Paper review

Paper name: Automatic image-to-world registration based on x-ray projections in cone-beam CT-guided interventions

- Authors: Hamming NM, Daly MJ, Irish JC, and Siewerdsen JH
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Summary of motivation, method and results

In this paper, the author first introduces a common image-to-world registration—the registration of image and tracking coordinate systems, required by real-time surgical navigation, e.g. tracking a surgical tool or a robot drill. Then the drawbacks of a conventional version of this image-to-world registration procedure—localizing markers manually in image coordinates via mouse click and determining tracking coordinates with a handheld trackable pointer, is presented, such as time consuming and not robust enough. So, the author comes up with an automatic method to perform this image-to-world registration between intra-operative cone-beam CT and an optical tracking system.

To achieve this goal, the author first designed a multi-modality (MM) markers consisting of an infrared reflective sphere with a tungsten sphere (BB) placed precisely at the center, to permit automatic detection in both the image and tracking reference frames. Second, some image processing methods such as intensity thresholding and pattern matching are performed to locate BB markers directly in 2D projections acquired in each CBCT scan. Third, 3D image coordinates of these BB markers are computed using back projection and C-arm geometric calibration. Meanwhile, the algorithm also received MM marker positions from IR tracking system. Finally, the transform for this image-to-world registration is computed by rigid point matching of image and tracker point sets using unit quaternions.

In the experiment part of this paper, two measurements—accuracy and reproducibility are employed to compare the automatic registration technique with the conventional manual registration. Also, a variety of marker configurations suitable to neurosurgery (markers fixed to cranium) and head and neck surgery (markers suspended on a sub-cranial frame) are compared to find an optimal design. (1)As to marker localization accuracy, the automatic technique exhibits sub-voxel accuracy for all marker configurations. (2)For fiducial registration error, the automatic technique indicates improved accuracy and reproducibility, compared to the manual technique. (3)According to the target registration error, the automatic technique achieves statistically significant improvement in precision than the manual in accuracy, although there is not statistically significant in accuracy.

Good points in this paper

First, the author comes up with a new marker design. The method of placing tungsten sphere BB marker at the center of reflective spherical marker makes sure that these two point sets represent the same locations in the coordinate systems of the imaging and tracking systems. Here the idea of creating same point set between two coordinate systems connects two systems together. Moreover, precise centering is achieved by designing a support post such that the BB rests at the center of the superior-inferior plane of the reflective marker and creating a well at the center of the reflective marker for accurate BB placement in the anterior-posterior and left-right planes.

Second, the author extends the use of this automatic registration to various marker configurations. Three “out-FOV” configurations in which MM markers are attached to a curved acrylic plate could achieve three advantages: (1) overcome the lack of anatomic spots rigid enough to attach fiducials on (2) place the centroid of all MM markers nearer to sub-cranial targets therefore improving target registration error (3) allow flexible design of acrylic plate design so that its appearance during imaging will not obstruct surgery. After imaging, this acrylic plate can be removed therefore totally not affecting surgery. Such configurations, along with automatic registration, could address the challenges to accurate guidance of head and neck surgery.

Third, the idea of using search window and edge search window in BB segmentation can largely reduce computation by taking advantage of the information from former segmentation result as well as back projection and forward projection in Cone Bean CT imaging. Accordingly, the average computational time to segment the eight BB centroids from all acquired projections was 30 s and 22 s for the in-FOV and out-FOV arrangements, respectively (MATLAB, R2007a, The Mathworks, Natick MA, running on a dual-core PC, 2.4 GHz, Dell Computers, Round Rock, TX).

Critical assessment on this paper

- **Head motion**

The paper did not mention method of compensating patient's head motion, which in fact happens sometimes during surgery and requires registration update.

