FLUOROSCOPY-BASED NAVIGATION IN COMPUTER-AIDED ORTHOPAEDIC SURGERY

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Abstract: We present a summary of the state of the art of fluoroscopy-based systems in computer-aided orthopaedic surgery (CAOS). The goal of CAOS is to improve the surgeons' performance in surgeries in where intraoperative X-ray fluoroscopic images are pervasive. The systems include a real-time tracking device, a computer with image processing and visualization software, a fluoroscope connected to the computer via a video frame grabber, and optionally a robot. We first motivate the need for CAOS systems and describe the general principles of fluoroscopy-based navigation. We then describe four classes of systems: (1) CT based systems, (2) fluoroscopy-based systems, (3) CT and fluoroscopy-only systems, and (4) systems combining fluoroscopy and surgical robots. We describe the technical principles of each, evaluate their pros and cons, and conclude with perspectives. *Copyright ©2000 IFAC.*

Keywords: medical systems, medical applications, image registration, tracking systems, robotics, navigation systems.

1. INTRODUCTION

Current orthopaedic practice heavily relies on fluoroscopic images to perform a variety of surgical procedures including fracture reduction, pedicle screw insertion, total hip replacement, and osteotomies, to name a few. Fluoroscopic images are X-ray images acquired using a mobile X-ray system called a C-arm (Figure 1). They are used during surgery when direct sight of anatomical structures is unavailable, as is the case in closed and minimally invasive surgeries. The images help the surgeon determine the relative position of bones and implants, and help monitor the advance of surgical tools as the surgery progresses.

While ubiquitous and inexpensive, X-ray fluoroscopy has several important limitations. Fluoroscopic images are static, two dimensional, uncorrelated projections of moving spatial structures. Significant surgeon skills are required to mentally recreate the spatio-temporal intraoperative situation and maintain hand/eye coordination while performing surgical gestures. For example, when drilling a pedicle screw into a vertebra, surgeons continuously adjust the position and orientation of the drill based on fluoroscopic anterior/posterior and lateral views taken several tens of seconds. The surgeon's reduced capability leads to positioning errors and complications in a non-negligible number of cases. Because the images are static and their field of view is narrow, frequent use of the fluoroscope is necessary, lead-

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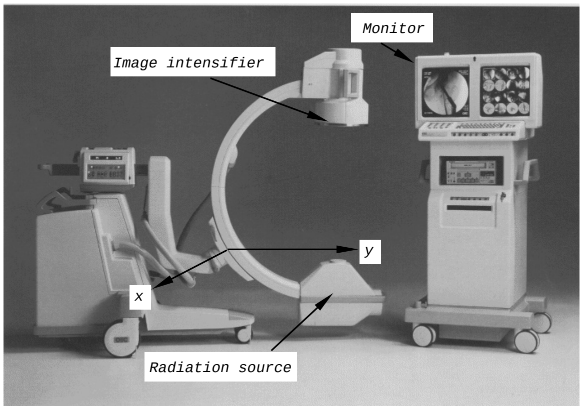


(a) Photograph of a fluoroscopic C-arm

(b) Fluoroscopic X-ray image showing a femur head and a drill tip.

Fig. 1. Intraoperative X-ray fluoroscopy.

ing to significant cumulative radiation exposure to the surgeon. Each minute of exposure (about 60 shots) produces radiation of 4 rads, the equivalent of one Computerized Tomography (CT) study (Sanders, 1993). Many procedures require up to 30 minutes of exposure. An additional disadvantage of fluoroscopic images is that they show significant geometric distortion and varying intensity between shots, precluding their use for quantitative measurements and accurate navigation.

Yet, fluoroscopy can still play an important role in future orthopaedic surgery systems. Recent research shows that computer-aided systems can significantly improve the accuracy of orthopaedic procedures by enhancing or replacing altogether fluoroscopic guidance. Orthopaedic procedures lend themselves well to these types of systems because bones are large rigid structures which can be precisely imaged and effectively tracked in real time. By correcting and enhancing them, a limited number of fluoroscopic images can be used for accurate free-hand navigation, registration, and even precise robot guidance. Examples of systems used in clinical applications include total hip and knee replacement, spine surgery, and trauma.

