SURGICAL TOOL ALIGNMENT BY LASER GUIDANCE USING FLUOROSCOPIC-BASED NAVIGATION TECHNIQUE

A System Implementation and Validation Study

Jack T. Liang[1], Shinya Onogi[2] and Yoshikazu Nakajima[1,2]

[1] *Graduate School of Engineering, University of Tokyo, Yayoi 1-1-1, Tokyo, Japan*

[2] *Intelligent Modling Laboratory, University of Tokyo, Tokyo, Japan*

Keywords: Laser Guidance, Computer Aided Surgery, Fluoroscopic Surgery.

Abstract: This paper provides a novel method for intuitive and CT-less surgical navigation based on fluoroscopic-based navigation and laser guidance technology for minimal invasive orthopaedic surgery. This method does not require intra-operative registration of three-dimensional surface model derived from pre-operative CT/MRI volumes and is able to project surgical path planed intra-operatively onto the patient's skin directly. In this paper, implementation of this method and basic in vitro guidance accuracy validation were performed. Tool insertion path planning was performed on three 2D images from a pinhole imaging source taken at different incident angles. A 3D insertion pathway was generated and projected using two laser beams. Our Fluorolaser system has a planning accuracy of 1.07±0.60 mm, 0.73±0.38 degrees and an overall guidance accuracy of 1.11±0.62 mm, 0.80±0.68 degrees. These results demonstrate that the proposed method has great potentials to ensure accurate and intuitive surgical procedures.

1 INTRODUCTION

Fluoroscopy is commonly used for real-time viewing of patient anatomy during percutaneous or less invasive orthopaedic surgical procedures. It provides real-time 2D views using a fluoroscope. However, its usage comes at the expense of increased exposure to radiation; difficulties in obtaining and processing multi-planar visualization; and the mental burden for surgeons to interpret 3D positions from 2D images.

To address the visualization problem, X-ray computed tomography (CT)-based and magnetic resonance (MR)-based are developed to simplify surgical procedures. However, CT-based navigation has large amounts of radiation exposure while MR-based navigation does not provide high bone intensity resolution and can only be used in non-metal containing environments. To address radiation exposure, X-ray fluoroscopic navigation, or virtual fluoroscopy, has been developed to guide surgical tool placement (Foley, 2000; Hofstetter, 1999; Leloup, 2008). However, these systems superimpose surgical tool location over pre-acquired x-ray images and displays navigational plans via a secondary display device. This unintuitive guidance method forces surgeons to mentally calculate real-world tool locations from a display panel during surgery.

Laser-based navigational guidance systems have been developed for spinal pin insertion and pelvic implant fixation surgeries (Sasama, 2002). It generates surgical plans and uses two laser beams to project point-of-entry and insertion orientation directly onto the patient’s skin (Nakajima, 2004). Thus, a direct guidance is achieved and surgeons no longer need to mentally interpret positioning information from a screen. However, CT or MR-image is required for surgical planning.

This paper presents an improved system that employs two laser sources to guide surgical tool insertion using surgical planning from two or more fluoroscopic X-ray images taken intro-operatively. In particular, we elicited the virtual fluoroscopic planning technique. As far as the authors know, this is the first study to integrate the virtual fluoroscopic planning technique with the dual-laser guidance technique for practical manual execution of surgeries. This novel combination yields an original surgical navigation and guidance system that displays tool insertion path directly in the surgical field without use of any pre-surgical techniques. We showed the feasibility of this method with a basic system validation using a pin-hole camera.

T. Liang J., Onogi S. and Nakajima Y..
SURGICAL TOOL ALIGNMENT BY LASER GUIDANCE USING FLUOROSCOPIC-BASED NAVIGATION TECHNIQUE - A System Implementation and Validation Study.
DOI: 10.5220/0003763903190323
In *Proceedings of the International Conference on Biomedical Electronics and Devices* (BIODEVICES-2012), pages 319-323
ISBN: 978-989-8425-91-1

2 MATERIALS

The proposed fluoroscopic-based dual-laser guided (Fluorolaser) navigation system consists of three major components: a Laser Guidance System (Nakajima, 2004) with built-in tracking capabilities using the hybrid Polaris Spectra (Northern Digital, Waterloo, ON, Canada); active infrared markers (AdapTrax 15 Marker, Northern Digital, Waterloo, ON, Canada); and a web camera (P1C30 series, Elecom, Osaka, Japan) used in place of an X-ray fluoroscope. We implemented the fluorolaser software using C++ (Visual Studio 2005, Microsoft co.) with OpenCV library. It connects to the laser guidance system over TCP/IP and to the Polaris tracking device via RS-232c. The two functional parts of this new system, guiding and planning, will be discussed in this section.

