Feasibility of Marker-Free Motion Tracking for Motion-Corrected MRI and PET-MRI

Andre Z. Kyme, *Member*, *IEEE*, Julian Maclaren, Murat Aksoy and Roland Bammer

***Abstract* – Prospective motion correction is a very promising compensation approach for magnetic resonance imaging (MRI) studies impacted by motion. It has the advantage over retrospective methods of being applicable to any pulse sequence. In prospective motion correction of brain studies, the magnetic field gradients and radio frequency waveforms are adjusted in real time in response to motion of the head, thereby maintaining a fixed frame of reference for the brain inside the scanner. A key requirement of this approach is accurate and rapidly sampled head pose information. Optical motion tracking is typically used to obtain these pose estimates, however current methods are limited by the need to attach physical markers to the skin. This readily leads to decoupling of the head and marker motion, reducing the effectiveness of correction. In this work we investigate the feasibility and initial performance of an optical motion tracking method which does not require any attached markers. The method relies on detecting natural features or amplified features (from skins stamps on the forehead) using multiple cameras, and estimates pose using a 3D-2D registration between a growing database of known 3D locations on the forehead and these features. We have performed out-of-bore and in-bore experiments to test the accuracy performance of this marker-free method for very small feature patches consistent with the limited visibility afforded by head coils used during imaging. The results showed excellent agreement between the marker-free method and our current ground truth method based on wireless MR-sensitive markers.**

I. Introduction

Whether used as a standalone technique or in combination with another modality such as positron emission tomography (PET), magnetic resonance imaging (MRI) has immense value for non-invasively studying the human brain [1]. Head motion, however, remains a key factor limiting the spatial and quantitative accuracy of MR measurements. Motion on the order of 1 mm or less can introduce blurring and ghosting artifacts in anatomical imaging, false activations in functional MRI, bias in functional parameters derived from diffusion-weighted MRI, and reduced spectral resolution and reproducibility in MR spectroscopy [e.g. 2-4].

Prospective motion correction (MC) is a general approach to compensate for head motion in MRI. It involves real-time adjustment of the magnetic field gradients and radio frequency (RF) waveforms during scanning to maintain a fixed spatial relationship between the head and imaging volume [5]. A key requirement of prospective MC is accurate and rapidly sampled pose (position/orientation) estimates. In principle, these can be obtained using optical motion tracking [6]. In practice, however, two major challenges exist. Firstly, nearly all current optical tracking approaches rely on fixing physical markers to the head, which often leads to decoupling of head and marker motion. Indeed, although the accuracy of marker-based tracking may be a few tens of microns in bench-top experiments [7], in some cases it may be several millimeters because of this decoupling [5]. Secondly, MRI of the brain uses a specialized head coil comprising several receiving channels; the coil is usually very enclosed with only a few small gaps. Therefore, although the development of in-bore MR-compatible cameras has increased the potential accuracy of motion estimates, it also presents a new challenge: how to capitalize on the potential accuracy when only small patches of the face are visible through the coil.

Our goal is to address these two challenges through the development of a marker-free head tracking approach in which pose is accurately determined from skin features confined to very small patches of the forehead. The specific aim of this work was to investigate the feasibility of marker-free optical motion correction for brain MRI using out-of-bore and in-bore phantom experiments with ground truth motion.

II. Methods

A. Camera and coil setup

Two MR-compatible CMOS cameras (640x320 or 1280x720 resolution) were securely mounted to an 8-channel head coil (Invivo) using a 3D-printed bracket (Fig. 1). The physical separation of the cameras was approximately 50 mm and both cameras had line-of-sight through the same channel opening. Stereo camera calibration was performed using a checkerboard pattern of 4 mm squares moved to approximately 30 different positions within the FoV of both cameras. Intrinsic and extrinsic camera parameters were then computed using the Matlab Calibration Toolbox [8].

Manuscript received Dec 8, 2016. This work was supported by an Early Career Researcher Research Innovation Award, Faculty of Health Sciences, University of Sydney and the Center of Advanced MR Technology at Stanford (P41 RR009784), Lucas Foundation. A. Z. Kyme was supported by a Cassen Fellowship provided by the Education and Research Foundation, SNMMI, USA.

A. Z. Kyme was with the Department of Biomedical Engineering, University of California Davis, Davis, CA, USA, and is now with Biomedical Engineering, School of Aerospace, Mechanical and Mechatronic Engineering, Faculty of Engineering, University of Sydney, Australia (telephone: +61 2 93512260, email: andre.kyme@sydney.edu.au).

J. Maclaren, M. Aksoy and R. Bammer are with the Department of Radiology and Lucas Center, Stanford University, USA (jmacl@stanford.edu, maksoy@stanford.edu, rbammer@stanford.edu).

B. Out-of-bore motion experiment

A 6-axis robot arm (C3-A601ST, Epson America Inc.) with 20 μm repeatability was used to apply discrete arbitrary motion in six degrees of freedom to a polystyrene head phantom inside the camera-mounted head coil (Fig. 1). An image from Subject #5 of the face recognition database in [9] was color-printed on paper and glued to the forehead of the phantom to simulate a realistic skin surface. We also tested adding a small (25 mm x 13 mm) 'feature patch' comprising arbitrary text and symbols above the left eyebrow. This simulated a concentrated source of features directly onto the skin, in contrast to traditional methods requiring physical attachment of markers/features. Using the robot we applied 19 known poses to the phantom and for each one collected synchronized stereo camera images for offline motion estimation (described below). A cross-calibration was also performed between the cameras and robot to convert estimated poses to robot coordinates for direct comparison with the applied motion.

