MINI-SYMPOSIUM: COMPUTER AIDED/ROBOTIC ORTHOPAEDIC SURGERY

(i) Registration techniques for computer navigation

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Summary
Mathematically, registration is a process to determine a geometrical transformation that aligns points in two frames of reference, so that the attributes associated with those points can be viewed and analyzed jointly. Clinically, registration is an important step in computer-assisted surgical navigation to correlate morphological information collected in different surgical stages, before, during and after the operation. This paper gives an overview of registration techniques as applied to computer-assisted surgical navigation for orthopaedic interventions. Challenges in quantifying registration accuracy are discussed, and emerging new registration techniques are presented.

Introduction
With the advent of advanced pre and intraoperative imaging means, the development of sophisticated algorithms for image data processing and visualization, and the accessibility of devices for sub-millimetric, real-time tracking of objects in space, computer navigation systems and robotic devices have been created that aim at enhanced surgical accuracy and reliability, reduced radiation exposure, and ultimately improved clinical outcome. These techniques were initially developed for intracranial interventions, and after further refinement can now cover various procedures in orthopaedics and traumatology. Conceptually, the concept of computerized surgical navigation is analogous to ground-positioning satellite systems as used in cars, constantly displaying the car’s location on a digital map. In order to generate such feedback during surgery three tasks have to be fulfilled by a computer navigation system: (a) a virtual object (VO) generated e.g. from computed tomographic (CT), magnetic resonance (MRI), fluoroscopy (FLC), or ultrasound (US) image data sets, or even from point digitization, has to be provided serving as the "digital map" of the patient, (b) the spatial location of all important instruments has to be measured in real-time by a tracking device, also termed navigator, in three dimensions and in relation to the patient frame of reference established on a therapeutic object (TO), i.e., the part of the patient’s anatomy to be operated on, and (c) the relative instrument position has to be transferred into the space of the virtual object to enable its visualization at the correct location.
The technique used to fulfill this last task is called registration. It is a process to determine the geometrical relationship that aligns points in two frames of reference, i.e., those of virtual and therapeutic objects, so that the attributes associated with those points can be viewed and analyzed jointly. Registration, also known as matching, is an important step in computer navigation to correlate information collected in different surgical stages, before or during the operation. Without registration, a detailed surgical plan and corresponding simulations of the surgical procedure, prepared preoperatively, cannot be optimally implemented in the operating room, thus relying solely on the spatial sense of the surgeon.

Motivated by the needs and challenges arising from clinical practice, a wide variety of different medical image registration approaches have been developed and realized following numerous methodologies. The survey articles by Fitzpatrick,1 Lavallee,2 and Maintz3 provide excellent sources for in-depth discussion of medical image registration, associated problems and solution strategies. It should be noted that registration techniques used for image fusion are substantially different from those used for computer navigation. In the former case, all geometric data are matched and their associated attributes are fused within a single, unique coordinate system while in the latter case they also have to be registered with the physical space of the patient.

The purpose of this paper is to give an overview of registration techniques used in current systems for surgical navigation.

Theory and terminology

From an operational point of view, the inputs of registration are two entities to be registered; the output is a geometrical transformation, which is a mathematical function used to transform points in one entity to points in the second.1 Each entity defines its own local frame of reference and there are attributes associated with points in those entities, e.g., gray values in a CT volume. We define the entity to be transformed the floating entity and the other the reference entity. Mathematically, any registration technique can be described by three main components: (a) a geometrical transformation, which relates the reference and floating entities; (b) a similarity measure which measures similarity between reference and transformed floating entities; and (c) an optimization scheme which determines the optimal geometrical transformation by maximizing the similarity measure.