This paper presents a summary of the state of the art of fluoroscopy-based systems for computer-aided orthopaedic surgery. We first describe the principles of fluoroscopy-based navigation and then describe four classes of systems including either CT, fluoroscopy, or both, and optionally a surgical robot. We describe the technical principles or each, evaluate their pros and cons, and conclude with perspectives.

2. FLUOROSCOPY-BASED SYSTEMS

The main goals of computer-integrated orthopaedic surgery systems are: (1) to improve the surgeon's hand/eye coordination and spatial perception, (2) to improve the accuracy of the surgical gestures and implant placements, (3) to reduce the cumulative radiation exposure to the surgeon, and (4) to shorten surgery time.

The elements of a computer-integrated fluoroscopy-based system are a standard fluoroscopic C-arm, a position tracking system, a computer workstation with data processing and visualization software, and optionally, a robot. The C-arm unit captures the fluoroscopic images that are used during surgery and are down-loaded to the computer via a video frame grabber. The tracking system provides accurate, real-time position information of tools and anatomy to which markers have been rigidly attached. The most common is a system with optical cameras following infrared light-emitting diodes. The computer is used preoperatively for modeling and planning, and intraoperatively for data fusion and display. Robotic devices are used for precise positioning, tool guiding, and for bone cutting. Preoperative data usually includes CAD models of implants and surgical tools, and CT data sets from which 3D bone surface models are constructed.

Before fluoroscopic images can be used, they must be corrected for distortion and calibrated. For some units, the distortion can be up to several millimeters in the borders and is pose-dependent. To correct the images for scale, calibration is necessary to determine the camera's intrinsic parameters. Recent research has shown that both can be reliably achieved to an accuracy of 0.5mm or less by imaging phantoms of known geometry (Brack *et al.*, 1998; Yaniv *et al.*, 1998).

A key technical enabler for system integration is establishing a common reference frame between the different devices and data models. This process, called *registration*, consists of finding a rigid transformation from one coordinate system to another so that all features that appear in one modality are aligned with their appearance in the second. Without it, no navigation and quantitative information integration is possible.

Task/Class	CT	FL	CT+FL	Robot
CT image?	yes	no	yes	yes
Preop planning	yes	no	yes	yes
Fiducials/contact	yes	no	no	yes
In clinical use	yes	yes	no	yes
Commercial Avail.	several	two	no	one

Table 1. Comparative classification of fluoroscopy-based systems (CT = Computed Tomography, FL = Fluoroscopy)

Rigid registration techniques can be divided into four categories of increasing complexity: (1) mechanical or stereotactic registration, where the registration is carried with a fixed frame or a passive mechanical arm of known geometry; (2) fiducial-based registration, where the registration is carried by affixing fiducials of known geometry to the anatomy of interest, imaging the patient with the fiducials, and then localizing the fiducial with a mechanical arm or a tracking system; (3) “cloud-of-points” registration, in which instead of implanting fiducials, a set of points is acquired by touching the surface of the rigid anatomy and matching it to the surface of the 3D model; and (4) image-based registration using anatomic structures to match the contours of 2D images to the contours of the 3D model (no fiducials or direct contact is required). It does not requires fiducials or contact, but requires more sophisticated image processing techniques. To date, it has been shown that submillimetric accuracy in clinical situations can be reliably achieved with the first three methods. Similar results have yet to be achieved with image-based methods.

We distinguish between four types of systems: (1) CT-based systems, (2) fluoroscopy-only systems, (3) CT and fluoroscopy-based systems, and (4) systems combining fluoroscopy and surgical robots. Table 1 summarizes the characteristics and of each, which we evaluate next.

2.1 *CT-based systems*

CT-based systems, which are the most common, replace fluoroscopic images with a virtual reality, multi-view display of 3D instrument and bone models. The bones surface models are constructed for each patient from preoperative CT data. After elaborating a preoperative plan with these models, the bones preoperative and intraoperative positions are registered with implanted fiducials or by intraoperatively acquiring points on the surface of the bones (”cloud-of-points” registration). The changing positions and orientations of the surgical instruments and bones are tracked in real time.

