In-Vitro Accuracy Study of Contact and Image-Based Registration: Materials, Methods, and Experimental Results

Z. Yaniv, O. Sadowsky, and L. Joskowicz

School of Computer Science, The Hebrew University of Jerusalem, Israel.

This paper describes methods, materials, and experimental results for determining the in-vitro accuracy of algorithms and protocols for rigid registration. We quantify the in-vitro accuracy of contact-based methods (fiducials and landmark + cloud of points) and fiducial fluoroscopic X-ray image-based methods for active optical tracking. Our experiments show sub-millimetric accuracy for contact-based registration and 3mm accuracy for fiducial image-based registration.

1. INTRODUCTION

A key advantage of computer-assisted surgery systems is the ability to integrate information from different modalities, such as preoperative CT, intraoperative X-ray fluoroscopic images, and tool position data. The integration allows surgeons to simultaneously visualize in real time the relative position of anatomy and surgical tools. The enhanced spatial hand-eye coordination of the surgeon helps improve outcomes, reduce cumulative surgeon exposure to X-ray radiation, and facilitate minimally invasive procedures.

An essential step of the integration is the registration of multimodal information. Registration is the task of finding a transformation from one coordinate system to another so that all features that appear in one modality are as closely aligned as possible with their appearance in the second. Many approaches to multimodal registration have been proposed, depending on the anatomy and on the data to be registered [7].

Determining the accuracy of different modalities and algorithms is essential to understand their applicability to clinical problems and to provide the experimental basis for improving algorithms and data collection protocols. Recent work reports on the accuracy of optical tracking [2], on the clinical accuracy of frameless stereotaxy [5], and preliminary results on fluoroscopic image-based registration [3,4]. Pennec and Thirion [8] describe a theoretical framework for evaluating the uncertainty of rigid registration.

This paper summarizes our study on the accuracy of contact-based and fluoroscopic X-ray image-based rigid registration methods with an active optical tracker [9]. It is motivated by our work on image-guided computer-assisted orthpaedic surgery [6]. We describe two new phantoms registration, the experimental setup, and the results for contact-based fiducials, landmarks + cloud of points registration and for fiducial image-based registration. The experiments show sub-millimetric accuracy for contact-based registration and 3mm accuracy for fiducial image-based registration.

2. RIGID REGISTRATION

Rigid registration techniques can be divided into three categories: 1) fiducial-based registration, in which markers of known geometry are identified in both data sets; 2) landmark and cloud-of-points registration, in which an initial guess is obtained with a few inaccurate landmark points and then refined with a set of points collected from the object surface, and 3) image-based registration, in which fiducials or object contours in the 2D image are matched to their corresponding geometry in the 3D model. We use the following four-step methodology for all our experiments [7]:

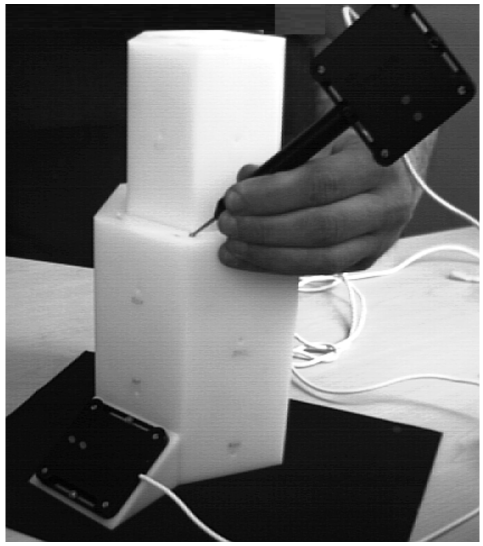
1. Feature extraction and selection: determine which features from each data set are candidates for matching. For the tracker data, the tool and phantom positions provide the feature data. For the images, we use the ray emanating from the camera focal point to the center of the circle corresponding to the imaged fiducial (metal spheres)
2. Feature pairing: a correlation between the same feature in the two modalities is established: which feature will be matched to which in the two modalities. For fiducial-based registration, the pairing is known in advance. For cloud-of points and contour image-based registration, we use the Iterative-Closest Point algorithm [1].
3. Similarity formulation: a global similarity measure is established on the basis of the pairing. Similarity is stated as a minimization problem: given a set of paired points, the goal is to compute the transformation which will minimize the sum of the distance between all pairs. Instead of formulating a nonlinear optimization problem, we use the small angles linear approximation and formulate a linear programming problem [9].
4. Dissimilarity reduction: the dissimilarity between the two data sets is reduced by minimizing a disparity function between feature pairs. Instead of solving the nonlinear minimization problem, we solve an approximated linear programming problem by iterative linear optimization. We have found that this is faster, more robust, works for a wider set of initial guesses, and typically converges to the accurate solution in less than 10 steps.