A geometrical transformation can be classified by its complexity into "rigid transformations", where distances between points and angles between lines and planes in the floating entity are preserved, and "non-rigid or deformable transformations", where geometrical relations are stretched or deformed. Mathematically, a rigid transformation can be uniquely described by a rotation and a translation, while the description of a non-rigid transformation is not unique. According to the geometrical transformation used in the registration process, we can categorize the registration techniques for computer navigation into two groups: rigid registration and deformable registration. Most computer navigation systems for orthopaedic surgery only incorporate rigid registration, considering the fact that bone is a rigid, non-deformable tissue. However, deformable registration, specifically statistical model based deformable registration4 or bone morphing,5 has been recently integrated into a few commercially available computer navigation systems.

Before we introduce various registration techniques for computer navigation, it is worth explaining an important distinction between registration and another common concept in computer navigation: calibration.2 In general the purpose of calibration and registration is the same. Both aim at determining the geometrical relationship between the frames of reference located in different entities. However, the distinction between registration and calibration is also apparent. According to Lavallee,2 if two frames of reference are rigidly connected to a same object, then their geometrical relation will be estimated through calibration procedures; if associated coordinate systems are totally independent, they are linked through a registration process. For instance, in MRI-based navigation, the geometric distortion induced by the field inhomogeneity is estimated through a calibration procedure using phantom measurements, whereas the relation between a preoperative MRI of a patient and the physical space of this patient is determined through a registration process. Another example of calibration in computer navigation was the introduction of the so-called registration-free systems4 based on a navigated Iso-C3d C-arm (Siemens Medical AG, Erlangen, Germany), in which the challenging and often time-consuming intraoperative registration process is replaced by an offline and procedure-independent calibration. The principle of such an approach is simple, although its technical implementation is not trivial. In the offline calibration step, the relation between a reference coordinate system rigidly affixed to the Iso-C3d C-arm and the image volume of reconstruction is determined through a paired-points matching process. Intraoperatively, as soon as the CT-like volume data set of the patient is acquired, the navigation system immediately knows its position and orientation in the patient reference coordinate system using the rigid transformation obtained through the offline calibration procedure and the transformation between the patient reference coordinate system and the device reference coordinate system, which is obtained in real time from the tracking device.

Registration techniques for computer navigation

As registration is an embedded component in a computer navigation system, the input data to the system, collected at different surgical stages, before or during operation, determine the type of registration technique. Table 1 summarizes the relationship between the type of input data and the type of registration technique. For a more comprehensive classification of different registration techniques, we refer to previously published review papers on this topic.1–3
Rigid registration techniques for computer navigation

3D/3D feature-based rigid registration technique
Related methods in this category for finding global, rigid transformation to register the virtual and therapeutic objects are paired-points matching and surface matching. They are the registration techniques implemented in the first generation of computer navigation systems for orthopaedic surgery and still the most widely used registration techniques in nowadays CT-based navigation systems. This is not surprising, considering that the similar problem to register two sets of geometrical features (e.g., registration of two point sets or registration of points to surface) has been well studied in the fields of robotics and computer vision, which existed long before the introduction of computer navigation. Thus, the existing body of knowledge allows us to establish a rough taxonomy of the different solutions proposed in the literature. Well-known paired-points matching algorithms range from iterative solutions to analytic, direct methods using quaternion theory or singular value decomposition while the most well-known surface matching solution is the so-called iterative closest point (ICP) algorithm.

Mathematically, both registration techniques are similar. They both use the geometrical features (points, lines, surface) corresponding to the same anatomical or fiducial structures to derive the registration transformation. However, in paired-points matching, the correspondences are assumed to be known while in surface matching, those correspondences need to be iteratively determined, as shown in Fig. 1 for the specific task of registration for dorsal spinal interventions.

