Results

The model has to be evaluated in terms of accuracy, robustness and speed. In a first evaluation, sequences of anatomic structures were used. Accuracy and robustness were evaluated by registering reconstructed point clouds with a polygon model from a laser scanner. The first results indicated that the surface model is reconstructed with millimeter precision. An important criterion for the usability of the surface model is its real-time capability because it has to handle live intraoperative video streams. When we only reconstruct the point cloud without meshing it, we achieve 20–30 fps on our test system with a resolution of 320 × 240. When point cloud meshing is performed for every fourth point (about 10,000 reconstructed points) by the fast meshing method and the mesh is rendered with VTK, we achieve about 17–20 fps. With the standard triangulation from VTK we only achieve about 4 fps. When meshing is performed for every reconstructed point (about 40,000), the speed drops to 10–14 fps (compared to 0.8 fps from VTK). The mesh quality is only slightly worse at the edge of the image and in areas with erroneous points that are not reconstructed.

Conclusion

First results promise that the surface model is accurate, robust and fast enough so that it can be used intraoperatively to register it with a preoperative soft tissue model. These results have to be verified in a next evaluation step by registering models of silicone phantoms with the corresponding surface model and, later, in a real surgical environment. Additional optimization is necessary to ensure the practicability of this method. Further research activities focus on 3D registration with a volume model of the surgical site so that this model is updated and adjusted. The next step is the integration of a force-torque sensor in a laparoscopic instrument to add more information in the registration process. Secondly, an appropriate volume model has to be developed.

References


Target registration error in point-based rigid-body registration: a worst-case analysis

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Keywords Accuracy · Target registration error · Rigid-body registration

Purpose

Point-based rigid registration is the method of choice for aligning medical images and datasets in many diagnostic and image-guided surgery systems. Points, commonly called fiducials, can be implanted spheres, bone screws, adhesive skin markers, and anatomical landmarks. They are selected on each dataset and paired based on their correspondence. Quantifying the registration error is of great clinical importance, as it has direct implications on treatment decisions and their risks assessment. However, since the targets locations after registration usually cannot be measured directly, the Target Registration Error (TRE) is often estimated with the Fiducial Registration Error (FRE) [2], or with Fitzpatrick’s TRE (FTRE) formula [3]. The formula incorporates an estimate of the unknown Fiducial Localization Error (FLE), which is assumed to be uniform, independent, and isotropic for all fiducials. Low FRE-TRE and FTRE-TRE correlations have been reported in clinical practice [1–4] and in hypothetical scenarios [5]. Recently developed TRE estimation methods model anisotropic, inhomogeneous FLE distributions [6–8]. While simulations show that these estimators are better than the FRE and the FTRE, it remains to be shown whether they better reflect clinical situations. Closely related is the question of characterizing the scenarios for which the FRE, the FTRE, and other estimation formulas are good estimators of the TRE.

Method

We have developed a constructive proof that shows that in the worst case, the FRE-TRE, and the FTRE-TRE of two paired point fiducial sets are independent, regardless of the number of targets, their locations, the number of fiducials, and their configuration. The worst case is obtained by modeling the FLE as an affine anisotropic inhomogeneous bias with two fiducial location perturbation functions, named isoTRE and isoFRE, that are designed to perturb the fiducials locations in a specific pattern so as to obtain any desired FRE or TRE. To verify the correctness of our theoretical results, we performed extensive simulations on synthetic and clinical data from our previous study on 10 patients who underwent image-guided neurosurgery [1]. We derived the image and physical space FLE from 3 skin markers, 4–9 anatomical landmarks, and 9 setups per patient, and used one of the skin markers as a target. We then computed the FRE and TRE, and used them as ground-truth.

![isoFRE and isoTRE](image)

**Fig. 1** Worst-case sensitivity analysis results for one patient scenario. The setups were generated with 0–2.8 mm bias (λ) in increments of 0.1 and random isotropic noise of: a-b 0.28 mm (10%); c-d 0.54 mm (20%), and e-f 1.4 mm (30%). In each case, we report the deviations ΔFRE and ΔTRE and the Kendall correlation coefficient τ. The horizontal solid lines show the FRE and TRE values without noise. The circles show the FRE and TRE values with the noise isoFRE and isoTRE functions.
measured values. We generated numerous worst-case scenarios for the synthetic and clinical data by varying the FLE bias. To quantify the sensitivity of the worst-case FRE, FTRE, and TRE, we added isotropic random noise to the isoFRE and isoTRE functions. In the first experiment, we selected data from one patient in one setup and computed the FRE and TRE variations and their distribution for different bias and noise values. In the second experiment, we used all the data and computed FRE, FTRE, and TRE variations as a function of bias and noise.

**Results**

In the verification experiments on synthetic and clinical data, all the actual FRE, FTRE and TRE values were exactly as predicted, up to numerical calculation error $<10^{-14}$. The results of the two sensitivity experiments are summarized in Figs. 1 and 2. In the first experiment (Fig. 1), the low correlations suggest that the FRE and TRE are nearly independent in a relatively large vicinity of the worst-case scenario. The results of the second experiment (Fig. 2) show that adding random noise of up to 50\% (1.2 mm) of the bias to the FLE model only changes the measured FRE and TRE values by 10\% (0.3 mm), with an ensuing low FRE-TRE correlation.

**Conclusion**

In the worst case, the FRE-TRE, and the FTRE-TRE are independent, regardless of the number of targets, their locations, the number of fiducials, and their configuration. Thus, the FRE and FTRE may not always be used as surrogates for the TRE. Adding isotropic noise of up to the sum of the mean image and physical space FLE modifies only slightly the mean FRE, FTRE and TRE values. This suggests the existence of a dense set of ‘almost-worst-case’ scenarios for which the FRE and TRE and the FTRE and TRE are weakly correlated. Our results generalize previous examples and contribute to the mathematical understanding of TRE estimation in point-based rigid-body registration by characterizing the worst-case scenario and its neighborhood. While it is not known if the worst-case scenario is clinically realistic and how likely it is to occur, it raises important questions and directions in the formal exploration of the topic.

**References**


**Respiratory organ deformation of the esophagus in a large animal model for image-guided Interventions**


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**Keywords** Navigation · Soft tissue imaging · Surgery · Image guidance · Animal model

**Purpose**

Image guidance and navigation promise benefits for interventional procedures regarding accuracy, speed and patient safety. However in thoracoabdominal interventions these principles are not well established due to considerable organ motion and deformation that is mostly caused by respiration. The purpose of this study is to quantify the magnitude of respiratory organ motion and deformation of the esophagus in a large animal model for image guided procedures.

**Materials and methods**

Conventional hemoclips (Olympus Medical TM) were used to mark the esophagus in five levels (cervical, upper/mid/lower thoracic, gastro-esophageal junction) by esophagogastroscopy (Karl Storz TM) in a porcine model ($n = 10$, German landrace, 20–34 kg). The animals were under general anaesthesia with machine ventilation. CT-Scans (Siemens SOMATOM Sensation TM) were obtained in different

Fig. 2 The effect of random noise on the worst-case scenarios. FRE, FTRE, and TRE sensitivity results for 378,000 scenarios generated from clinical data of 10 patients, 9 scenarios each, for a constant bias of 2.4 mm and random noise of 0 to 4.8 mm in 0.1 increments. The plots show the average (circle), standard deviation (vertical interval), and maximum (square) of the absolute value differences $|\Delta F|$, $|\Delta F|$, and $|\Delta T|$, and $|\Delta T|$: (a–b) the FRE, (c–d) FTRE, and (e–f) the TRE values.