye looking at monitor then operates a drilling tool follow with the path that shown in a monitor. Therefore, surgeon needs to concentrate at monitor and also do an operation at the same time that leads to less concentration in operation.

This paper developed guidance system using surgical guidance robot. The robot is placed down at the side of operation table. At the end effecter of robot is attached with laser pointing to point a trajectory path of distal interlocking holes then surgeons can easily drill a hole along with laser beam line. Therefore, surgeons can concentrate only in surgical area and do not swap concentrate between monitor and surgical area. The robot is consisted of four joints as shown in figure 5. The first joint used to move a robot parallel with distal interlocking hole. The second joint used to move a robot perpendicular with distal interlocking hole. The third joint used to move a robot when intramedullary nail tilt left or right. The last joint used to move an end of effecter to mark a laser beam to the distal interlocking hole.

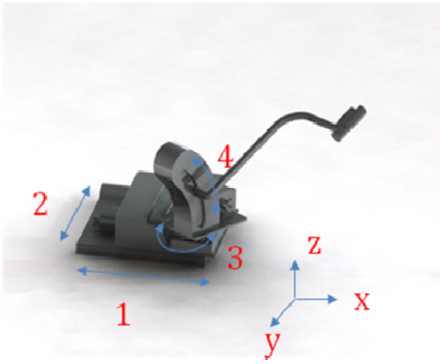

Figure 5. A design of robot-guidance.

Moreover, the system provides an alert system that can warn a surgeon when surgeon does not control a drilling tool along with laser point. The alert system is created by modifying a drilling tool. The drilling tool is attached with a sensor at the rare of tool as shown in figure 6. When a computer is calculated a trajectory path, the trajectory path will be sent to control a guidance robot for guiding a trajectory path. It is easy to control this guidance system because it does not interfere surgeons when they do the operation.

(a) (b)

Figure 6. (a) a prototype of robot guidance. (b) a sensor attachted to a drilling tool.

IV. CONCLUSION AND DISCUSSION

This paper presents a design and development of preliminary fluoroscopic navigation system. The system requires two or three fluoroscopic images to recover distal interlocking holes. The guidance system uses robot guidance. That robot is attached with laser to point a trajectory path and also provide an alert system to warn a surgeon when drill outside a laser beam. Therefore, it is easy for surgeons to operate this system. However, the limitation of this system is about a line of sight of the optical tracking and laser beam.

ACKNOWLEDGMENT

This work was supported by National Metal and Materials Technology Center (MTEC). The author would like to thank Prof. Banchong Mahasaviriya, M.D. of Siriraj Hospital, Mahidol University, for a technical knowledge of intermedullary operation. The author also thanks all researchers in Center for Biomedical and Robotic Technology (BARTLAB) for any assistance. This project is supported by MTEC Project No. MT-B-50-BMD-14-125-G. The first author is supported by the U-IRC scholarships, NSTDA, Thailand.

REFERENCES

[1] J. M. C. Krettek, T. Miclau, P. Schandelmaier, I. Linnemann, and H. Tscherne, "Deformation of fermoral nails with intramedullary insertion," *J. Orthopaedic Res.*, vol. 16, pp. 572-575, 1998.

[2] S. Skjeldal and S. Backe, "Interlocking medullary nails radiation doses in distal targeting," *Arch. Orthopaedic Trauma Surg.*, vol. 106, pp. 179-181, 1987.

[3] G.M. Whatling, L.D.M. Nokes, "Literature review of current techniques for the insertion of distel screws into intramedullary nails," int. *J. Care Injured.*, vol. 37, pp. 109-119, 2006.

[4] Russell H. Taylor, Dan Stoianovici, "Medical Robotics in Computer-Integrated Surgery," *IEEE Trans. Robot. Automat.*, vol. 19, no. 5 pp. 765–781, 2003.

[5] T. Leloup, W. E. Kazzi, O. Debeir, F. Schuind, and N. Waree, "Automatic flouroscopic image calibration for Traumatology Intervention Guidance," *Proc. Int. Conf. Computer Tool (EUROCON 2005)*, 2005, vol. 1, pp. 374-377.

[6] T. Leloup, W. E. Kazzi, F. Schuind, N. Warzee, " A Novel Technique for Dislat Locking of Intramedullary Nail Based on Two Non-Constrained Fluoroscopic Images and Navigation," *IEEE Trans. Med. Image.*, vol. 27, pp. 1202-1212, 2008.

[7] G. Zheng, X. Zhang, L.P. Nolte, " Automatic Pose Recovery of the Distal Locking Holes from Single Calibrated Fluoroscopic Image for Computer-Assisted Intramedullary Nailing of Fermoral Shaft Fractures," *MIAR 2006, LNCS 4091*, Springer-Verlag Berlin Heidelberg., pp. 195-202,2006

[8] L. Joskowicz, C. Milgrom, M. Shoham, Z. Yaniv, A. Simkin, "Robot-guided long bone intramedullary distal locking concept and preliminary results," *Proc. Computer Assisted Rodiology and Surgery*, 2003, pp. 485-491.

[9] Z. Yaniv and L. Joskowicz, "Precise robot-assisted guide positioning for distal locking of intramedullary nails," *IEEE Trans. Med. Img.*, vol 24, no. 5, pp. 624-635, May 2005.

[10] Fitzgibbon, A. W., Pilu, M and Fischer, R. B., "Direct least squares fitting of ellipses," *Proc. of the 13th Int. conf. on Pattern Recognition*, pp. 253-257, September 1996.

[11] Intel Corporation, "Open Source Computer Vision Library," Reference Manual, Copyright © 1999-2001.

[12] J. Suthakorn, P. U-Thainual, and B. Mahaisavariya, "An Efficient Algorithm for Recovering Distal Holes' Axes in Intramedullary Nail." *Proceedings of the 3rd WACBE World Congress on Bioengineering 2007*, Bangkok, Thailand, July 9-11, 2007.

[13] J. Suthakorn and P. U- Thainual, "A New Algorithm for Recovering Distal Hole Pose in Intramedullary Nail," *Proceedings 5th World Congress on Biomechanics*, Munich, Germany, July 29-August 4, 2006.

[14] C. Neatpisarnvanit, and J. Suthakorn, "Intramedullary Nail Distal Hole Axis Estimation using Blob Analysis and Hough Transform," *Proceedings 2006 IEEE International Conference on Robotics, Automation and Manufacturing (RAM 2006)*, Bangkok, Thailand, June 7-9, 2006.