The operational procedure for paired-points matching is simple. At least three pairs of distinct points are defined preoperatively in the virtual object and intraoperatively in the therapeutic object. The former set of points is usually identified using the computer mouse and marking the desired location within the image data. For the intraoperative acquisition, a probe is used. In the case of a navigation system it is tracked by the navigator and for robotic surgery it is mounted onto the robot’s actuator, which the surgeon then guides to the location to be recorded. Once both point sets are available, the transformation that links the underlying coordinate systems can be derived using one of the previously mentioned paired-points matching algorithms. Obviously this procedure is highly interactive during both the preoperative definition of registration points and the intraoperative acquisition of their counterparts. Consequently, this step is error-prone, in particular because a good registration result and thus an accurate performance of the navigation system strongly depend on an optimal selection of the registration points and the exact identification of the pairs. To improve the accuracy of this step, alternative and complementing techniques have been proposed. Probably the most obvious was the implantation of artificial objects to create easily and exactly identifiable spots for paired-points registration. Percutaneous markers, pins, or complex marker carriers have been suggested. These artificial objects are easily identifiable in the images and intraoperatively on the patient. As a consequence, carrying out an exact matching between the rigid bodies is then very easy or can even be automated. However, these methods require the artificial markers to be represented in the preoperative images, thus necessitating their implantation prior to image acquisition through an additional intervention. For reasons such as costs, infection risk, patient discomfort, etc. none of these methods have gained wide clinical acceptance.

Table 1 The relationship between the type of input data and the type of registration technique for computer navigation.

<table>
<thead>
<tr>
<th>Types of input data</th>
<th>Preoperative</th>
<th>Intraoperative</th>
</tr>
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<tbody>
<tr>
<td>CT or MRI</td>
<td>Locations of fiducial markers</td>
<td>3D/3D feature-based rigid registration</td>
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<td></td>
<td>Digitized anatomical points</td>
<td>3D/3D feature-based rigid registration</td>
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<td></td>
<td>Calibrated 2D fluoroscopic images</td>
<td>2D/3D image-based rigid registration</td>
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<tr>
<td></td>
<td>Calibrated 1D (A-Mode), 2D (B-Mode), or 3D ultrasound data set</td>
<td>3D/3D image-based rigid registration</td>
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<td></td>
<td>Calibrated CT-like volume data</td>
<td>Image fusion based rigid registration</td>
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<td>Knowledge about volumetric imaging device</td>
<td>Volume data</td>
<td>Modality-based rigid registration</td>
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<td>Statistical model</td>
<td>Digitized anatomical points/“surgeon–defined anatomy”</td>
<td>3D/3D feature-based deformable registration</td>
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<td></td>
<td>Calibrated 2D fluoroscopic images</td>
<td>2D/3D image-based deformable registration</td>
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<td></td>
<td>Calibrated 2D/3D ultrasound images</td>
<td>3D/3D image-based deformable registration</td>
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Without the use of artificial objects, paired-points matching cannot fulfill the accuracy requirements of most computer-assisted orthopaedic surgical procedures and is thus often complemented with surface matching. Surface matching uses the surface of the virtual object as a basis for
registration. With the help of the navigator, points are captured on the therapeutic object’s surface, which are then mapped onto the virtual object’s surface. The technique is based on the fact that a small number of points digitized on the accessible bone surfaces usually describe the surface very precisely. Preoperative image processing allows for the extraction of the exact shape of the bony surface from preoperative CT images. Using this approach, it is not possible to analytically calculate the transformation between the virtual and therapeutic object. The correct transformation must be searched for, usually using a similarity function that measures the degree of correspondence between the points and the surface. A major advantage of surface matching is that it removes the dependence on the error-prone identification of corresponding anatomical landmarks, as long as the intraoperatively collected points lie on the surface of the anatomy, which has been delineated in the preoperatively acquired medical images.

**2D/3D image-based rigid registration techniques**

The above described feature-based rigid registration is an invasive procedure, which requires either implanting artificial objects or exposing parts of the anatomy to enable contact-based point digitization. As a less invasive alternative, fluoroscopy-based 2D/3D registration (see Fig. 2) has generated a lot of interest.9

