A Phantom Based Approach to Fluoroscopic Navigation for Orthopaedic Surgery

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Abstract. The use of the C-arm fluoroscope for surgical navigation in various Computer Assisted Orthopaedic Surgery Systems (CAOS) has been an important success of research into CAOS technology. To use the fluoroscope for quantitative surgical navigation involves calibrating its 2D images and tracking the spatial position of the fluoroscope's image beam. This allows 3D reconstruction of anatomy from a series of 2D fluoroscopic images. This paper presents a new technique for determining the C-arm position and calibrating the image beam. This technique is based on a small imaging phantom that is placed close to the patient. This paper also briefly describes the CAOS system developed at Hull that uses this imaging phantom and reports on in vivo and in vitro studies.

1 Introduction

The C-arm fluoroscope is an indispensable intraoperative 2D imaging device for orthopaedic surgery but it does pose a radiation hazard to the theatre staff and patients. The fluoroscope is frequently used for surgical navigation in various Computer Assisted Orthopaedic Surgery Systems (CAOS).

The usual approach of using the C-arm fluoroscope for quantitative surgical navigation is by calibrating the 2D image to provide accurate 2D images. By tracking the position of the corresponding image beams, reconstruction can then give the 3D location of the anatomy at the operation site. The most common technical solution is to retrofit a device to the x-ray receptor end of the C-arm (e.g. Traxtal Technologies FluoroTrax). This device comprises a calibration grid and is surrounded by IREDs which are tracked by a camera system. C-arm fluoroscopes have now been developed that include tracking of a calibrated image beam, e.g. Medtronic Sofamor Danek's FluoronavTM and SurgiGATE[®] (Medivision, Oberdorf, Switzerland).

The flexibility that the C-arm provides has led to intraoperative surgical navigation CAOS approaches for spine, total hip replacement, high tibial osteotomy, femoral

neck fractures, distal locking of intramedullary nails, etc. The operating experience in fluoroscopic navigation and its use for the identification of anatomical landmarks, axes and planes has led to many CAOS navigation approaches that were previously based on preoperative CT surgical planning being replaced by CT-free CAOS approaches, e.g. spinal and pelvic surgery.

Another feature of having a quantified C-arm fluoroscope is its potential for virtual fluoroscopy (VF) [1]. Typically in VF a number of fluoroscopic images are taken of the patient during actual surgery. For each image, the position and geometry of the associated image beam is recorded. During surgery the position of the surgeon's instrument and bone(s) being operated upon are optically tracked by IREDs attached to them. This allows the computer to produce virtual fluoroscopic images by overlaying the projection of the instrument onto previously captured images.

The above approach to surgical navigation has a number of potential problems.

1. The calibration device attached to the C-arm camera reduces the useful imaging volume of the fluoroscope.
2. The optical tracking volume is large as the C-arm is often moved between the AP and lateral position, etc.
3. The calibration / registration zone is distant from the operation site and this may cause magnification of errors.
4. The markers of the calibration grid appear in the fluoroscopic image.

The authors have developed an alternative approach to calibrating and tracking the C-arm of the fluoroscope for surgical navigation for CAOS. This is based on a small tracked phantom that is placed in the C-arm image space close to the operating site. Section 2 presents this phantom based technique.

This phantom based approach is used in our Computer Assisted Orthopaedic Surgical System (CAOSS) for trauma surgery. This CAOSS has been used for over 4 years in preclinical trials and its navigation modules include implanting compression hip screws and locking of distal screws for intramedullary nails. Section 3 discusses the CAOSS and results from in vivo and in vitro studies. The paper concludes with a discussion that compares our tracked phantom to the explicitly tracked C-arm approach to surgical navigation.

2 Phantom-Based Approach to C-Arm Calibration and Tracking

To use fluoroscopic images for surgical navigation requires that, firstly, the 2D fluoroscopic images are accurately calibrated and, secondly, that the position of the corresponding fluoroscopic image beam is known accurately. The latter allows the partial 3D reconstruction of the operation site by projecting various 2D features extracted from 2D fluoroscopic images into 3D.

2.1 Preoperative Calibration of X-Ray Images

The fluoroscopic 2D images suffer from a number of distortion effects [2]. This image distortion has components which are static and dynamic. The latter is due partially to the influence of magnetic fields on the image intensification tube of the C-arm.

The calibration includes a preoperative step where an x-ray translucent plate containing an evenly spaced grid of 64 x 64 balls placed on the x-ray receptor cover of the C-arm is imaged. From this image, software calculates a distortion-undistortion map. Intraoperatively, all fluoroscopic images are then displayed with the distortion removed. Sufficient image accuracy is obtained by calibrating in just two positions, i.e. with the C-arm vertical and horizontal. This calibration is typically required once a month.

