Cross-Calibration Accuracy Requirements for Prospective Motion Correction

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Purpose: Cross-calibration of the optical tracking system and the scanner is an essential step in prospective motion correction [1]. Errors in cross-calibration cause inaccuracies in motion correction and subsequent motion artifacts in the image. However, cross-calibration can be time consuming. Thus, in a clinical setting, it is desirable to skip cross-calibration and use pre-calibrated rigid mounts to position the camera. However, rigid mounts and scanner specs can drift over time, invalidating the pre-calibration. Additionally, coil-mounted camera systems [2,3] rely on the availability of the accurate position of the patient table, which may not always be satisfied. For evaluating the robustness of these rigid-mount systems, it is desirable to establish standards on the required accuracy of cross-calibration. In this study, we assessed the accuracy requirements of cross-calibration using a simulation environment.

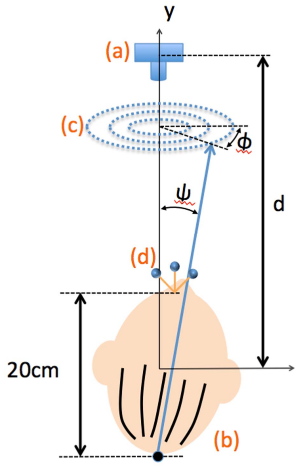

Figure 1 The simplified simulation environment that was used to assess the required accuracy of cross-calibration. The camera (a), head (b), marker (d) and the scanner are aligned along the y-axis. Without loss of generality, the head and the scanner center and orientation were assumed to be the same. The simulated motion is shown in (c). The maximum pixel position error within the head volume was used to quantify the accuracy of motion correction.

Methods: The computer simulation environment we used for this study is shown in (**Fig. 1**). Following the setups in [3] and [4], the camera (**Fig. 1a**) was placed either on the coil (d=20cm) or on the scanner bore (d=40cm), and the marker (**Fig. 1d**) was assumed to be on the head 10 cm away from the center of the head. The head was placed at the center of the scanner and was assumed to be a sphere with a 10cm radius (**Fig. 1b**). *Numerical Simulations:* In order to simulate cross-calibration errors in 3D, the location of the camera was perturbed incrementally with a maximum of 5mm translation or 5° rotation for three translational and three rotational components. Shaking and nodding motions were simulated such that the tip of the head followed circles of varying radii with the back of the head being the pivot point, as shown in **Fig. 1c**. For each simulated motion of the head, the motion update of the scanner was calculated using the ground truth and the perturbed cross-calibration information using the following formula (3):

$$\mathbf{T}_{s_0\to s_i} = \mathbf{T}_{c\to s_0}\mathbf{T}_{m_0\to c}\mathbf{T}_{m_0\to m_i}\mathbf{T}_{c\to m_0}\mathbf{T}_{s_0\to c} \qquad [1]$$

Here, $\mathbf{T}_{s_0\to s_i}$ is the scanner update, $\mathbf{T}_{c\to s_0}$ is the ground-truth or the perturbed cross-calibration matrix, $\mathbf{T}_{m_0\to m_i}$ is the motion of the marker and $\mathbf{T}_{m_0\to c}$ is the position of the camera with respect to the marker. A perfectly accurate cross-calibration will yield no net displacement of the head with respect to the scanner after prospective correction of the scan volume. However, the perturbation of the cross-calibration matrix $\mathbf{T}_{c\to s_0}$ will result in an inaccurate scan volume update $\mathbf{T}_{s_0\to s_i}$, which will result in an error of the pixel positions of the head even after motion correction. Thus, in order to quantify the accuracy of motion correction, the maximum pixel position error over all pixels within the spherical head volume was calculated. Mathematically, the expression for the maximum pixel position error is:

$$\varepsilon(\psi) = \max_{\mathbf{x}\,\epsilon\,\text{head volume}} \max_{\phi} \left\| \mathbf{T}^{perturbed}_{s_0\to s_i}(\phi,\psi)\left(\mathbf{T}^{ground\ truth}_{s_0\to s_i}(\phi,\psi)\right)^{-1}\mathbf{x} \right\| \qquad [2]$$

In this study, considering routinely used image resolutions, the maximum pixel position error was set to $\varepsilon(\psi) = 0.5$mm. Head motion was simulated for 0°<ψ<20°, 0°<ϕ<360° (**Fig. 1c**). For each head motion, the maximum allowable perturbation (i.e. error) in cross-calibration $\mathbf{T}^{perturbed}_{s_0\to s_i}$ was calculated for three translational and three rotational components separately that would give a maximum pixel position error $\varepsilon(\psi) = 0.5$mm

