

Real-Time Imaging Plane Control using Tip Tracking Coils and Motion Prediction

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Introduction

MRI-guided radio frequency ablation (RFA) is a promising technique for guiding and conducting thermal therapies such as electrophysiology (EP) procedures. Treatment efficacy, reliability, and patient safety can be greatly improved by performing real-time non-invasive temperature mapping during the procedure. However, the most commonly used MR thermometry method based on proton resonance frequency (PRF) shift, which relies on the subtraction of intra-treatment phase images from that of a pre-treatment baseline phase image, is very sensitive to motion. Previous efforts such as referenceless [1] and multi-baseline [2] methods utilize image registration and can correct for in-plane motion only with 2D imaging. Using a 3D imaging method is typically slow and computationally expensive, therefore not suitable for real-time applications. In this work, a novel method is proposed to control and update the imaging plane location in real-time based on the information obtained from catheter-based tip tracking coils and motion prediction algorithm, making the target appear stationary in the reconstructed images.

Materials and Methods

Multiple miniature solenoid MRI tracking coils were incorporated onto the distal end of a 6 F catheter. The tip tracking MRI sequence was implemented on the RTHawk platform [3] using the 4-projection Hadamard method [4]. When the catheter does not move relative to the target tissue, the motion detected by the tip tracking coils can be regarded as that of the moving organ. A fast 2D gradient-echo spiral imaging sequence with 6 arms was interleaved with tip tracking sequence with a temporal window of 240 ms (Figure 1). When the catheter moves, its new tip location is detected by the tracking coil, and the imaging location is immediately updated for the subsequent imaging cycles. Since the movement is continuous, the time delay between imaging and catheter tracking causes the information from the catheter tracking to be slightly outdated at the time of imaging. To overcome this, a motion prediction algorithm utilizing Extended Kalman Filter (EKF) was employed. The Kalman filter addresses the general problem of trying to estimate the state $x \in \mathbb{R}^n$ of a discrete-time controlled process. In this study, we've established an elliptical movement model (Figure 2) for EKF. The state vector is defined as $x = [\theta, \omega, a, b, X_c, Y_c]^T$ and the location of the tracking coil $[X, Y]^T$ as measurement. Once the EKF state vector converges, the imaging location can be predicted using the current state estimate \hat{x} as:

$$\hat{X}_{\text{imaging}} = \hat{X}_c + \hat{a} \cos(\hat{\theta} + \hat{\omega} \Delta t), \quad \hat{Y}_{\text{imaging}} = \hat{Y}_c + \hat{b} \sin(\hat{\theta} + \hat{\omega} \Delta t)$$

where Δt is the time delay between imaging and catheter tracking sequences.

Experimental setup consisted of a cylindrical phantom doped with CuSO_4 solution that contains the catheter with tracking coils. 2D real-time spiral imaging was performed using a FOV of 32 cm and acquisition matrix of 121×121 . All experiments were performed on a 1.5 T scanner (HDx, GE Healthcare, Waukesha, WI) using a modified 4-channel cardiac coil for imaging and up to 4 channels for tracking. The RTHawk engine running on a workstation (Dell Precision T5500, OS: Ubuntu 13.04) was used for real-time reconstruction and visualization. The EKF algorithm was implemented using the MRPT (mrpt.org) C++ library. Periodic linear motion over a distance of 2 cm was induced by the scanner table rocker capability. Note that this linear motion is a special case of the elliptical motion where a or $b = 0$. Post-acquisition registration was applied to evaluate the phantom displacement in the image space (Figure 3).

Results and Discussion

The detected phantom displacement shown in Figure 4 consists of 3 segments: (a) the displacement with no imaging location control applied, which reflects the induced periodic linear movement of the table, (b) the displacement with imaging location controlled by the catheter tracking information without the prediction algorithm, and (c) the displacement with the prediction algorithm applied. The standard deviation of the segment (c), which is half of segment (b), clearly demonstrates the improvement achieved when the motion prediction algorithm is utilized. Further improvement can be achieved with higher spatial resolution and optimal noise handling by EKF.

Conclusion

The proposed method employing both catheter tracking information and motion prediction algorithm for real-time imaging location control demonstrates the feasibility of obtaining stabilized imaging immune to motion and can benefit MR thermometry involving complex organ motion. It also demonstrates the versatility of the RTHawk platform for real-time MRI-guided interventions. In addition, the proposed method can be utilized to not only improve MR thermometry but also be applied to other scenarios when continuous monitoring of a specific target location is needed.

References: [1] Rieke V, *et al*, Magn Reson Med 2004; 51:1223-1231; [2] Vigen K, *et al*, Magn Reson 2003; 50:1003-1010; [3] J. M. Santos, *et al* Proc. 26th Annu Int Conf IEEE Eng Med Biol 2004; 1:1048 –1051. [4] Dumoulin CL, *et al*, Magn Reson Med 2005; 29:411–415.

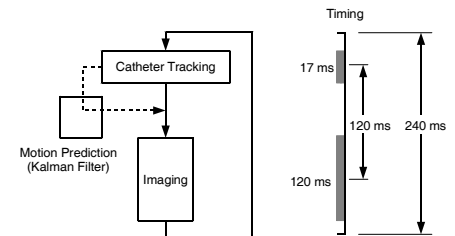


Figure 1: Diagram of imaging location control using catheter tracking and timing.

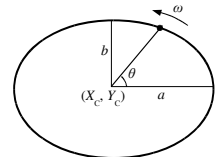


Figure 2: The elliptical movement model used in EKF for motion prediction.

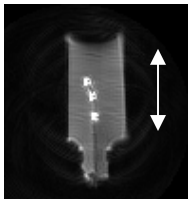


Figure 3: Phantom imaging for displacement evaluation.

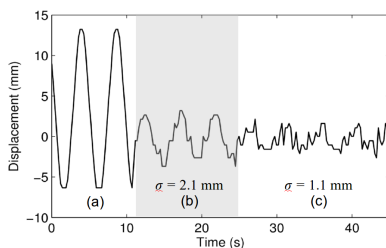


Figure 4: Phantom displacement detected from image registration.