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 be 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 coordinate systems is known, and it is used as ground-truth to validate the algorithm.

Validation with Real Data
Figure 1 illustrates the registration error scales linearly with noise in collected points, demonstrating the algorithm’s robustness to noise.

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

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

<table>
<thead>
<tr>
<th>Metric</th>
<th>ICal Phantom</th>
<th>Lumbar Spine Phantom</th>
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<tbody>
<tr>
<td>Rotational Error (°)</td>
<td>1.49</td>
<td>0.76</td>
</tr>
<tr>
<td>Translational Error (mm)</td>
<td>0.74</td>
<td>1.15</td>
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</tbody>
</table>

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>
<thead>
<tr>
<th>Metric</th>
<th>Point-Set Registration</th>
<th>Linear Object Registration</th>
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<tbody>
<tr>
<td>Mean TRE (mm)</td>
<td>1.34</td>
<td>1.18</td>
</tr>
<tr>
<td>Mean PRA (mm)</td>
<td>3.98</td>
<td>3.46</td>
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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.plus Toolkit.org). Future work involves refining the matching step of the algorithm, further automating the algorithm, and image registration.

References


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