An example of such a system is the HipNav system for acetabular cup placement in total hip replacement (Simon *et al.*, 1997). Preoperatively, HipNav allows the surgeon to plan the orientation of the acetabular cup to prevent implant impingement. Intraoperatively, it shows the position of the pelvis and the cup in real time, providing the surgeon with a visual tool to place the cup in the planned orientation. Other systems include systems for total knee arthroplasty (Fadda *et al.*, 1997) and for total knee replacement (Leitner *et al.*, 1997), systems for pedicle screw insertion (Lavallée *et al.*, 1995*b*; Nolte *et al.*, 1995), illiosacral screw placement (Glossop and Hu, 1997), pelvic osteotomies (Langlotz *et al.*, 1999) and pelvic fracture reduction (Carrat *et al.*, 1998). Commercial systems for spine surgery include the Sofamor Danek's StealthStation and the Medivision system. Figure 2 shows a spine procedure.

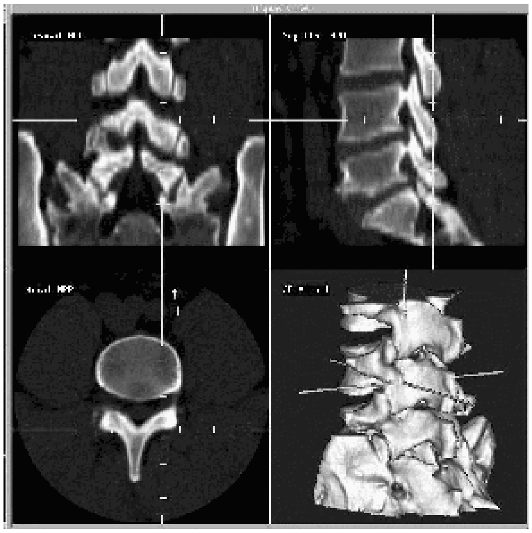


Fig. 2. Computer screen of CT-based navigation for pedicle screw insertion. The cross hair shows the position of the instrument's tip.

The strengths of CT-based systems are that they provide the most accurate 3D geometric models, allowing precise preoperative planning, real-time multi-view and spatial display, and submillimetric accuracy registration with implanted fiducials. They eliminate radiation to the surgeon, and significantly reduce radiation to the patient. The drawbacks are that they require a preoperative CT, which for some procedures is not standard practice, and that they require implanted fiducials or direct contact for registration, which precludes its use in percutaneous procedures.

2.2 *Fluoroscopy-only systems*

Fluoroscopy-only systems approximate continuous fluoroscopy by repositioning in real time two-dimensional contour models of instruments based on tracking data displayed on enhanced static fluoroscopic images. The anatomy of interest,

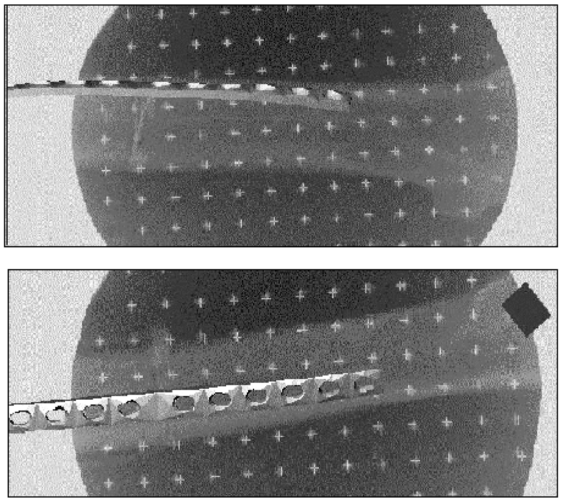


Fig. 3. Two images of fluoroscopy-only navigation showing a femur and a plate moving relative to it (Bachler *et al.*, 1999).

the surgical tools, and the C-arm are instrumented and tracked in real time. A few dozen enhanced fluoroscopic images at carefully chosen viewpoints and moments are acquired, corrected from geometric distortion, calibrated, and correlated. Composite images are then created by projecting the moving instruments onto the static fluoroscopic images showing the anatomy. As long as the relative position of the anatomical objects does not change, the images correspond to what would be seen if continuous fluoroscopy was used.