2.1 Insertion Guidance Using Lasers

The intersection of two emitted laser-beams simultaneously guides surgical tool's entry position and its inserting orientation as shown in Fig. 1. The intersectional line l_0 made by laser planes S_1 and S_2 represents the insertion path in 3D space. The insertion point p_0 is the intersection of l_0 and the patient's body surface S_0. Insertion point guidance is robust to deformations of the body surface, represented by changes from S_0 to S_0' in Fig. 1. Surface S_0' represents any deviations from S_0 in both height and shape due to body surface relocation, deformation or obstruction by soft tissues. For proper surgical tool alignment, the tip of the surgical tool is placed at p_0 and the length aligned to l_0. Orientation alignment can be verified using the projections of the lasers on the side of surgical tools. Proper alignment is indicated by two parallel lasers.

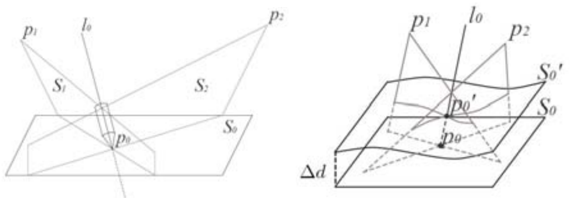

Figure 1: Left: Schematic diagram of the laser guidance method. Right: Robust entry point displayed for surface relocation, deformation or occulsion by soft tissue using dual laser-beams.

2.2 Navigational Planning

Infrared markers are placed on the imaging device and on the surgical object to create the localizer-fluoro coordinate system (CS_F) and localizer-subject coordinate system (CS_S), respectively. The surgical planning process requires multiple sets of inputs. Each set consists of three pieces of information obtained from the surgical environment: an image of the surgical object and the insertion site obtained by the imaging device and the three-dimensional coordinates of the two markers when the image is taken. For each set of inputs, a two-dimensional surgical tool insertion path is manually drawn onto the acquired two-dimensional image. Using camera calibration parameters, this 2D plan is projected along the ray-lines of the imaging device to obtain a plane in 3D space. The plane is formulated in CS_F and transformed for use in CS_S.

Following Fig. 2, two 2D plans from two sets of inputs yields two planes in 3D space. The intersection of two planes yields a line in 3D space where the directional vector of the line is the cross products of the normal of the two planes. This intersection line represents the insertion path in 3D space. If three sets of inputs are used, three 2D plans are made to give three planes in 3D space. This gives rise to three intersection lines in 3D space. Regression of these lines is performed to obtain a line of best fit, which represents the optimal surgical insertion path. This optimal insertion path is stored in CS_S and thus is robust towards any slight movements of the surgical object.

The optimal path is then transformed into the localizer coordinate systems (CS_L). Laser guidance is realized by using two laser sources to project the mathematical representation of this insertion path.

3 METHODS

We validated the Fluorolaser system using a pinhole web-camera, which is mathematically similar to a fluoroscope (Navab, 1999). We prepared a simple validation setup using a flat surface and surgical insertion tool, the K-wire (150 mm length, 3 mm diameter). Guidance accuracy was validated by tracking the position of the K-wire, which represented the desired surgical tool insertion path and the surgical tool itself. An active infrared marker and a guidance sleeve were attached for position tracking and alignment, respectively. Proper tool orientation alignment was indicated by parallel laser beams on the guidance sleeve, as stated previously.

3.1 Experimental Design

We created a virtual coordinate system on a flat

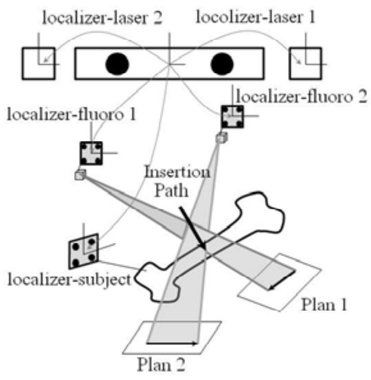

Figure 2: Fluorolaser transformation matrices: localizer to laser 1 and laser 2, localizer to subject, and localizer to fluoroscope. Fluoroscope is positioned at two arbitrary locations. Two 2D plans are used to calculate insertion path in 3D space.