3. MATERIALS AND METHODS

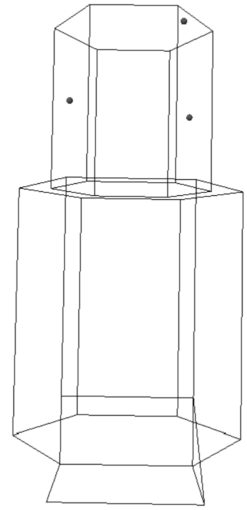
We implemented the registration algorithm and designed two phantoms to quantify the in-vitro accuracy of contact-based registration (fiducials and landmarks + cloud of points) and of fiducial fluoroscopic X-ray image-based registration.

To determine the position of the pointers and phantoms, we use Northern Digital's Polaris^{TM} and active Traxtal^{TM} calibration and pointer instruments. To obtain X-ray fluoroscopic images, we use a Phillips B29 X-ray fluoroscope with a 9" field of view. The images are digitized and downloaded to a PC computer via a frame grabber. The images are corrected for distortion, and the intrinsic camera parameters for each fluoroscope pose are obtained with the method described in [6]. The pose (position and orientation) of the C-arm is obtained with an active plate rigidly attached to the image intensifier.

The contact registration object, shown in Figure 1(a) is a Delrin^{TM} two-step hexagonal tower with 31 holes whose depth has been measured with a precision of 0.1mm. Its height is 250mm, inner diameter 70mm, and outer diameter 110mm. The holes are placed so as to maximize the different distances between them. Attached to the tower is an active tracking plate that serves as a dynamic reference frame. Points on the surface of the



(a)



(b)

Figure 1. (a) Photograph of the hexagonal registration tower and a pointing tool touching one of the holes; (b) Landmark choice for landmark-based registration.

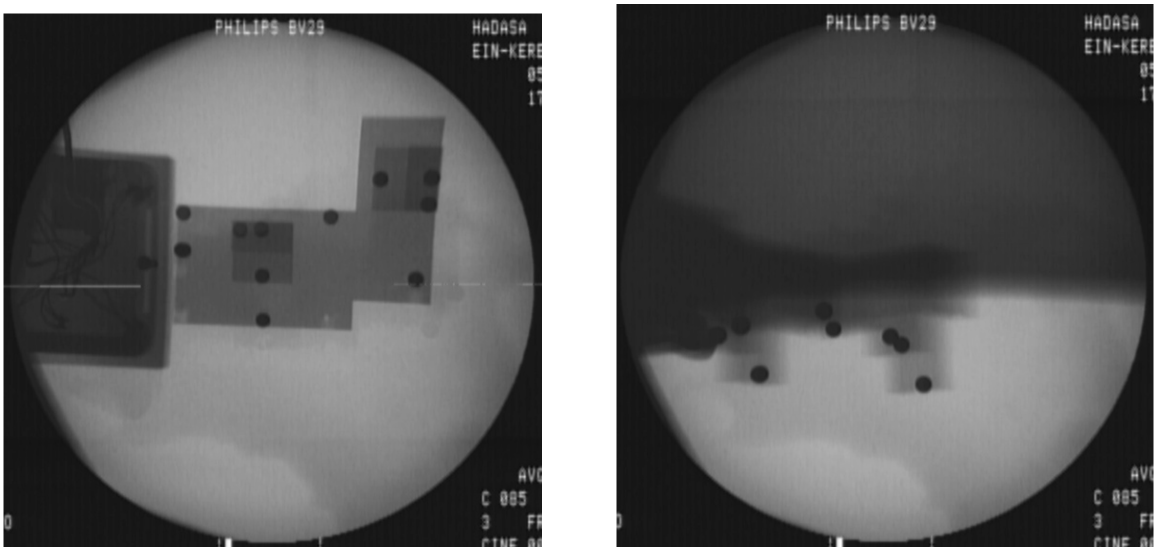
object and at the hole locations are acquired using a tracked pointer. The pointer is pre-calibrated using the CalTraX^{TM} calibration unit. The phantom geometry and holes location is known and modeled as a 3D object to an accuracy of 0.1mm or better. Contact-based registration is performed by acquiring a set of points on the phantom and comparing them with their locations with the ones on the 3D model.

The image registration object is an L-shaped 60x80x40mm Delrin^{TM} object consisting of four rectangular blocks glued together in a known configuration. The object has nine 4mm steel ball-bearings embedded in it, and 10 holes whose depth has been measured with a precision of 0.1mm or better. It also has attached to it an active tracking plate. Image-based registration is performed by locating the sphere centers in the images (after dewarping and calibration of the C-arm) and comparing them with the ones computed from the C-arm and phantom location, and the geometric model of the phantom. Figure 2 shows AP and lateral fluoroscopic images of the object.

