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Image-based registration for a neurosurgical robot: comparison using iterative closest point and coherent point drift algorithms

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Abstract

Stereotactic neurosurgical robots allow quick, accurate location of small targets within the brain, relying on accurate registration of pre-operative MRI/CT images with patient and robot coordinate systems during surgery. Fiducial markers or a stereotactic frame are used as registration landmarks; the patient's head is fixed in position throughout surgery. An image-based system could be quicker and less invasive, allowing the head to be moved during surgery to give greater ease of access, but would be required to retain a surgical precision of ~1mm at the target point.
We compare two registration algorithms, iterative closest point (ICP) and coherent point drift (CPD), by registering ideal point clouds taken from MRI data with re-meshed, noisy and smoothed versions. We find that ICP generally gives better and more consistent registration accuracy for the region of interest than CPD, with a best RMS distance of 0.884±0.050 mm between aligned point clouds, as compared to 0.995±0.170 mm or worse for CPD.

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Keywords: Registration; ICP; CPD; neurosurgery; robot;

1. Introduction

Stereotactic neurosurgery allows procedures such as biopsy[1], neuroendoscopy[2] and electroencephalography[3] to be performed accurately and minimally invasively. Use of a stereotactic robot can improve speed and accuracy by

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removing the need to manually locate the required entry point and direction for each action on the patient's head; for this, accurate registration between the patient, robot, and preoperative images is needed. A stereotactic frame or fiducial markers[4] can provide physical landmarks for preoperative registration; the frame also keeps the patient's head in place throughout the surgical procedure[5]. However, if registration could be performed quickly and accurately using a simple, image-based technique such as 3D surface capture, it would allow the head to be moved during surgery to a more convenient position and re-registered, allowing the surgical plan to be adjusted accordingly. The lack of features in the proposed imaging area (the back and top of the head) makes the problem more difficult.

1.1. Comparing registration methods

Two popular methods of point cloud registration are the iterative closest point (ICP) and coherent point drift (CPD) algorithms. ICP[6] works by pairing each point in the 'source' point cloud (the one which is to be transformed) with the nearest point in the 'reference' point cloud (points in the reference cloud can be paired to more than one source cloud point), then estimating the transformation that will most reduce the mean square of the distances between pairs. The points are then re-paired; the process is repeated until the stopping conditions are met.

Coherent point drift (CPD)[7] treats registration as a probability density estimation problem, in which one point cloud is treated as the probability distribution of the centroids of a Gaussian mixture model, and the other as data points drawn from the distribution; registration is then performed by finding the position at which the probability of the data points being observed is maximised. Motion coherence of the centroids is imposed to preserve topological structure. Myronenko and Song (2010)[8] tested CPD on example point clouds and showed it to be more accurate and robust to noise and outliers than ICP, but the examples were not similar in shape to those considered in this paper.

During neurosurgery the patient will be draped, apart from the area being operated on, therefore we are principally interested in the accuracy of registration using surface capture images of the top and back of the head. This region has few features, which may affect the robustness of the registration algorithm. We test ICP and CPD on this region for a range of transformations, using surfaces generated from MRI data, with and without added noise and with smoothed noise.

1.2. Imaging devices and surface representation

3D surface capture images can be produced using a variety of devices, including those that make use of infrared structured light (Microsoft Kinect[9], Intel RealSense[10]), visible structured light (Birmingham Surface Capture System[11]), and infrared time-of-flight (Microsoft Kinect v2[12]). These systems are all capable of producing a point cloud representation of a surface and could be used in the operating theatre to capture a 3D model of the head. In this work representative point clouds are produced from MRI data, in order to focus on the accuracy of the registration algorithm, not the imaging technique.

2. Methods

In this paper, we compare ICP and CPD registration methods for a predefined region of the head surface, examining the effect on registration accuracy of noise and of smoothing the noise.

2.1. Point cloud creation

In order to investigate registration methods independent of imaging technique, point clouds were extracted from the MRI data of ten healthy adult subjects using NIRFAST[13]. The 'head-top' region of interest (ROI) was defined as all points above a line between the inion and a point 2 cm above the nasion (Fig. 1). In order to create an idealised point cloud to register to the initial 'ground truth' point cloud, each ROI point cloud was re-meshed in MeshLab[14] by the following process: the outer-pointing normal was calculated for each surface point using its 100 nearest neighbours; a surface mesh for the ROI was created using the algebraic set surfaces variant of the marching cubes algorithm[15], with a grid resolution of 1000; Poisson-disk sampling was performed to give a point cloud with approximately the same number of points as the initial point cloud (a difference of less than 0.5% in all cases).