Critical Review

Paper:

3D-2D registration for surgical guidance: effect of projection view angles on registration accuracy.

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Project Overview and Relevance

Our project involves using 3D-2D image guidance to align a drill guide along the pedicle of a patient using the UR5 robotic arm. The first part of the project (up to the expected deliverable) consists of doing this procedure with tracker based guidance. Then, we plan to substitute the tracker based for image guidance so as to ease integration into the surgical workflow, since 2D fluoroscopy is already available in many operating rooms.

This paper is relevant to our project since it quantifies the error (target registration and projected distance) between conventional EM based tracking (in our case this will be optical) and 3D-2D registration done using the GI method. Additionally, the paper emphasizes using target registration error (TRE) as a more robust characterization of error. Specifically, the paper delves into examining the effects of magnification, pixel and voxel sizes, and the angular separation of multiple 2D projections on TRE as compared to the EM tracker and a reconstructed cone beam CT (CBCT) image as truth and error metrics. The information from this paper can not only be used to optimize surgical workflow, but it can also help us characterize our error and provide a basis for decision making when we tackle the 3D-2D integration

Mathematical Background

3D-2D Registration Algorithm

CT images are converted from Hounsfield units (HU) to linear attenuation coefficients and the intraoperative 2D x-ray projections are log-normalized. The algorithm then solves the "transformation of a 3D image… such that a 2D projection computed from the 3D image (i.e. a digitally reconstructed radiograph (DRR)) yields maximum similarity to the intraoperative 2D image." It does this by using the gradient information (GI) metric where p_F is the fixed image and p_M is the moving image:

$$GI(p_F, p_M) = \sum_{(i,j)\epsilon\Omega} w_{i,j} \min\left(\left|g_{F,i,j}\right|, \left|g_{M,i,j}\right|\right).$$

Where i, j are pixel indicies within the image domain Ω and the gradient (g) is

$$g_{i,j} = \nabla p(i,j) := \left(\frac{d}{d_i} p(i,j), \frac{d}{d_j} p(i,j)\right).$$

The weighting function w favors small gradient angles (i.e. alignment of edges):

$$w_{i,j} = \frac{1}{2}\left(\frac{g_{F,i,j} g_{M,i,j}}{|g_{F,i,j}|, |g_{M,i,j}|} + 1\right).$$

Furthermore, when N projections are provided, respective similarity measures are summed (the N projections are treated as one large image):

$$GI = \sum_{n=1}^{N} GI(p_{F,n}, p_{M,n}).$$

From this, the transformation (3D-2D registration) is solved by an iterative search of the translational and rotation components that maximize GI.

$$T_{Fluoro}^{CT} = argmax\ GI\left(p_F, p_M\left(T\left(t_x, t_y, t_z, r_x, r_y, r_z\right)\right)\right)$$

Finally, the covariance matrix adaptation evolution strategy (CMA-ES) was used as the optimizer to solve for T (shown-above).

Summary of Experimentation and Results

Registration accuracy/Angular seperation

The following diagram shows the relevant system of coordinate transforms:

