Linear Object Registration:
A Registration Algorithm using Points, Lines, and Planes

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Introduction

Motivation

Surgical tool registration allows clinicians to view physical objects and images (from multiple modalities) in a common navigation space. This is of vital importance in image-guided therapies. Most applications use point-set registration algorithms; however, landmark points are not present on all surgical tools. Thus, these tools must registered using a different method.

Objective

We propose a registration algorithm which uses points, lines, and planes (linear objects) for registration. The objective is not to develop a more accurate algorithm, but to provide an alternative when landmark points are not available. The algorithm should guarantee convergence to the optimal solution and work when one set of linear objects is a permuted subset of the other.

Although the described application is surgical tool registration, this algorithm applies to any physical object which can be localized with a pointing device.

Methods

Linear Object Registration Algorithm

Given a set of linear objects collected in the sensor coordinate system and a set of linear objects defined in the surgical tool coordinate system:

1. Map collected points to linear objects via principal component analysis.
2. Match linear objects in the two coordinate frames using distances to a set of reference points.
3. Calculate the linear object centroid in each coordinate frame.
4. Perform point-set registration with known correspondence using centroid projections and direction vectors.
5. Iteratively adjust the translation and rotation:
   a) Find the closest point on the defined linear object to each collected point.
   b) Calculate the average translational difference between point-sets.
   c) Calculate spherical point-set registration with known correspondence.

Validation with Simulated Data

The following workflow was used to generate simulated data:

1. Generate random linear objects in the phantom coordinate system.
2. Generate a randomly distributed set of points on each linear object.
3. Create a transformation matrix with random rotation and translation.
4. Apply the random transformation matrix and Gaussian noise to points.

It produces a set of defined linear objects in the surgical tool coordinate system and a set of collected linear objects in the sensor coordinate system. The transform between the two coordinates system is known, and it is used as ground-truth to validate the algorithm.

Validation with Real Data

Figure 1. Photograph of user collecting points on the a) fCal phantom [1], b) lumbar spine phantom [3], and c) LEGO® brick phantom [4].

To validate the algorithm with real data, three previously designed surgical navigation phantoms were used (Figure 1). For each phantom, each face of the rectangular prism exterior was defined as a plane. Additionally, two lines were defined on the lumbar spine phantom where the vertebrae are mounted to the base. A subset of fiducial points on each phantom were used as references.

The fiducial points defined on each phantom were used to perform point-set registration, the result of which was used as ground-truth. Because the LEGO® brick phantom does not have fiducial points machined on it, ultrasound calibration was performed to assess the quality of registration.

Results

Validation with Simulated Data

Figure 2 illustrates that the registration error scales linearly with noise in collected points, demonstrating the algorithm's robustness to noise.