A straightforward way of updating the image-to-world registration—the registration of Cone Bean CT image and tracker coordinate, after head motion is detected, is to perform another automatic registration described in this paper again. This could update the registration accurately, but requires another time of being exposed to radiation from Cone Bean CT imaging. In addition, placing the curved plate above the patient head and taking Cone Bean CT imaging will more or less cost a short pause on the surgery.

A more proper method is to mount an optical dynamic rigid body on some part of the head clamp and use optical tracker to correct for head motion. Similar method was described in chapter III.C in the paper *Accuracy Improvement of a Neurosurgical Robot System* by Haidegger T. etc. on 2008. In this paper, they changed from a prior control scheme that used only the robot's encoders to determine the position of the tool tip, to the other method that is based on the StealthStation measurements. This change was based on the idea that, from the patient's point of view, the use of optical tracker for patient motion increased safety and accuracy resulting from its ability to automatically correct for certain unintentional motions in the operating room, although the optical tracker introduces additional noise and a little less accurate measurement than the robot.

Similar to the setup in this paper which contains an optical dynamic rigid body (DRB) mounted directly on the skull or on the cranial frame, here we can mount a DRB on part of the head clamp. By placing the tracker in a proper orientation, it can keep the ability to monitor the relative position of the two frames (DRB and MM markers), and therefore detect and compensate for unintentional motions of the patient with respect to the tracker.

The equation of computing the transform between Fiducial local frame to CBCT image frame is ${}^{Fid}_{CBCT}T = {}^{Fid}_{loc}T \cdot {}^{loc}_{CBCT}T$. Here Fid, CBCT, loc means Fiducial local frame, CBCT image frame, tracker frame respectively. It is ${}^{Fid}_{loc}T$ that will change if head motion happens.

After attaching a DRB to head clamp, we can get another equation ${}^{loc}_{DRB}T = {}^{loc}_{Fid}T \cdot {}^{Fid}_{DRB}T$. Here DRB means optical dynamic rigid body frame. The tracker is able to detect the position of DRB, that is, ${}^{loc}_{DRB}T$, in real-time. Assuming the head clamp can fix the patient head and DRB tightly and connect them into a rigid body, and then ${}^{Fid}_{DRB}T$ is constant. Thus, ${}^{loc}_{Fid}T$ can be computed for correction in real-time. Introducing ${}^{loc}_{Fid}T$ into first equation, ${}^{Fid}_{CBCT}T$ can be computed and updated in real-time.

- **Segmentation**

The algorithm of segmenting BB markers was not illustrated in details, although it might have been a challenging step in the whole algorithm. From the paper, at least we know that the method such as intensity thresholding and pattern matching requires pre-knowledge of the intensity pattern of BB markers in CBCT images for parameter setting. The author might have incorporated such pre-knowledge in his MATLAB implementation. An alternative to segment BB markers may be more commonly used algorithm, for example, Hough Transform implemented in itk or OpenCV, with carefully picked parameters including circle radius range, intensity threshold, Gaussian derivate function, etc.

- **Possible future work for this paper**

First, as the author mentioned, the automatic registration method was undergoing integration in ongoing clinical trials of intra-operative CBCT-guided head and neck surgery. Note that the implementation of the algorithm in this paper was totally based on MATLAB platform. To integrate in clinical trial, the algorithm needs to be re-implemented in a language with higher software portability.

Second, the idea of having two point-set representing the same spatial locations for registration in this paper can be extended to other navigation technology such as Micron Tracker. In that situation, a BB marker can be placed on the intersection point of those black and white ‘blocks’. Besides this, Micron Tracker has extra advantage that it is smaller and less heavy than common optical tracker. Thus, Micron Tracker can be placed in C-Arm and rotate with it.

Third, this automatic registration method can be used in CIS-2 project *Integration of CBCT and a skull base drilling robot system* after finishing re-implementation, since the surgical workflow in this project does require several times CBCT imaging and image-to-world registration. Hopefully, by conducting this automatic method in parallel with CBCT reconstruction, image-to-world registration will become unobstructive to surgical workflow.