We have studied how dynamic distortion varies with the position of the C-arm. We observed the main effects are a twisting effect and a translation. Preoperative calibration in 2 positions considerably reduces the sizes of these effects. It should also be noted that the intraoperative C-arm tracking (see Section 2.2) in fact includes inherent calibration that further reduces dynamic distortion remaining after applying the preoperative calibration mapping.

2.2 Tracking the Fluoroscopic Image Beam Using a Small Imaging Phantom

Tracking the spatial position of the fluoroscope's image beam with an optical tracking system involves accurate localisation of the position of the x-ray source and the image plane of the C-arm. Our tracking approach involves placing a small registration phantom in the image space of the C-arm. This phantom consists of an H arrangement of 21 metal balls that measures approximately 2" x 2" by 1/2" (Fig. 1). The projection of these balls appears in a fluoroscopic image. The phantom is held by an end-effector and a lockable passive arm (Fig. 2). The position of the phantom is tracked by an optical camera tracking system. When a patient is imaged, software undistorts the image using the static calibration mapping and then automatically detects the position of the phantom in the image. Knowing the position of the phantom, an algorithm calculates the position of the C-arm in the coordinate space of the tracking system.

Fig. 1. Image phantom used for tracking the image space of the C-arm

Significant obscuration of the phantom frequently occurs in the image due to shadow of soft tissue, bone edges, retractors, etc. Furthermore, image contrast varies considerably between images and patients, and varies considerably within an image.

Software has been developed that is robust to such problems. The software comprises two distinct algorithms. The ball detection algorithm first detects a candidate set of metal ball projections from the image. The second, the phantom detector algorithm, selects a subset of these metal balls that provide a feasible projection of the phantom. The ball detection algorithm uses contrast gradient in two directions to initially select possible ball projections. It then applies a series of six filters to eliminate less promising projections. These filters include tests for size, shape, proximity, contrast and gradient variation. The robustness of the phantom detection algorithm is achieved by detection requiring a minimum of 14 balls.

Fig. 2. Passive arm and end-effector for holding the imaging phantom in OR. The passive arm is clamped to horizontal bar of operating table. The position of the end-effector is tracked by 7 IREDS. There are two positions for the phantom used; one for AP and one for lateral imaging.

The software developed for the detection of the phantom from a fluoroscopic image has been extensively tested and fine-tuned using a database of over 200 fluoroscopic images obtained from early uses of the imaging phantom in the operating theatre.

Our tracking approach for the C-arm takes account of the C-arm flex both in terms of change in position of the x-ray source and change in direction of the x-ray beam. Also, as mentioned in Section 2.1 it caters for the dynamic distortion of images as it corrects for linear components of rotation and translation errors.

Extensive computer simulations were used to determine a phantom design that had the best trade-off between the reconstruction performance and the clinical need to make the phantom as unobtrusive as possible. In vitro tests have shown that a fluoroscopic image has a maximum calibration error of less than 0.5 mm.

3 Clinical Applications of the Phantom-Based Surgical Navigation

We have developed the Computer Assisted Orthopaedic Surgical System (CAOSS) for trauma orthopaedic surgery. This system uses intraoperative fluoroscopic navigation using the imaging phantom. The CAOSS comprises a trolley, an optical tracking system, an optically tracked end-effector attached to a lockable passive arm, the imaging phantom and various guiding cannulas. The CAOSS trolley houses a PC-based

computer system, the optical tracking hardware, a monitor and a frame grabber with a video feed from the C-arm fluoroscope.

The camera array is mounted on the theatre laminar flow enclosure. This tracks the position of the end-effector via seven IREDs attached to it. The end-effector and passive arm are rigidly mounted to the side bar of the operating table (Fig. 2). The passive arm has three joints that are lockable via a single twist handle.

The end-effector is used by the surgeon to position the image phantom and to position the guiding cannulas. The guiding cannula has a sharp serrated end and this prevents whiplash and helps keep the guide wire straight.

The CAOSS currently has three surgical planning modules, namely: insertion of compression hip screw for femur neck fractures, distal locking of intramedullary nails for femur fractures and insertion of three cannulated screws for femur neck fractures [3]. Only the first two operations are described here. In addition we have developed a general purpose orthopaedic surgical navigation system using a virtual fluoroscopy approach that is based on the image phantom. It is currently being evaluated in vitro for unicompartmental knee replacement [4].

3.1 Insertion of Compression Hip Screw

The CAOSS for this operation was first used in the operating theatre in May 2000. Since then some 30 operations have been performed.

The computer-based planning for this operation requires an AP and a lateral fluoroscopic image of the fracture site. The anatomical features used for planning the surgery are the shaft of the proximal femur and the femoral neck and head. In the operating theatre these three anatomical features on the two images are marked with a mouse. The 2D projection of the femur shaft axis and the femoral neck and head centres is then determined. These 2D projections from the two views are reconstructed to create a 3D surgical plan.

