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Calibration and Registration of a Freehand Video-Guided Surgical Drill for Orthopaedic Trauma

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Abstract

Pelvic trauma surgical procedures rely heavily on guidance with 2D fluoroscopy views for navigation in complex bone corridors. This “fluoro-hunting” paradigm results in extended radiation exposure and possible suboptimal guidewire placement from limited visualization of the fractures site with overlapped anatomy in 2D fluoroscopy. A novel computer vision-based navigation system for freehand guidewire insertion is proposed. The navigation framework is compatible with the rapid workflow in trauma surgery and bridges the gap between intraoperative fluoroscopy and preoperative CT images. The system uses a drill-mounted camera to detect and track poses of simple multimodality (optical/radiographic) markers for registration of the drill axis to fluoroscopy and, in turn, to CT. Surgical navigation is achieved with real-time display of the drill axis position on fluoroscopy views and, optionally, in 3D on the preoperative CT. The camera was corrected for lens distortion effects and calibrated for 3D pose estimation. Custom marker jigs were constructed to calibrate the drill axis and tooltip with respect to the camera frame. A testing platform for evaluation of the navigation system was developed, including a robotic arm for precise, repeatable, placement of the drill. Experiments were conducted for hand-eye calibration between the drill-mounted camera and the robot using the Park and Martin solver. Experiments using checkerboard calibration demonstrated subpixel accuracy [-0.01 ± 0.23 px] for camera distortion correction. The drill axis was calibrated using a cylindrical model and demonstrated sub-mm accuracy [0.14 ± 0.70 mm] and sub-degree angular deviation.

Keywords

Image-guided surgery; intraoperative imaging; computer vision; augmented reality; orthopaedic trauma

1. INTRODUCTION

Fractures of the pelvic ring constitute 3–7% of skeletal injuries^{1–4} and present a major source of socioeconomic burden and healthcare cost. Standard treatment procedures include

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closed or open reduction,^{5–7} followed by internal fixation under fluoroscopic guidance. The surgery involves the placement of guidewires (e.g. K-wires) within the bone followed by fixation with cannulated screws. The procedure presents considerable challenge and complexity even to experienced surgeons, owing to the complexity of the pelvic shape and narrow bone corridors adjacent to nearby critical anatomy. Visualizing the K-wire trajectory using 2D fluoroscopy often requires multiple trials, whereas 3D navigation is uncommon due to additional workflow requirements and small field-of-view. Procedures often involve long fluoroscopy run times with mean time >2 min⁸ (hundreds of radiographic views), major challenges to outcomes and complication rates up to 30%.¹

Prior solutions in related work include the Navigation System II (Stryker Inc., Kalamazoo, MI), which relied on optical approaches for tracking the surgical drill. This solution required a clear line-of-sight between the tracker and drill, additional equipment, and disruptions to the routine OR workflow. Another promising system⁹ introduced a drill-mounted monocular camera that used binary markers, demonstrating the potential value of a drill-mounted solution, although the work noted challenges due to occlusion by other tools or OR staff.

To accommodate the demanding clinical workflow of orthopaedic trauma surgery, an image-guided navigation framework for guidewire placement is proposed. The solution involves a miniature video camera mounted onboard a surgical drill to provide real-time drill trajectory visualization in fluoroscopy as well as preoperative CT and/or intraoperative cone-beam CT (CBCT) if available. Continuous registration of the guidewire trajectory is achieved between the video camera and fluoroscopy using multimodality (optical and radiographic) radio-opaque markers placed about the surgical field (e.g., on a ring placed on the surgical drape. Optionally, the markers are registered to preoperative CT and/or intraoperative CBCT via 3D-2D registration. Whereas the current procedures are typified by hundreds of radiographs (i.e., fluoroscopic views), the proposed system could operate with as few as two projections - one to confirm entry point, and another to confirm final placement of the K-wire.

To this end, the work reported below is the first presentation of this concept, focusing on the computer vision system for drill-mounted video guidance, its requirements, and design of calibration jigs. Methods covered in this work include: (i) camera distortion correction / rectification; (ii) surgical drill guidewire-to-camera frame registration; and (iii) hand-eye calibration between the camera frame and freehand drill positioning (with a UR3e robot providing a precise testbed surrogate for freehand control, as shown in Fig. 1).

