Robotic Registration of Patient-Specific 3D Elbow Models from Sparse Probe Contacts for Arthroscopic Debridement

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INTRODUCTION

Arthroscopic elbow debridement is challenging due to the endoscopic camera's limited field of view and insufficient depth perception. To address these limitations, we aimed to develop a 3D visual context to assist surgeons intraoperatively [1], [2]. This approach requires accurate alignment of the virtual model with respect to the tools and the real-world frame. In this work, we perform virtual-model-to-patient registration using sparse surface contacts from a tracked probe, since bone exposure and long-term fiducials are impractical under minimal access [1].

MATERIALS AND METHODS

We use 3D Slicer (www.slicer.org) [4] to obtain a CT-derived elbow mesh; throughout, we refer to this CT-segmented mesh as the model and to its 3D-printed replica as the phantom, which is mounted on a rigid custom holder.

We use a Quanser HD2 user-interface robot with an auxiliary foot pedal; a custom 3D-printed add-on converts the handle to a single-tip tracked probe, which is also rendered in the 3D Slicer scene. The probe's pose (position and quaternion orientation expressed in the HD2 coordinate frame) is streamed into 3D Slicer and mapped into the scene's RAS (Right-Anterior-Superior) world frame via a calibrated transform chain. The foot pedal acts as a sampling gate, enabling continuous point capture while depressed. After collecting surface points on the phantom with the tracked probe, we estimate a rigid alignment in two stages. First, a coarse initializer uses principal component analysis (PCA) to roughly orient frames and random sample consensus (RANSAC) to obtain a plausible pose while rejecting inconsistent/noisy samples.

We then refine the alignment using the iterative closest point (ICP) algorithm in point-to-plane mode and utilize signed distance field (SDF) optimization in a complementary manner to enhance robustness and convergence [3]. The RANSAC initializer and ICP refiner are implemented with Open3D [5].

RESULTS AND DISCUSSION

Errors are reported as the RMS distance at predefined surface checkpoints. These checkpoints are distinctive features on the virtual model (ridge peaks, valley apices, sharp edges). After registration, the corresponding phantom checkpoints are touched with the tracked probe to log their coordinates. We then compute the RMS of the 3D distances between each matched pair.

On a separate simple-shape phantom, 986 collected points and 6 checkpoints yielded 2.44 mm RMS. For the elbow phantom (in two independent poses), we obtained 3.84 mm RMS with 2,800 collected points and 8 checkpoints, and 2.71 mm RMS with 3,336 collected points and 7 checkpoints. Initialization and refinement are adequate, but residual error arises from robot pose/joint noise and human point collection; in some cases, local minima also limit achievable accuracy.

Fig 1. Quanser HD2 with custom single-tip probe and 3D-printed elbow phantom mounted on a rigid holder.

CONCLUSIONS

We have demonstrated robot-frame to CT-frame registration using sparse, contact-only points collected with a robot-held probe, achieving 2.71–3.84 mm RMS accuracy on elbow phantoms without fiducials or wide bone exposure.

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