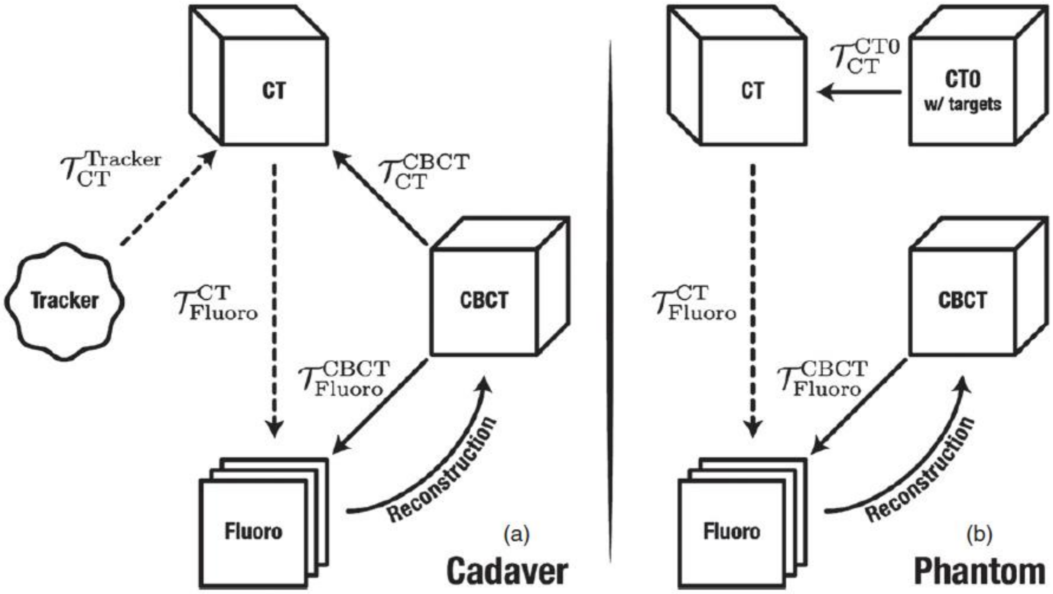

Figure 3. Flowcharts depicting the coordinate transforms for (a) cadaver and (b) phantom studies. Dotted lines signify the final registrations used for both fluoroscopy and tracker guidance.

The primary objective of this series of experimentation was to devise a system that could compare registration accuracy between 3D-2D and conventional tracking systems, and specifically, study the effect of angular separation on each of the experiments described below. The EM tracker was registered to the preoperative CT using surface fiducials recorded by the EM pointer tool (which had two six DoF EM sensors attached to itself) and segmented in CT. The CBCT to CT registration was done by mapping the EM targets (implanted EM coils in the cadaver) by means of 3D-3D registration using stochastic gradient descent optimization. A reference marker was used in both cases to account for specimen motion. Note that the CBCT image was reconstructed from the Fluoro image using the Feldkamp algorithm. Finally, metrics to define error (projection error (PDE) and target registration (TRE)) were defined to contextualize the results.

CT slice thickness and detector binning

The analysis described above (looking at difference in registration accuracy between EM versus 3D-2D) was repeated for varying pixel and voxel size. Voxels and pixels were binned across the range 0.6-4.8 mm and 0.3-2.4 mm respectively. The Siddon algorithm was used in place of a linear projection (for 3D-2D) to remove bias associated with coarser voxels. Essentially, the point of the experiment was to see how voxel and pixel binning size affected the 3D-2D registration and more specifically how it affected the minimum difference in angular separation between two fluoro images.

C-arm magnification

Refer to Figure 3 above. This experiment looked at the effect of magnification defined as:

$$m \coloneqq \frac{SDD}{SOD}\ where\ SDD\ is\ the\ source\ detector\ and\ SOD\ is\ the\ source\ object\ distance.$$

The effects of magnification were studied on a rigid anthropomorphic phantom instead of a cadaver. The magnification was varied from m=1.6 to 2.8.

Characterization of PDE and TRE:

$$PDE_{3D2D} = L2_{norm}\left((P_{Fluoro}T_{Fluoro}^{CT}T_{CT}^{CBCT}x_{CBCT}) - (P_{Fluoro}T_{Fluoro}^{CBCT}x_{CBCT})\right)$$

$$PDE_{Tracker} = L2_{norm}\left((P_{Fluoro}T_{Fluoro}^{CBCT}(T_{CT}^{CBCT})^{-1}T_{CT}^{Tracker}x_{Tracker}) - (P_{Fluoro}T_{Fluoro}^{CBCT}x_{CBCT})\right)$$

$$TRE_{3D2D} = L2_{norm}\left((T_{Fluoro}^{CT}T_{CT}^{CBCT}x_{CBCT}) - T_{Fluoro}^{CBCT}x_{CBCT}\right)$$

$$TRE_{tracker} = L2_{norm}\left((T_{Fluoro}^{CBCT}(T_{CT}^{CBCT})^{-1}T_{CT}^{Tracker}x_{Tracker}) - (T_{Fluoro}^{CBCT}x_{CBCT})\right)$$

Results

Refer to appendix for a full representation of all the results.

Discussion

The primary result of the paper is to demonstrate that even a small angular separation ($\Delta\theta \sim 10\ degrees$) is sufficient to get a TRE < 2mm. Furthermore, the paper demonstrates (both using PDE and TRE) that 3D-2D registration is more accurate than the EM tracker (which is the conventional method in use). In addition, the paper shows that with smaller voxel and pixel size, the minimum angular separation required is smaller, but if the mismatch is too large (i.e. large voxel, small pixel) then there is error in the optimization. Additionally, the paper showcases that a magnification of m=2 (normally used magnification in OR) is actually optimal for 3D-2D registration when examining the TRE. Finally, TRE was shown to be a more robust metric for characterizing 3D localization especially in the case where there is low depth resolution.