The computer plans a trajectory for the guide wire of the compression hip screw by constructing a 3D line from a way point in the femoral head that intersects with the femoral shaft axis at the same angle as the hip screw and plate (typically 115° to 135°). The way point is taken to be one quarter distant along the 3D line joining the centre of the head with the centre of the neck. This trajectory is then overlaid on both AP and lateral images. The depth of the drill hole is also calculated. The surgeon reviews the suggested guide wire trajectory and, if necessary, modifies it by moving the entry point of the guide wire on the femur shaft or moving the waypoint.

3.1.1 In Vivo Study of Insertion of Compression Hip Screw

During 2002 and 3, a group of 10 patients underwent surgery using CAOSS for insertion of compression hip screw. There were 8 female and 2 male patients with ages ranging between 75 and 93 years (mean age 84.7 years). Mean follow up time was 11.5 months (9 to 21 months).

Fluoroscopic Images: Theoretically only four fluoroscopic images are required for insertion of a guide wire into the femoral neck when using CAOSS. An AP and lateral images is required for surgical navigation and another pair of images to confirm guide

wire insertion. The average number of images required in this study was 6 with a range of 4 – 10. Three patients required the minimum of 4. Additional images were sometimes required because the imaging phantom was not fully in the image beam. A learning curve was observed with later cases requiring fewer images.

Time taken: this is the time taken just to plan the trajectory and then to insert the guide wire, under computer guidance, into the femoral neck of the patient. The average time taken to perform the procedure was 17.2 minutes (range 8 – 23 minutes). Again a learning curve was observed with times reducing with experience.

Position of the screw: Baumgaertner [5] describes the tip apex distance (TAD), which is the sum of the distances between the apex of the femoral head and the tip of the lag screw in the femoral head, both in anteroposterior and lateral views. They observed that cut out of implants had a TAD of more than 25 mm. We used TAD to confirm the position of the screw. Eight patients had TAD within the acceptable range of 25 mm with an average of 17.6 mm (range 6.7 - 20 mm). Two patients had a TAD of 31 mm. No cut out of the implant was seen during follow up.

3.2 Distal Locking of Intramedullary Nail

Many femur fractures are treated with intramedullary (IM) nails. To achieve stability, locking screws are used at both ends of the IM nail. The difficult part of the operation is inserting the distal locking screws.

The CAOSS surgical navigation module uses an AP and lateral image of the distal end of a nail. In the AP view, the IM nail and the long bone are identified by marking them with a mouse. In the lateral view, the nail is identified and each distal hole is identified by a surrounding square. CAOSS software then automatically determines the nail axis and recovers the geometry of both the distal holes from these images [6]; this provides the drilling axis of both holes and the length of screws needed for locking. An important feature is that the projection of the distal holes in the images need not be perfect circles. To drill each hole, the surgeon positions a guiding cannula using guidance displayed on the computer's monitor.

The conventional manual approach suffers from problems such as extended time required for distal locking, radiation risk to patient and staff and misplacement of the screw. CAOSS offers the opportunity to address these shortfalls.

3.2.1 In Vitro Study of Intraobserver Error in IM Nail Surgical Planning

We are part way through an extensive study of intraobserver error for surgical navigation in the distal locking of IM nails. This study will systematically vary the parameters that might affect the surgical planning result. Besides giving a fuller understanding of intraobserver variability, this study may also identify areas where the system can be tuned to improve performance. Examples of parameters being varied include:

1. The position of the nail with respect to the C-arm image beam in the three orthogonal directions.
2. The position of the image phantom in the image space in terms of its distance from the patient and its position within the image plane.

3. Rotating the nail position by up to 20° in both directions from its position where a perfect circle projection of the hole appears in the lateral image.
4. Using different end-effectors and imaging phantoms.

In vitro laboratory tests were performed using various IM nails and also using a 14 mm diameter hollow metal tube with two holes of 5 mm diameter that are 3 cm apart. A metal tube was used to provide a controlled environment for tests as it does not have any curves along its long axis. A screw-guide was designed with a 5 mm diameter solid cylinder at one end which fits into the nail holes precisely. By mounting the screw-guide in the end-effector, its position can be tracked by CAOSS. Thus when the screw guide is placed in a nail hole, the screw guide axis gives the true trajectory of this hole. This can be compared with the trajectory that the CAOSS software predicts.