2. SYSTEM AND METHODS

2.1 System overview

Initial implementation of the video-guided drill system used a Stryker System 6 (Kalamazoo, MI) surgical drill/reamer (Part #6205), with a pin collet (Part #7203) for 3 mm diameter K-wire insertion, used commonly in pelvic procedures. For prototyping the concept, a Logitech C900 USB webcam (1920×1080 px resolution) was used as the miniature camera. The camera was mounted rigidly to the drill using a 3D printed chassis attachment. For error quantification, the setup was rigidly attached to the end effector of a 6 degree-of-freedom robotic platform (UR3e, Universal Robots, Denmark). The system was

operated using the TREK software platform¹⁰ for intraoperative guidance, offering a collection of modular components that leverages various open-source packages (e.g., 3D Slicer for graphical interface and OpenCV¹¹ for camera support). Overall system workflow is illustrated in flowchart of Fig. 2(a).

2.2 Camera calibration and distortion correction

The drill-mounted camera was used as a tracking device after calibration of the drill axis. A pinhole model was assumed, with focal length denoted as (f_x, f_y) and optical centers denoted as (u_0, v_0) . The lens distortion was modelled using a Brown-Conrady's even-order polynomial model.¹² In Eqs. 1–2, with (u, v) as the image point, $(\check{u}, \check{v})$ are the corrected image points, (u_0, v_0) are the centers of distortion, and r^2 equals $(u - u_0)^2 + (v - v_0)^2$.

$$\check{u} = f_u(u, v) = u + (u - u_0)[k_1 r^2 + k_2 r^4] + 2p_1(u - u_0)(v - v_0) + p_2[r^2 + 2(u - u_0)^2] \quad (1)$$

$$\check{v} = f_v(u, v) = v + (v - v_0)[k_1 r^2 + k_2 r^4] + 2p_2(u - u_0)(v - v_0) + p_1[r^2 + 2(v - v_0)^2] \quad (2)$$

Two parameters were used for both radial distortion (k_1, k_2) and tangential distortion (p_1, p_2). The closed-form solutions for camera intrinsics and extrinsics were used as the initial estimate, after which all parameters were simultaneously optimized. The reprojection error (RPE in Eq. 3) of image points was minimized using a Levenberg-Marquardt optimizer:

$$\text{Reprojection Error(RPE)} = \sqrt{\frac{1}{n} \sum_{i=1}^n (u - f_u(u, v))^2 + (v - f_v(u, v))^2} \quad (3)$$

The corners of a standard 9×6 checkerboard were used to detect the points on the image plane. Eighteen images of the board were taken from various camera poses. All further images captured were rectified and corrected for distortion before pose detection.

2.3 Surgical drill-to-camera registration

The drill was tracked in terms of two components: the K-wire axis and the tooltip. The axis was calibrated in two stages, using a 3D printed, square, ARBoard¹³ (3×3 grid, with inner marker removed, see Fig. 2[b]) attached to a cylindrical sleeve as the calibration jig. The jig was then moved along the K-wire axis, during which the origin of the ARBoard was recorded. In the second stage, the coordinates were fit to a cylindrical surface.¹⁴ Due to constraints on motion of the jig, the cylindrical axis represented the K-wire axis. The axis points in 3D space were then reprojected onto the camera image for visualization. With the maximum residual error in fitting denoted as δ , the residual angular error for a K-Wire length of 150 mm is given by $\tan^{-1}(\delta/150)$.

The tooltip was calibrated under the assumption that it was constrained to a divot on a rigid, planar, ARBoard pattern (4×3 grid, ref. Fig. 2[c]). Instead of pivoting the tool as in conventional approaches, the ARBoard was pivoted around the tooltip, thereby simplifying the calibration process. The coordinates of the ARBoard origin were then fit to a sphere.¹⁴

The center of the sphere determined the tooltip pivot. The tooltip of the drill was used preoperatively for verification of the registration accuracy.