*Figure 1* Paired-points matching vs. surface matching. (A) Paired-points matching where the correspondences between homologous anatomical landmarks are known; and (B) surface matching where intraoperatively acquired points are matched to preoperatively segmented surfaces.
The reported techniques for fluoroscopy-based 2D/3D registration can be split into two main categories: feature-based methods and intensity-based methods. Feature-based methods require an antecedent segmentation stage, which is error-prone and difficult to achieve automatically. Segmentation errors can lead to errors in the final registration. As a consequence, interactive and semi-automatic methods\textsuperscript{10} have been proposed to extract bone contours from the fluoroscopic images. But in general, this problem is still unsolved and is a field of very active research. In contrast, intensity-based methods directly compare the calibrated fluoroscopic images with digitally reconstructed radiographs (DRRs), which are obtained by simulating X-ray projections of a preoperative CT volume.\textsuperscript{11} No segmentation is required. One of the main factors that affects the accuracy of intensity-based methods is the choice of similarity measure, which is a criterion function that is used in the registration procedure for measuring the

\textbf{Figure 2} Screenshots of different stages of a CT-Fluoro matching process. (A) Pre-registration for CT-Fluoro matching; (B) final results of CT-Fluoro matching (courtesy of BrainLAB AG, Munich, Germany).
quality of image match. How to design a robust similarity measure so that the registration can be performed successfully in a practical setup is still an active research field. Major challenges result from outliers such as interventional instruments present in the projection images.

Compared to the feature-based methods, intensity-based methods suffer from higher computation cost, largely due to the process of DRR generation, but demonstrate potentially better accuracy and robustness and are more easily automated. Hybrid 2D/3D registration techniques which avoid the explicit segmentation step in the feature-based methods but require less computation cost have also been proposed recently.

**3D/3D image-based rigid registration techniques**

The above mentioned 2D/3D rigid registration technique exemplifies how registration between virtual and therapeutic objects can be achieved in a minimally invasive manner. Alternative non-invasive registration techniques, this time employing ultrasound data, shall be discussed next.

Although primarily designed for soft tissue imaging, ultrasonic devices also allow transcutaneous scanning of bone surfaces. Two types of approaches have been explored to use calibrated ultrasonic data for registration: feature-based and intensity-based approaches. Feature-based approaches attempt to acquire bony surface points from calibrated ultrasonic data and then take the acquired surface points as the input to a 3D/3D paired-points or surface matching technique as described in Section 3.1.1 to estimate the registration transformation. Promising results using calibrated or self-calibrating B-mode ultrasound probes have demonstrated their potential for surgical navigation. In Fig. 3 an experimental intraoperative setup for B-mode ultrasound-based registration is displayed. Currently, technology transfer is hindered by limitations related to automated and accurate localization and identification of the relevant anatomical structures from noisy images and signals. In contrast, intensity-based approaches directly make use of the calibrated ultrasound images (a series of sparse 2D images or a 3D volume) to find
Figure 4  Screenshots of different stages of an intraoperative bone morphing process. (A) Point acquisition; (B) calculation of morphed model; (C) verification of final result (courtesy of BrainLAB AG, Munich, Germany).
the registration transformation and thus avoid the difficulty of segmenting the bone surface at the US image level.\textsuperscript{15} However, robustness and accuracy are still challenging issues that need to be improved before these approaches can be transferred from the laboratory into the surgical theatre for routine use.

**Deformable registration techniques for computer navigation**

Preoperative CT imaging is the method of choice for a wide variety of navigated surgical interventions, and it is compulsory for the use of orthopaedic surgical robots. However, the high level of radiation received by patients, the large quantity of data to be acquired and processed, and the high logistic cost involved in acquisition and processing of CT data make them less functional. As alternatives, intraoperative imaging means such as fluoroscopy and ultrasound, or even the so-called "surgeon-defined anatomy",\textsuperscript{5} which is a technique based on point digitization, have been successfully used to create virtual objects intraoperatively. When compared to CT these techniques suffer from the fact that no complete 3D model structure information is available. The surgeon still needs to mentally fuse data acquired using these techniques.