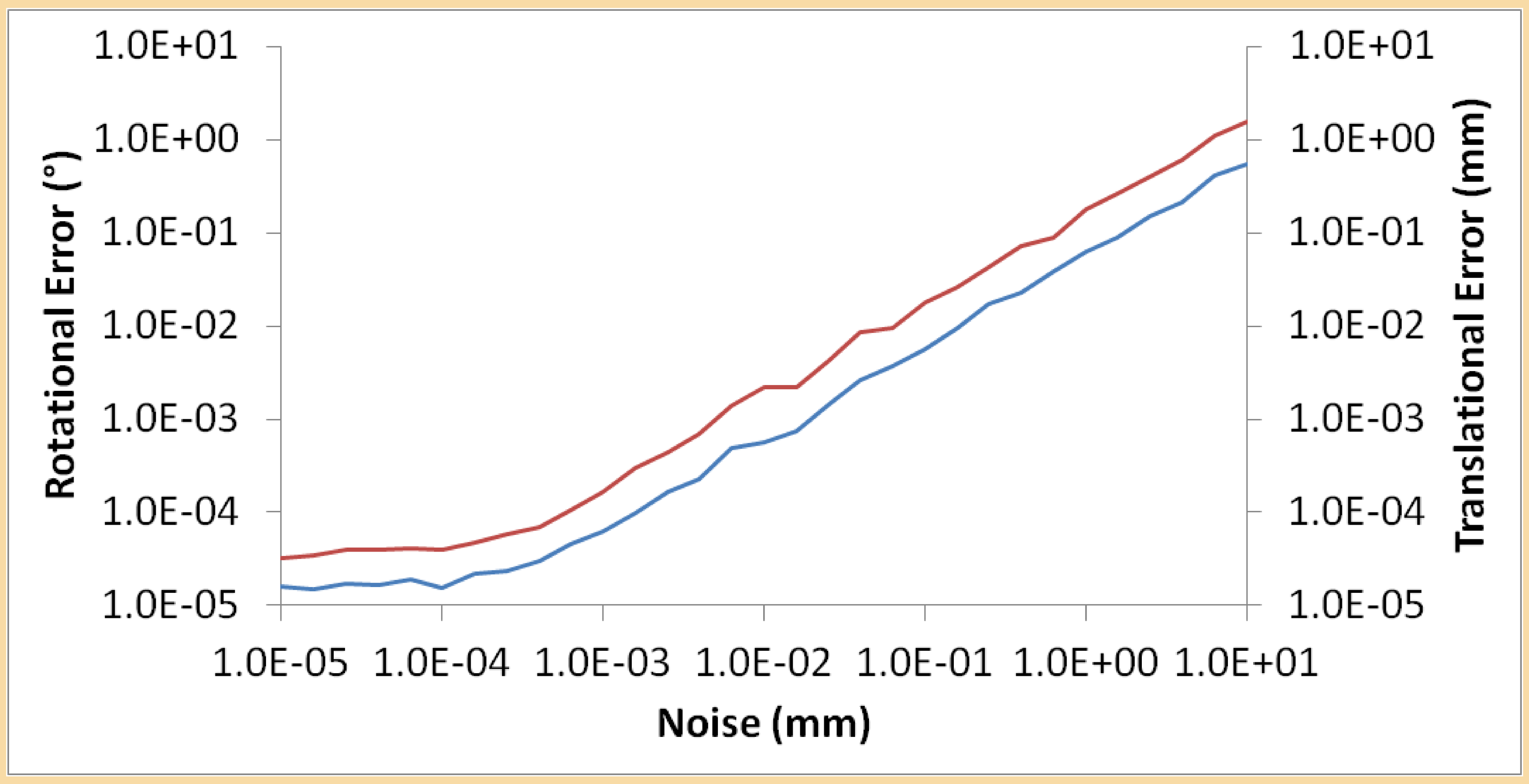

Figure 2. Plot of error in calculated registration as a function of noise for simulated data. Blue line indicates rotational error; red line indicates translational error.

Validation with Real Data

The root-mean-square registration error was significantly lower for linear object registration for each phantom (1.22mm vs. 2.13mm for the fCal phantom, 1.14mm vs. 1.33mm for the lumbar spine phantom, 0.45mm vs. 0.53mm for the LEGO® brick phantom).

Metric	fCal Phantom	Lumbar Spine Phantom
Rotational Error (°)	1.49	0.76
Translational Error (mm)	0.74	1.15

Table 1. Mean rotational and translational error for the fCal and lumbar spine phantoms compared to the ground-truth point-set registration.

Metric	Point-Set Registration	Linear Object Registration
Mean TRE (mm)	1.34	1.18
Mean PRA (mm)	3.98	3.46

Table 2. Target registration error (TRE) and point reconstruction accuracy (PRA) for point-set registration and linear object registration for the LEGO® brick phantom.

Table 1 displays the translational and rotational error in linear object registration compared to the point-set registration.

Table 2 shows the ultrasound calibration quality metrics for the LEGO® brick phantom. Target Registration Error (TRE) measures the distance from a target point's ground-truth position to its reconstructed position [2]. Point Reconstruction Accuracy (PRA) measures the distance from a target point's ground-truth position to its reconstructed position based on its location in the ultrasound plane [1].

Conclusions

The proposed registration algorithm is sufficiently accurate for practical registration of surgical phantoms and tools without fiducial points The algorithm is implemented as a 3D Slicer (www.slicer.org) module, to be used with the PLUS library (www.plustoolkit.org). Future work involves refining the matching step of the algorithm, further automating the algorithm, and image registration.

References

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