2.4 Hand-eye calibration

The Park and Martin¹⁵ hand-eye calibration routine was used to calibrate the camera frame with the robot's end effector frame (${}^R T_C$). To this end, a planar ARBoard (4×3 grid, ref. Fig. 2[c]) was tracked from the camera frame. Twenty-four simultaneous observations of the ARBoard (${}^C T_B$) and end effector poses (${}^B T_R$) were collected across various configurations. Denoting each instance by i , the chain is represented as:

$${}^B T_R \quad {}^R T_c \quad {}^C T_B = {}_{i+1} B T_R \quad {}^R T_{ci+1} \quad {}^C T_B \quad (4)$$

$${}_{i+1} B T_R^{-1} \quad {}^B T_R \quad {}^R T_c = {}^R T_{ci+1} \quad {}^C T_B \quad {}^C T_B^{-1} \quad (5)$$

Taking ${}_{i+1} B T_R^{-1} \quad {}^B T_R$ as A , ${}^R T_c$ as X , and ${}^R T_{ci+1} \quad {}^C T_B \quad {}^C T_B^{-1}$ as B in Eq. 5, the substitution yields $AX = XB$. The solution for the rotation matrix and translation vector is obtained using $R_A R_X = R_X R_B$ and $(R_A - I)t_X = R_X t_B - t_A$. The residual errors were quantified as the norm of rotation and translation components of T_c :

$${}_i T_e = {}_{i+1} B T_R \quad {}^R T_{ci+1} \quad {}^C T_B - {}^B T_R \quad {}^R T_c \quad {}^C T_B \quad (6)$$

Calibration was performed on an optical bench using the UR3e robot as a precise positioner. The practical calibration process in eventual clinical application does not require a setup including a robot arm, and can be done online.¹⁶ Measurement of registration accuracy and demonstration relative to a pelvis model (Sawbones, Vashon Island, WA) was also performed on the optical bench.

3. RESULTS

3.1 Camera distortion correction

The camera was found to have multiple distortion effects, including significant barrel distortion in the image. The calibrated camera parameters are listed in Table 1. The accuracy of camera calibration was verified by projecting the checkerboard corner points onto the image as described above (Section 2.2). Subpixel overall reprojection error was observed across all the images $[-0.01 \pm 0.23 \text{ px}]$. The error distribution for individual X and Y axes is shown in Fig. 3(a), with the overlap illustrated as the purple bars in the plot.

3.2 Surgical drill-to-camera registration

The surgical drill axis was calibrated by creating a point cloud from the detected marker poses in ~6000 video frames. The experiment was carefully setup to minimize motion blur and rolling shutter artifacts in the video. Using an error inlier tolerance of 0.1 mm for MLESAC,¹⁴ the residual error from the tracked point to the surface of cylinder was $0.14 \pm 0.70 \text{ mm}$, as shown in Fig. 3(b). The cylindrical diameter traced by the marker frame was 192.9 mm, yielding errors <1%, well within tolerance bounds for the envisioned application.

Assuming a guidewire length of approximately 15 cm, the measured error resulted in a maximum drill axis deviation of $\sim 0.5^\circ$ at the tip. The residual errors, along with camera position and calibrated axis are plotted in Fig. 3(c). The largest errors were observed at the extreme ends from the camera, consistent with the use of an intermediate focal length for camera calibration. Using the camera intrinsics and calibrated geometry, the axis was reprojected to the camera image for visualization as shown in Fig. 5(a).

Similarly to the drill axis calibration, marker board poses from ~ 2000 video frames were used for calibration of the drill tooltip. The observed marker coordinates were fit to a sphere with error inlier tolerance of 0.1 mm for MLESAC. The residual point-to-surface errors after fitting the tooltip were (-0.07 ± 0.29) mm as shown in Fig. 3(d). For a spherical diameter of 223.3 mm, the residual error was found to be $< 0.2\%$, and hence within reasonable tolerance bounds.

3.3 Hand-eye calibration

The residual errors were estimated as defined in Section 2.4. The norm error in translation as defined in Eq. 6, was (1.56 ± 0.72) mm, while the norm error in rotation was $(0.46^\circ \pm 0.25^\circ)$. The error along each individual axis is shown in Fig. 4(a). The camera frame vector was at an offset distance of 88.5 mm from the end effector frame; therefore, the error was approximately $(1.56/88.5) * 100 = 1.76\%$. The maximum deviation was observed in the z axis (with the frame shown in Fig. 2[b, c]) due to errors in the depth component during pose estimation. Another possible source of error is deflection in the camera mounting shell.