One way to address this dilemma is to do statistical deformable registration (SDR)\textsuperscript{4} or bone morphing,\textsuperscript{5} which is a method to reconstruct the geometrical shape of an object from sparse input data using a previously generated statistical shape atlas. In the context of computer navigation for orthopaedic surgery, the shape of the operated bone is predicted based on a statistical shape model (SSM) representing the typical shape of the bone, represented by the statistical mean and the associated morphological variations found in a collection of sample bones of a given population. The SSM is constructed by applying principal component analysis (PCA) to the aligned shape models of these sample bones. In order to create a good estimation of the individual patient’s bone, a rather small number of morphological features (surface points, rotation centers, anatomical axes, etc.) are acquired by the surgeon intraoperatively and enable the underlying algorithms to select parameters that guarantee precise shape prediction. This method therefore differs from the "surgeon-defined anatomy" method, in which abstract bone models are constructed from the acquired data following simple sampling schemes. In contrast, the input data to an SDR algorithm is used to extract the individual deviations of a particular patient from the statistical mean and to deform that mean accordingly. An example for an intraoperative bone morphing process is shown in Fig. 4. This method is heavily employed in so-called "image-free" navigation systems, mainly for knee and hip surgery. However, with the availability of statistical shape atlases of other anatomical regions, the technique could be applied to any part of the skeleton. Such approaches bear significant potential for future developments of computer navigation technology since they are not at all bound to the classical pointer-based acquisition of bony features. In principle, the reconstruction algorithms can be tuned to any type of patient-specific input, such as e.g. intraoperative calibrated fluorescent images or tracked ultrasound, thereby potentially enabling new minimally invasive procedures. Fig. 5 shows an example of bone surface reconstruction from calibrated fluoroscopic images and a statistical shape model. Moreover, prediction from statistical atlases is possible not only for the geometric shape of an object. Given a three-dimensional radiological atlas, "synthetic CT scans" could be predicted from intraoperatively recorded data.\textsuperscript{16}

**Quantifying registration accuracy**

Assessing the accuracy of a given registration algorithm in a quantitative manner is a difficult task. The accuracy of a registration transformation cannot be easily summarized by a single number, as it is spatially varying over the image. For paired-point rigid registration using fiducial points, Fitzpatrick et al.\textsuperscript{1} have presented a theory of error modeling that can predict the expected error distribution based on errors in localizing individual points, and the distribution of points. In this theory, the localization error of the fiducial points is defined as the fiducial localization error (FLE). The residual error in fitting of paired-points is called the fiducial registration error (FRE), which is actually the root mean square (RMS) error between homologous fiducials after registration and is used by most navigation systems in the market to report the registration accuracy. Although helpful to the surgeon to a certain extent, the FRE is less reliable than the target registration error (TRE), which is defined as the error between a measured anatomical target under the registration transformation and its corresponding location in the space of the virtual object. It should be noted that this theory of errors can be used to optimize the design of fiducial markers and the configuration of the fiducial marker distribution.

Another approach to quantify the registration accuracy of a given registration algorithm is to use a "gold standard", which is normally derived with high accuracy using fiducial markers. The registration accuracy can now be calculated by comparing the transformation calculated by the given...
registration technique with the known, "gold standard" solution.

Finally, a more practical approach that can be applied in day to day clinical routine is to perform visual verification. This is usually done by touching anatomical landmarks of the therapeutic object with a tracked pointer and visually checking whether the corresponding location in the virtual object is displayed correctly by the navigation system. This step is mandatory for a safe usage of a navigation system. It is important to note that a point distribution should be chosen, which assures a 3D positional control.

Emerging registration techniques for computer navigation

Registration is and will remain an active field of research. New methods and techniques will help to simplify the intraoperative matching procedure with the ultimate goal to fully automate it. In the following, two examples of emerging registration techniques will be presented, which hold potential for improving future computer navigation systems.