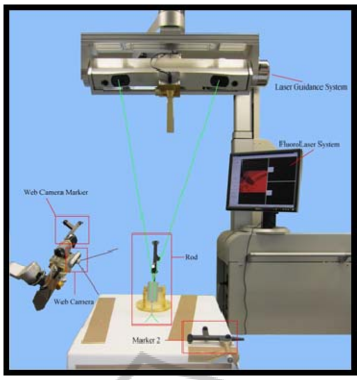

Figure 3: Experimental setup includes the laser guidance system, a flat surface, a web camera (fluoroscope imitation device) and a K-wire. Location markers are used to locate imaging device, K-wire and surface. Flat surface represents the surgical object.

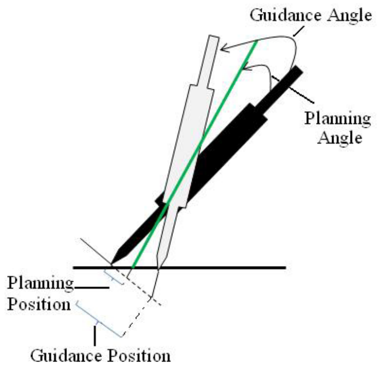

Figure 4: Black figure represents the initial K-wire position; white figure represents the final K-wire position; and green line represents the planned surgical insertion path in 3D space.

surface (Fig. 3) and selected the z-axis as the direction normal to the surface. We used a four factorial Box-Behnken experimental design method to create 28 validation trials by altering the intended insertion path mathematically. Its factors and levels are: x-axis (-50, 0, 50 mm), y-axis (-100, 0, 100 mm), polar angle (-30, 0, 30 degrees), and azimuthal angle (-30, 0, 30 degrees). Experiments were conducted for both two-image and three-image configurations for planning.

3.2 Experimental Protocol

First, the intended insertion path is shown by the dual-lasers in 3D space. This ground truth path is represented mathematically and altered according to the experimental design. The K-wire was placed according to the lasers. Using this initial k-wire position, 2D images were taken for planning. The K-wire was removed while planning was performed. Once the 3D insertion path was generated, the laser was turned on. The K-wire was repositioned using guidance by laser. Once lasers became parallel, final position of the K-wire was recorded.

3.3 Analysis

Fluorolaser accuracy validation looked at the displacement of relative tip locations between planed 3D insertion path, initial K-wire position and final K-wire position. We calculated the difference in tip positions in a plane that is perpendicular and

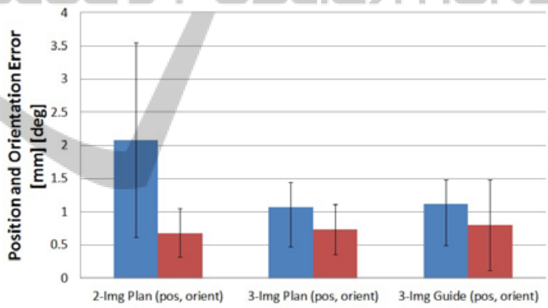

Figure 5: Positional and orientational error values shown in blue and red, respectively. Results include accruies for 2-image planning, 3-image planning, and 3-image guidance.

intersects the initial K-wire tip (Fig. 4). Planning accuracy refers to the error between actual insertion path and user-determined insertion path. Guidance accuracy refers to the error of the overall system. Transformation matrix between K-wire tip and marker was pre-obtained.

4 RESULTS

Results of 28 validation experiments are shown in Fig. 5. System planning accuracy using two 2D images for planning was 2.08±1.47 mm, 0.68±0.37 deg (degrees). Planning accuracy after linear regression of three 2D images was 1.07±0.60 mm, 0.73±0.38 deg. Positional accuracy is significantly improved using three images (P-value: $2.00\text{x}10^{-6}$).

Using three-images, max planning error was found to be 2.22 mm, 1.85 deg. The RMS and RMSE were 1.22 mm, 0.82 deg and 0.59 mm, 0.37 deg, respectively. The overall guidance accuracy using three 2D images was 1.11±0.62 mm, 0.80±0.68 deg. RMS and RMSE were 1.27 mm, 1.05 deg and 0.62 mm, 0.67 deg, respectively.