Evaluation of Paper

I thought that the paper was very well written and all the mathematical concepts were well explained. The paper is very relevant to our CIS II project since we are dealing with a surgical navigation system that initially will use tracker based guidance, but then switch to 3D-2D guidance. The characterization of the different error metrics (PDE and TRE) was especially useful since we would have to do similar experimentation to validate our results and accomplish our deliverable (having complete 2D-3D guidance to position a drill guide using the UR5). Furthermore, the improved robustness of GI with even a slight increase in angular separation of projections (tilt of the C-arm) means that we could achieve relatively low error registration while also minimizing radiation dose to the patient. The only con of the paper was that sometimes the descriptions for the experimental setup were too dense and there were not enough supplementary figures and pictures to rationalize how everything was setup/placed. Overall, the paper was fantastic and will help us a lot towards achieving our maximum deliverable of enabling 3D-2D image guidance for the UR5.

Appendix

Angular separation

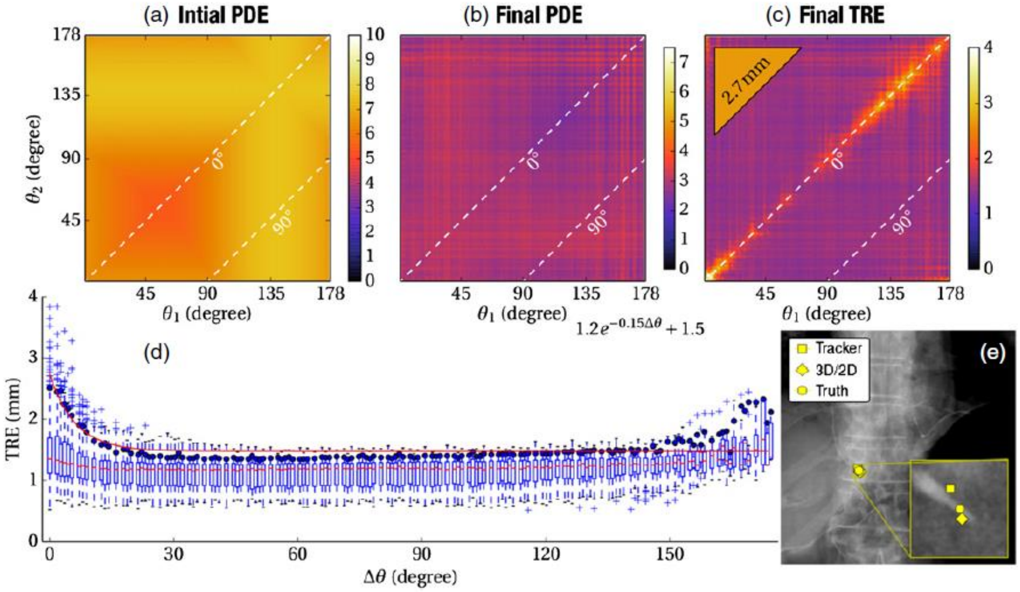

Figure 5. Effect of angular separation on 3D–2D registration accuracy. (a) The initial PDE prior to registration. (b) The PDE following 3D–2D registration. (c) The TRE following 3D–2D registration, (d) TRE plotted versus the angular separation ($\Delta\theta$) between projection views. (e) Example PA fluoroscopy image of the cadaver overlaid by the target position as assessed by (circle) truth, (diamond) 3D–2D registration and (square) the EM tracker.