Modality-based registration techniques

Technical insight into existing and new imaging devices may allow us to design fully automatic registration procedures. An example of such an approach was originally presented by Messmer et al., where the coupling was achieved by obtaining the geometric relation between a CT scanner and acquired images in a one-time offline calibration procedure and the name "modality-based navigation" was coined. This relation could subsequently be used to obtain patient-to-image correspondence for every new acquisition. Another example is the headset-based registration suite. In addition to a fully automated patient-to-image registration, it also checks the CT scan quality by detecting patient movement during scanning and by checking for scanner calibration quality. Such a technique provides the user with improved clinical accuracy throughout the surgical volume, while facilitating OR setup and enhancing ease of use. To date, this technique has been applied to skull-base surgery, but in principle it can be applied to any part of the skeleton.

Image fusion based registration techniques

Examples of image fusion based registration techniques have been presented above and include both rigid and non-rigid matching of a preoperative CT scan with multiple intraoperatively acquired calibrated image data, e.g. from image intensifiers or ultrasound units. Further research and development effort is necessary before these techniques can be applied in the operating theatre.

An image fusion based registration technique with potential for future routine use in trauma cases is described in Rudolph et al. It registers calibrated fluoro-CTs from an Iso-C to a preoperative CT volume. The used Iso-C system is a navigated mobile C-arm that enables the surgeon to acquire CT-like volume data intraoperatively with high resolution but reduced image quality and smaller field of view when compared to a standard CT scan. An offline calibration procedure (cf. Section 2) allows the surgeon to directly correlate the image volume to the physical space of the patient. By registering such a volume data to a preoperative CT volume, one can enhance the intraoperative visualization of the surgical field.

It is well known that CT and MRI data can provide complementary information about bone and soft tissue. Bone structures are better visualized by means of CT while MRI data would for instance let the surgeon assess the quality of joint cartilage. Van de Kraats et al. recently presented their non-invasive method for registration of MR images to intraoperatively acquired 3D rotational X-ray images (3DRX). Since the calibrated 3DRX system provides an intrinsic relation between the intraoperatively acquired 3DRX data and the patient, their method indirectly registers the MR with the patient, allowing image-interactive precise navigation in both 3DRX and MR data.

Discussion and conclusion

Registration is a key step in every computer navigated orthopaedic intervention. Conceptually it aims at establishing an accurate geometrical relationship that aligns points in two frames of reference, i.e. those of the therapeutic object and its virtual representations, e.g. generated from image data sets. It is a prerequisite for any image-interactive guidance and placement of orthopaedic devices, such as instruments and implants using robotic or navigation technology. Early CT-based orthopaedic navigation systems failed to penetrate the market due to complex, unreliable and often time-consuming matching procedures.

Since then different approaches that ultimately provide systems for day to day routine use could be identified among the computer-assisted orthopaedic surgery community. At first navigation technology providers and their clinical partners developed image-free navigation modules using the so-called "surgeon defined anatomy" concept. They successfully made their way into the operating theatre. However, image-free systems supply limited morphological information to the surgeon and thus only cover a few applications, such as knee and hip joint replacement. They do not provide a sound basis for interventions, where image-interactive surgical actions have to be performed, e.g. in fracture reduction and fixation.

The scientific community concentrated on improved design and realization of registration algorithms. They also broke new grounds by introducing statistical shape atlases and bone morphing concepts, initially to expand the potential of image-free systems.

Another area of progress was the integration of existing intraoperative imaging means into existing tracking concepts as exemplified by 2D fluoroscopic navigation. These systems for the first time allowed the collection of morphological information and its use for navigation in different stages during the operation. The early success of fluoroscopic navigation stimulated development activities of the image device manufacturers.
towards new intraoperative imaging means such as the 3D C-arm based fluoro-CT devices.

Due to these efforts the computer navigation community can revert to a wide spectrum of potential registration algorithms and techniques. In consequence orthopaedic navigation technology has successfully emerged into fields such as spinal and trauma interventions, which require image interactivity. Still surgeons are confronted with certain complexity of the resulting work flow and need considerable training to be in full control of the registration process. Further research and developments are necessary to achieve the ultimate goal of an accurate, reliable, and fast automated registration. This will require a concerted approach with a close partnership of expert surgeons and technologists.

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