Procedures under study include intramedullary nailing distal locking (Brack *et al.*, 1998; Hofstetter *et al.*, 1997), percutaneous discectomy, transpedicular and dynamic hip screw placements (Phillips *et al.*, 1995), removal of osteonecrotic lesions, canal drilling for graft positioning, pelvis tumor biopsies, and osteotomies (Brack *et al.*, 1998). Sofamor Danek and Medivision introduced commercial modules at the end of 1999. Figure 3 illustrates this procedure (Bachler *et al.*, 1999).

The advantage of the fluoroscopy-only technique is that it is closest to the current clinical practice: it is simple to use, has moderate equipment requirements, works directly on intraoperative data, and does not require a preoperative CT study or registration. It requires far fewer images than the conventional technique, thus significantly lowering the radiation exposure. Its main disadvantage is the same as conventional fluoroscopy: it relies on 2D images with a narrow field of view, which might be inappropriate for visualization of crowded complex structures. It does not support preoperative planning and is potentially less accurate than CT-based systems. Also, current systems require a distortion correction and calibration grid for every shot, which adds undesired markers to the images (white crosses in Figure 3).

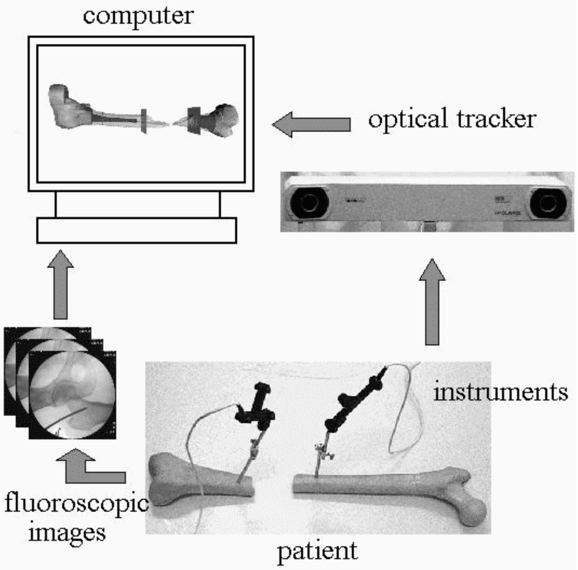


Fig. 4. Registration with fluoroscopic images (Joskowicz *et al.*, 1999).

2.3 *CT and fluoroscopy-based systems*

CT and fluoroscopy-based systems are like CT-based systems except that fluoroscopic images are used to register the preoperative CT model to the intraoperative situation. This type of anatomy-based registration is essential when other methods, such as attaching external fixators, implanting fiducials, or obtaining data points by direct contact on the surface of the bone is impractical, as is the case in a variety of closed and percutaneous procedures. It requires precise correction distortion and calibration of the fluoroscopic images, and matching of the 2D images to the 3D model via anatomy. Figure 4 illustrates the concept (Joskowicz *et al.*, 1999).

Performing automatic, accurate 2D/3D anatomical registration is a challenging task which has yet to find a satisfactory solution despite ongoing work (Guéziec *et al.*, 1998; Hamadeh *et al.*, 1998; Lavallée *et al.*, 1995*c*; Lavalleé *et al.*, 1995*a*). The main difficulty is automatic, robust, and accurate segmentation of bone contours or other features in fluoroscopic images, and efficient matching with the 3D model. Examples include systems for revision total hip replacement (Taylor *et al.*, 1999) and for closed medullary nailing (Joskowicz *et al.*, 1999). No commercial system of this type is available yet, although 2-3mm millimetric accuracy has been reported in in-vitro experiments (Guéziec *et al.*, 1998; Yaniv *et al.*, 2000).