4. EXPERIMENTAL RESULTS

Tracker and instrument calibration

To determine the intrinsic accuracy of the tracking instruments and characterize their drift over time, we sampled 10,000 tool locations after calibration for two pointers with active LEDs and for the registration hexagon. The standard deviation was 0.15mm, with min=0.2mm and max=0.7mm. The error increases when the tip of the instrument is considered instead of the virtual tool center. No significant drift over time was observed.



(a) AP (b) Lateral

Figure 2. (a) Fluorosocopic images of the L-shaped phantom for image-based registration.

Exp.	Mean	Std Dev	Max	Min
1	0.62	0.25	1.27	0.20
2	0.54	0.22	1.04	0.18
3	0.55	0.23	1.14	0.20
4	0.48	0.17	0.91	0.22
all	0.55	0.22	1.27	0.18

(a) Five fiducials

Exp.	Mean	Std Dev	Max	Min
1	0.44	0.23	0.98	0.12
2	0.46	0.21	1.14	0.18
3	0.49	0.34	1.50	0.10
4	0.67	0.33	1.36	0.09
all	0.51	0.30	1.45	0.09

(b) Ten fiducials

Table 1. Fiducial registration errors in mm.

Contact fiducial-based registration

We acquired the location of fiducial points (holes) using the tracked pointer by inserting the probe's tip into a subset of the holes, as shown in Fig 1(a), and registered them to their corresponding position in the geometric model. After registration, the locations of all 31 holes were acquired and compared with their expected location. The experiment was repeated a total of eight times with a choice of arbitrary fiducials. Half of the experiments were done with a choice of five arbitrary fiducials as input and half with ten fiducials. Fig 1(b) shows an example of a particular choice. The results are summarized in Table 1. We conclude from the data that our tool calibration and fiducial registration algorithm result in sub-millimetric accuracy of 0.53mm, and that five fiducial points are sufficient. The results seem near optimal taking into account that the Polaris tracking unit's maximal accuracy is 0.3mm and that the pointer calibration process does introduce similar errors.

Exp.	Mean	Std Dev	Max	Min
1	1.95	1.22	4.43	0.54
2	1.82	0.89	3.59	0.40
3	5.97	3.82	12.93	0.31
all	3.25	3.04	12.93	0.31

(a) Three landmarks with 2.5mm noise

Exp.	Mean	Std Dev	Max	Min
1	0.86	0.34	1.61	0.33
2	1.60	0.67	3.17	0.50
3	1.31	0.76	2.95	0.24
all	1.26	0.68	3.17	0.24

(b) Fifteen surface points

Table 2. Landmark and cloud of points registration errors in mm.

Point	Contact	Two images	Four images
1	0.23	4.12	3.20
2	0.68	4.38	3.04
3	0.49	4.00	2.80
4	0.40	3.37	3.21
5	0.10	3.46	2.82
6	0.19	3.81	3.33
7	0.50	3.46	2.87
8	0.29	4.14	2.73
all	0.36	3.84	3.00

Table 3. Image-based fiducial registration errors in mm for eight fiducials.

Landmark and cloud of points registration

We performed landmark and cloud of points registration as follows. First, we acquired three known landmark points (holes) for a first registration, and then acquired 15 unknown points on the hexagon surface. We added 2.5mm to the depth of each hole to simulate uncertainty in the landmark positions. The experiment was repeated with three different sets of landmarks: 1) two on opposite walls of the hexagon tower and one on the face between them (best case); 2) two on opposite walls of the hexagon tower and the third on the side (average case, Fig. 1b), and; 3) three on the same side of the hexagon (worst case). We then used this registration as an initial guess to the cloud of points registration. Table 2 summarizes the results. As expected, the third case yielded the worst results for coarse registration, but the error was significantly reduced by the second step.

Image-based registration with fiducials

We performed image-based fiducial registration by acquiring six images of the L-shaped phantom at different C-arm orientations. The C-arm pose was recorded with the tracker. We then acquired hole position data with a tracked pointer and did fiducial contact-based registration as above. We performed fiducial image-based registration with two and four images by locating the sphere centers and matching their corresponding camera rays with their position in the model. Table 3 summarizes the results. As expected, contact-based registration is much more accurate, and four images yield better results than two. Still, an error of 3mm is relatively high.

5. DISCUSSION AND CONCLUSIONS

Our results for contact-based registration are satisfactory and are similar to those obtained by other researchers. The results confirm that the registration algorithm based on linear approximation of the mean square pairwise distances is accurate, reliable, and converges for a wide range of initial configurations.

The current fiducial image-based results indicate that improvements are required. We conducted a detailed error analysis and concluded that most of the error comes from uncertainties in the tracking of the C-arm and in the calibration object. We have designed new hardware and are conducting experiments with it. We have also developed a segmentation program for contour-based registration and have begun experiments with the L-shaped phantom.

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