Box-Behnken surface responses for planning and guidance errors were desirable for the 28 different four-factor three-level combinations. There was no correlation between the system accuracies and the positional changes of imaging device.

5 DISCUSSION

Conventional navigation systems use a secondary viewing device to indirectly guide surgery. These operations are often mentally challenging and cumbersome to perform. The Fluorolaser system guides surgeries directly using two lasers to guide surgical tool alignment. Planning is performed using two or more images taken intra-operatively as oppose to complete CT or MRI registration data.

The entire surgical navigation process using the Fluorolaser system consists of two types of errors: planning error and guidance error. The latter has been validated previously (Lim, 2010). The former includes camera calibration error, and human errors for planning and re-positioning. In this study, we have evaluated planning and guidance errors of the system. Planning accuracy is limited by the camera calibration technique as well as user-based insertion path planning. Furthermore, this validation study was performed with the assumption of point-accuracy, which cannot be obtained from the K-wire tip or the crosshair created by the lasers. Generally, navigational systems designed for precutaneous surgeries using two-dimensional images are considered precise and accurate when position and orientation errors are within 2 *mm* and 2 *deg*, respectively. However, acute accuracies may be required for special types of surgeries such as surgeries in the brain and neck regions.

The presented evaluation of the Fluorolaser system may be limited. In our experiments, we could not use fluoroscope images and instead used normal camera images. Although different in the imaging techniques used, the system is invariable for both camera and x-ray images since both devices are theoretically assumed to be pinhole devices (Navab, 1999; 2000). Validations with x-ray images are necessary for actual surgeries.

Although this system is an improvement to conventional systems, clinical assessment is necessary to fully validate its robustness in actual surgeries. We intend to further validate this system using fluoroscopes and saw-bones or biological specimens to better mimic the surgical environment.

We are also considering the implementation of insertion depth guidance. The lack of the depth guidance may result in the need to acquire additional X-ray images or to use positioning trackers. We plan to introduce a physical stopper attachment for the surgical tool; however, problems may arise when during skin deformation. Adequate implementation of depth guidance using laser-beams may overcome these problems as well as expand the applicability of the system in different types of surgeries.

6 CONCLUSIONS

We have proposed a novel integration of the fluoroscope-based navigation and the laser guidance systems. This Fluorolaser system provides intuitive surgical tool insertion positioning in precutaneous surgeries without pre-operative CT/MRI volumes. Specifically, *in vitro* insertion path planning was performed using 2D images from a pinhole imaging source and insertion guidance was directed by lasers. The planning accuracy was 1.07±0.60 mm, 0.73±0.38 deg and overall guidance accuracy was 1.11±0.62 mm, 0.80±0.68 deg. This demonstrates the potential of the Fluorolaser system to be used in accurate and intuitive surgical procedures without registration of pre-operative CT/MRI volumes.

REFERENCES

Foley, K T., et al., 2000. Virtual Fluoroscopy. *Oper. Tech. in Ortho*, 10(1), pp. 77.

Hofstetter, R., et al., 1999. Fluoroscopy as an imaging means for computer-assisted surgical navigation. *Comp. Aid Surg*, 4, pp. 65.

Leloup, T., et al., 2008. A Novel Technique for Distal Locking of Intramedullary Nail Based on Two Non-constrained Fluoroscopic Image and Navigation. *IEEE Trans on Med Img*, 27(9), pp. 1202.

Sasama, T., et al., 2002. A Novel Laser Guidance System for Alignment of Linear Surgical Tools. *LNCS 2489 MICCAI'02*, pp. 125.

Nakajima, Y., et al., 2004. Available range analysis of laser guidance system and its application to monolithic integration with optical tracker. *International Congress Series*, 1268, pp. 449.

Lim, S., et al., 2010. Assessment for the feasibility of external-fixation pin guidance using laser navigation. *Jap. Soc. Of Comp. Aid Surg.* 12.

Navab, N., et al., 1999. Camera-Augmented Mobile C-arm Application. *LNCS 1679 MICCAI'99*, pp.688.
Navab, N., et al., 2000. Visual Servoing for Automatic and Uncalibrated Needle Placement for Percutaneous Procedures. *IEEE CVPR'00*, 2, pp. 1063.