In an initial series of 10 tests the nail position was varied with respect to the image space. The mean translation error for the planned drilling trajectory at the entry to the distal hole (of the distal hole pair) was 0.19 mm with a maximum error of 0.45 mm and a standard deviation of 0.12 mm. The mean angular error between the axis of the distal hole and the CAOSS predicted drilling trajectory was 0.18° with a max error of 0.42° . For the proximal hole the translation errors were 0.26, 0.44 and 0.10 mm respectively, and the rotational errors were 0.15° and 0.26° , respectively. The full set of intraobserver results is to be published shortly. These results indicated that these accuracy results are invariant to the position of the imaging phantom in the image space. It is also worth noting that accuracy of our approach depends on the relative error of the tracking system and not its absolute error. As the volume tracked is small, this relative error is very much smaller than the absolute error of the tracking system.

4 Discussion

Our small H-shaped phantom technique for the image calibration and the C-arm tracking of the fluoroscope has been used for over 36 months as part of our CAOSS preclinical trials for hip trauma surgery. Qualitative assessment of the complete system indicates satisfactory clinical performance in terms of accuracy. The laboratory tests of the phantom indicate a maximum calibration error of 0.5 mm of a fluoroscopic image. The phantom approach will work with any modern C-arm fluoroscope.

Our imaging phantom approach has advantages over existing fluoro navigation systems that use explicit C-arm tracking via an optically tracked grid attached to the C-arm's x-ray receptor. The key differences in the approaches are as follows.

1. The optically tracked volume for an imaging phantom is close to the operation site and it interferes very little with the set up in operating theatres. For C-arm tracked systems the tracked volume is very much larger as the x-ray receptor has to be tracked through a 90° vertical rotation of the C-arm and it is more likely to interfere with theatre set up, e.g. interference with vertical sterile drapes. The image phantom approach also suffers less from losing line of sight, as the tracked volume is very much smaller.
2. There is significantly less image obscuration with an imaging phantom. There are only 21 opaque markers of the phantom in the image. In C-arm tracking the whole

image is splattered by markers, however, some systems replace some markers in the image by their surrounding background which is undesirable.

3. The imaging phantom has to be manually placed in the image space. This is an extra step and multiple images may be required to achieve correct placement.

Another difference between the two approaches to fluoroscopic navigation is image calibration. In the phantom based approach, primary calibration occurs in two positions preoperatively but this is fine tuned by a secondary intraoperative calibration that is inherent in the phantom's design. In C-arm tracking the image is calibrated intraoperatively with every image. Our approach to calibration is more precise due to a denser calibration grid and calibration being closer to the operation site.

5 Conclusion

This paper presented a new approach for image calibration and image space tracking of a fluoroscope based on a small imaging phantom. This is an effective and viable alternative to the existing explicit C-arm tracking method of attaching a calibration grid and IREDs directly to the x-ray receptor of the C-arm. This approach is suitable for surgical navigation that requires interoperative fluoroscopic navigation. The imaging phantom has a number of ergonomic and efficacy advantages over the C-arm tracking approach. A study has shown that a surgical target can be reconstructed from a pair of fluoroscopic with a translation error of less than 0.5 mm. This imaging phantom has been used clinically in a Hull hospital for the past 4 years as part of CAOSS. Implementing a drilling trajectory under computer guidance by CAOSS provides a total system accuracy of less than 1.5 mm and an angular accuracy of less than 1°.

References

1. Hofstetter R, Slomczykowski M, Sati M and Nolte L-P (1999). Fluoroscopy as an imaging means for computer-assisted surgical intervention. *Computer Aided Surgery*, 4, 65-76
2. Boone JM, Seibert JA and Blood W (1991). Analysis and correction of imperfections in the image intensifier TV-digitiser imaging chain. *Medical Physics*, 18, 236-42
3. Viant WJ, Phillips R and Mohsen A (1999). Computer assisted positioning of cannulated hip screw. in Lemke HU, Vannier MW, Inamura K and Farman AG (eds), *CARS'99 Computer assisted radiology and surgery*, Amsterdam, Elsevier, 751-5
4. Phillips R, Peter V, Faure G-E, Li Q, Sherman KP, Viant WJ, Bielby M, Mohsen AMMA (2002), A Virtual Fluoroscopy System based on a Small and Unobtrusive Registration / Calibration Phantom, *Proceedings of Computer Assisted Radiology and Surgery, CARS 2002*, 275-280, Springer Verlag, June 26-29, 2002, Paris
5. Baumgaertner MR et al. (1995), The value of tip apex distance in predicting failure of fixation of peritrochanteric fractures of the hip. *J Bone Joint Surg-Am*; 77(7):1058 – 1064
6. Zhu Y, Phillips R, Griffiths JG, Viant WJ, Mohsen A, Bielby M (2002), Recovery of distal hole axis in intramedullary nail trajectory planning, *IMEchE Part H Journal of Engineering in Medicine*, 216,(5),323-332