Magnification

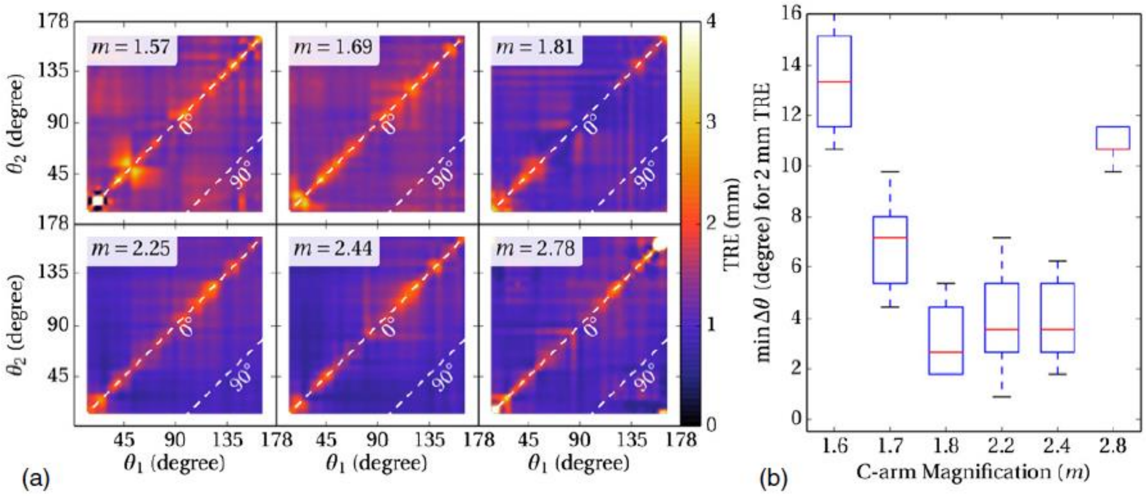

Figure 7. Effects of C-arm magnification on 3D–2D registration accuracy. (a) TRE as a function of projection view angles. (b) Minimum angular separation required to achieve TRE better than 2 mm measured as a function of C-arm magnification.

Detector Binning/Slice Thickness

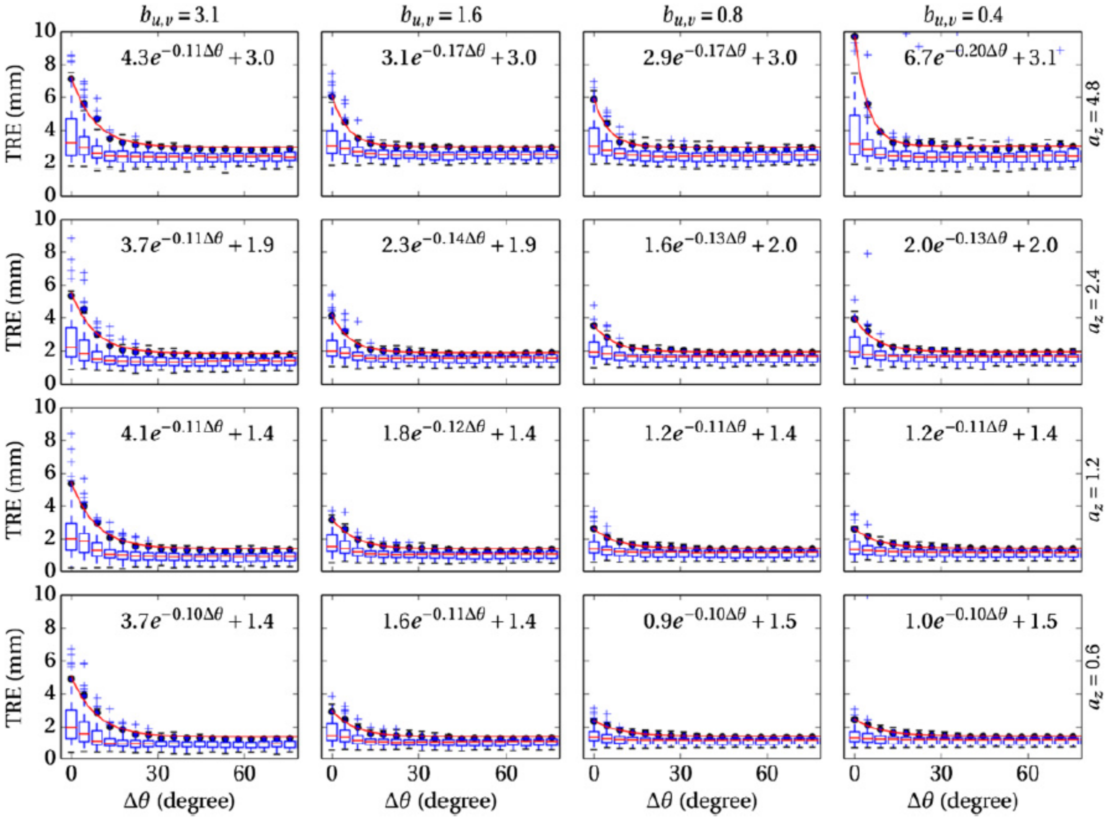

Figure 6. Effect of CT slice thickness (rows, $a_z = 0.6$–4.8 mm) and pixel binning (columns, $b_{\mathrm{u,v}} = 0.3$–2.4 mm) on the TRE of 3D–2D registration.