Initial implementation of the system and illustration of the drill-mounted video guidance relative to CT is illustrated in Fig. 5. As described above, the video scene is registered to fluoroscopy by radiographically opaque AR marker boards, which in turn is registered to CT by 3D-2D registration between the preoperative CT and the fluoroscopic views. Note that the markers do not need to be present in the CT image. The markers can be placed on the patient (i.e., on the surgical drape about the surgical field) anywhere within the field-of-view of the camera and fluoroscopy system, and their position can be modified during the procedure, as needed for the surgical workflow, with no negative impact to navigation. Alternatively, the markers could be placed together on a frame - e.g., a ring - placed on the surgical drape about the surgical field. The system is thereby intended to provide 3D navigation capability without conventional trackers: conceptually, the drill-mounted video system is the tracker, and the patient anatomy provides the means for registration to CT.

4. CONCLUSIONS

The presented work demonstrated the first steps toward a practical, accurate, and robust system for guidewire placement and navigation in pelvic trauma surgery. The proposed navigation approach offers the potential to reduce radiation dose and fluoroscopy time with minimal workflow disruption compared to conventional fluoroscopic guidance. Through a video-guided freehand drill, the planned navigation trajectory is augmented into 2D camera space and can be registered with 3D CT/CBCT scans through a single fluoroscopy frame. The system therefore operates without the need for additional trackers or time-consuming calibration. Pending continuing development, testing, and validation, such a system could

bring the high level of precision and quality assurance associated with high-end 3D navigation systems to a practical form suitable to broad utilization in trauma surgery. The initial setup shows promising results in terms of augmented, real-time drill axis overlay with sufficient marker precision, showing errors $<0.5^\circ$ in rotation and $<2\%$ in translation, across all aspects.

Future work involves testing the system in combination with multi-modality (optical-radiographic) markers detectable by both fluoroscopic (2D) imaging and video to facilitate 3D-2D image registration¹⁷. Validation in preclinical studies will be evaluated in terms of target registration error and fiducial registration error as well as potential reduction in radiation dose and consistency with (and/or potential improvements to) routine clinical workflow.

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Figure 1.

Experimental setup for calibration and registration of a surgical drill with a mounted camera. The UR3 robotic arm is used for precise positioning in the preoperative (one-time, offline) calibration process. A pelvis phantom is shown with a CT image slice containing a planned drill trajectory (in blue). Reference frames $\{P\}$, $\{B\}$, and $\{CT/F\}$ refer to Patient frame, Base/world frame, and CT/Fluoro Image frame, respectively. The transforms ${}^C T_D$ (Camera-to-Drill) ${}^D T_P$ (Drill-to-Patient), and ${}^P T_{CT/F}$ (Patient-to-CT/Fluoro Image) relate the pose of the (freehand) drill to the CT and surgical plan.

Figure 2.

(a) Overview of the system for video guidance of a surgical drill. The flowchart shows the relationship of reference frames and their transformations from the robot (in practice, freehand) / world reference frame to CT or CBCT. (b) A 3x3 ARBoard for axis calibration was rotated around the guidewire axis while tracked by the camera (fit to cylindrical model). (c) A 4x3 ARBoard for drill tip position calibration (fit to spherical model), also used for hand-eye calibration between the robot and camera frame.

Figure 3.

(a) Reprojection error in image using estimated camera parameters. (b) Histogram of residual errors from the surface of the cylinder after axis calibration. (c) Residual errors after axis calibration, with maximum errors observed at extreme ends. (d) Residual errors from the surface of the spherical model after tooltip calibration.

Figure 4.

(a) Boxplot of residual errors in translation vector after hand-eye calibration between the camera and end effector frame. (b) Residual errors in rotation after hand-eye calibration.

Figure 5.

Visualization of drill-mounted video augmented with the drill axis trajectory and registered to CT of a pelvis phantom. (a) Video frame from the drill mounted camera. (b) Rendered CT volume. and (c, d) axial and sagittal CT slices. The screenshot shows the implementation in TREK - involving a 3D Slicer visualization and an underlying library of multi-tasking and registration tools for image guidance.

Table 1.

Camera calibration parameters and their respective estimation errors

	X	Error (X)	Y	Error (Y)
Focal Length (px) (f_x, f_y)	1508.0	± 1.3	1500.6	± 1.3
Principal point (px) (u_0, v_0)	960.4	± 0.9	599.3	± 0.7
	Param. 1	Error	Param. 2	Error
Radial distortion (k_1, k_2)	-0.0797	± 0.0010	0.0564	± 0.0027
Tangential distortion (p_1, p_2)	0.0013	± 0.0001	-0.0007	± 0.0002