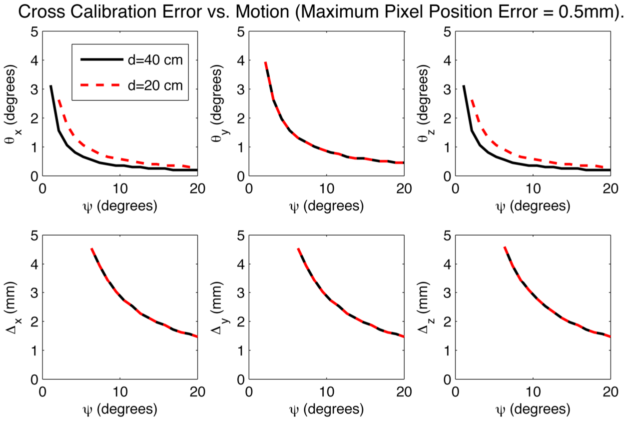

Figure 2 Graphs of maximum allowed error in cross-calibration that would give a maximum pixel position error of 0.5mm inside the head. The simulations were performed for camera position of d=20cm and d=40cm. The x axis is the motion of the head (ψ in Fig. 1) and the y axis are the cross-calibration error for the rotational and translational components in cross-calibration.

Analytical simulations: In this case, the simulations were simplified to 2D such that only z-rotation of the head was simulated, and the cross-calibration was perturbed in two translational and one rotational axis. This way, the dependence of the maximum pixel position error ε on the error in cross-calibration was determined analytically using equations [1] and [2].

Results: The results of numerical simulations are shown in **Fig. 2**. The graphs show that for a bore-mount setup (d=40cm), the cross-calibration has to be accurate within 0.3° ($\theta_{x,y,z} < 0.3°$) and 3 mm ($\Delta_{x,y,z} < 3$mm) to correct for ψ=10° head motion, and it has to be within 0.2° ($\theta_{x,y,z} < 0.2°$) and 1.4 mm ($\Delta_{x,y,z} < 1.4$mm) to correct for ψ=20° head motion. For a coil mount setup (d=20cm), the cross-calibration has to be accurate within 0.5° ($\theta_{x,y,z} < 0.5°$) and 3 mm ($\Delta_{x,y,z} < 3$mm) to correct for ψ=10° head motion, and it has to be within 0.3° ($\theta_{x,y,z} < 0.3°$) and 1.4mm ($\Delta_{x,y,z} < 1.4$mm) to correct for ψ=20° head motion.

For the simplified 2D case, the dependence of the maximum pixel position error ε on the error in cross-calibration was determined to be:

$$\varepsilon_{\theta_z} = 1200 sin\left(\frac{\theta_z}{2}\right) sin\left(\frac{\psi}{2}\right), \varepsilon_{\Delta_x} = 2\Delta_x sin\left(\frac{\psi}{2}\right), \varepsilon_{\Delta_y} = 2\Delta_y sin\left(\frac{\psi}{2}\right) \qquad [3]$$

Discussion & Conclusions: In this study, we provided the minimum cross-calibration requirements for prospective optical head motion correction. For the 2D analytical simulations, the analytical expressions (**Eq. [3]**) revealed no dependence on the baseline position of the camera *d* (**Fig. 1**), and the perturbation of the cross-calibration matrix resulted in a shift of the pixel positions. The maximum pixel position error ε was found to be linearly proportional to the errors (θ_z, Δ_y, Δ_x) in cross-calibration. Although the results in Eq. [3] are overly simplified, the linear relationship also holds true for the 3D numerical case. However, it must be noted that in reality, the sensitivity of the cross-calibration will also depend on the orientation of the camera with respect to the scanner, the motion axes, and the position of the head. However, the reference numbers established in this study will still help in system design. One important implication of the results in this study is that if the scanner table location is used to re-calibrate a coil-mount optical tracking system, the accuracy of the table position reported by the scanner has to be within 1.4mm to correct for 20° head motion.

References: [1] Zaitsev et al, Neuroimage, 2006 [2] Qin et al, MRM, 2009 [3] Aksoy et al, MRM, 2012 [4] Maclaren et al, PloS ONE, 2012. **Acknowledgements**: NIH (2R01 EB00271108-A1, 5RO1 EB008706, 5R01 EB01165402-02), the Center of Advanced MR Technology at Stanford (P41 EB015891), Lucas Foundation, Oak Foundation, GE Healthcare.