These systems aim to combine the advantages of CT-based systems with anatomy-based registration: precise 3D models, preoperative planning, no need for implanted fiducials or direct contact for registration, reduced intraoperative exposure to radiation. The disadvantages are that they require an additional CT study, that their clinical accuracy is yet to be determined, and that they have not been demonstrated clinically.

2.4 *Fluoroscopy and robotics systems*

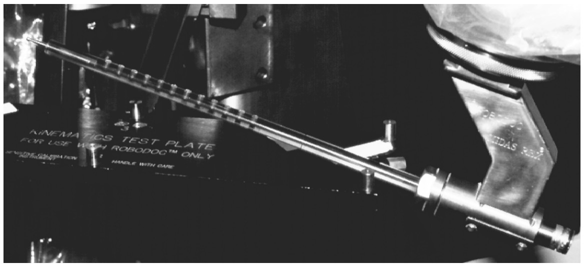
Semi-active and active mechanical systems for tool positioning and cutting can be integrated to the previous systems (Taylor, 1999). The first example of the integration of an active robot is the ROBODOC system (Taylor *et al.*, 1994) for canal milling in total hip replacement. Prior to taking the preoperative CT, three fiducials are implanted in the patient's femur. Their centers are then located on the images, and the surgeon plans the optimal position of the implant. Based on this position, the program generates a cut file of the canal for the robot to machine. To register the cut file to the intraoperative situation, the robot is brought in contact with each implanted fiducial. The robot then machines the canal according to the cut file. Another example is the ACROBOT system (Davies *et al.*, 1997) for total knee replacement, which incorporates a semi-active guide for positioning the surgeon's saw.

Two systems that incorporate a robot and fluoroscopy are a system for revision total hip replacement (Taylor *et al.*, 1999) (Figure 5) and a system for pedicle screw insertion (Santos-Munne *et al.*, 1995). In these system, the robot holds a radio-lucent calibration object with fiducial at its tip which is imaged in the vicinity of anatomical structures from several viewpoints. After processing the images, the system determines to submillimetric accuracy the position and orientation of the robot tip with respect to the anatomy.

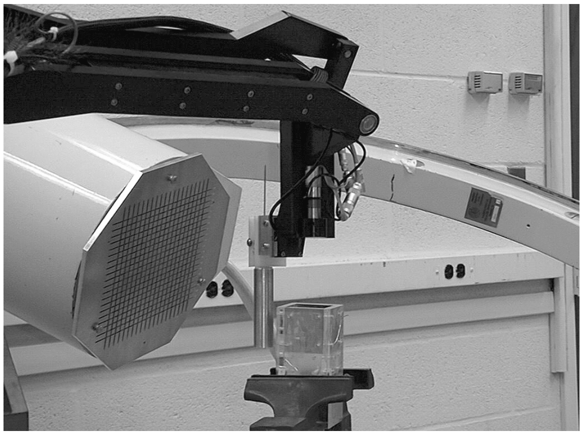
3. PERSPECTIVES

Ongoing clinical trials indicate a trend of early acceptance of computer-integrated systems, especially CT-based systems, which have been in use since 1995. Over 7,000 computer-aided pedicle screw insertions, and 3,000 ROBODOC surgeries have been performed worldwide to date, with very satisfactory short term clinical results. Clinical experience with fluoroscopy-only systems is also starting to be published.

Two recent trends of interest include the improvement of intraoperative imaging: surgical CT and MRI devices, which will enable surgeons to obtain intraoperative spatial images, and the construction of 3D models from fluoroscopic images. This later "poor man's CT" has great potential, since it in principle does not require new imaging hardware. Recent research has shown that about 100 images are necessary, which is still impractical for most cases (Navab *et al.*, 1999; Desbat *et al.*, 1999). Another promising trend is the integration of other imaging modalities, such as ultrasound and MRI data. More challenging applications include soft tissue, such as ligaments, tendons, and muscles, which require deformable models and registration.



(a) Robot tip with calibration rod



(b) In-vitro setup of fluoroscopic robot guidance

Fig. 5. Fluoroscopic robot guidance (Taylor *et al.*, 1999).

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