C. In-bore motion experiment

The camera-mounted head coil was placed inside a GE MR750 3T scanner (GE Healthcare) and a cross-calibration performed to relate the camera and scanner coordinate systems. We used a spherical plastic phantom with a small (37 mm x 10 mm) 'feature patch' positioned in the FoV of the cameras. The phantom also had three rigidly attached wireless MR markers to provide ground truth motion during an MR acquisition [10]. We moved the phantom to 6 discrete poses during a single acquisition while data were acquired continuously from the wireless MR markers. At each pose, synchronized stereo images were collected for offline pose estimation.

D. Motion estimation

The feature-based pose estimation method reported previously for PET imaging of rats [11] was adapted for this work. In this method, features are detected and matched across multiple camera views to accumulate a database of head landmarks; pose is then estimated based on 3D-2D registration of the landmarks to features in each image. Estimates were compared to the ground truth motion applied by the robot or obtained from the wireless markers.

III. Results

The mean camera/robot cross-calibration errors were 0.09 mm (max 0.18 mm), 0.07 mm (max 0.13 mm) and 0.10 mm (max 0.25 mm) for *x*, *y* and *z*, respectively. Figure 2 shows the discrepancy, in millimeters, between the ground truth and estimated positions of a test point located in the striatum. Estimation was better (and usually with sub-millimeter discrepancy) with added features. Figure 3 shows the feature-based pose estimates of the in-bore phantom compared to the wireless MR markers for out-of-plane rotation (the most challenging degree of freedom to estimate accurately). Feature-based estimates were within 0.2 mm/0.2 deg. of the wireless markers despite features being confined to an area of only 4 cm^2.

IV. Discussion and Future Work

Both the out-of-bore and in-bore phantom experiments showed excellent agreement between estimated and ground truth motion. For the out-of-bore phantom experiment, the residual discrepancy of motion estimates is most likely due to limitations in our cross-calibration method rather than the pose estimation. During our cross-calibration procedure, the cross-calibrated volume was in the immediate vicinity of the end-effector. During the experiment, however, because the polystyrene phantom was attached to the end-effector, the calibrated volume was approximately 250 mm from where features were derived for pose estimation. It is well known that cross-calibration error increases rapidly away from the cross-calibration volume [12], therefore this is very likely the cause of the residual error seen in Fig. 3 (red curve). The in-bore experiment (Fig. 4) did not suffer from this cross-calibration limitation.

Our experiments demonstrate that even very small feature-rich patches are sufficient for accurate motion tracking of the head. This is vital if tracking is to be performed in the tight geometry and limited line-of-sight afforded by modern multi-channel head coils inside the MR bore. Although the experiments we describe here do not use purely native features on the forehead, the feature patches can be printed directly on the skin, removing the potential for decoupling that readily occurs with markers attached to goggles, neoprene caps or stuck directly onto the skin. Motion experiments involving volunteers with and without forehead stamps are underway.

IV. Conclusion

Our goal is to develop methods to accurately and conveniently track head motion within the extremely tight space constraints of an MRI scanner. This is vital for the clinical viability and optimal performance of prospective motion correction in standalone MRI and hybrid MRI-PET systems. Here we have demonstrated the feasibility of using very small, dense feature patches directly on the skin for marker-free optical pose estimation in a realistic MRI setup. We are currently extending this idea to investigate the use of skin-safe forehead stamps for estimating arbitrary head motion in *in vivo* volunteer studies.

Acknowledgment

A. Z. Kyme was supported by a Cassen Fellowship provided by the Education and Research Foundation, SNMMI, USA. The work was also supported by an Early Career Researcher Research Innovation Award, Faculty of Health Sciences, University of Sydney and the Center of Advanced MR Technology at Stanford (P41 RR009784), Lucas Foundation.

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Fig. 1. Out-of-bore experimental setup: Epson C3 6-axis robot used to control the pose of a polystyrene head phantom inside an 8-channel head coil; custom bracket for mounting two MR-compatible cameras to the coil for prospective motion correction.

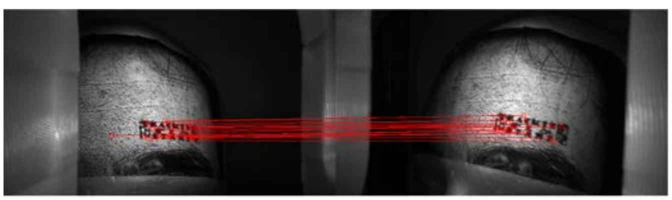

Fig. 2. Feature detection and matching. A subset of the nearly 300 matches obtained when a small feature patch was added above the left eyebrow of the forehead image.

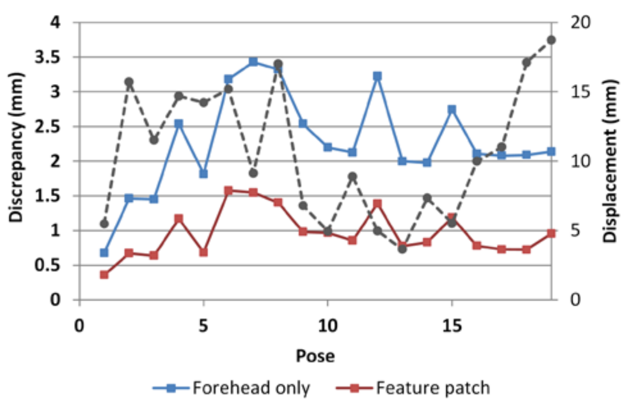

Fig. 3. Out-of-bore experimental results. Discrepancy (plotted on left axis) between the location of a striatal test point determined using the marker-free approach and ground truth (robot). Marker-free estimates were obtained using the forehead only (blue) and using a small feature patch above the eyebrow (red). Plotted on the right axis for reference is the displacement of the test point for each movement (black dotted line).

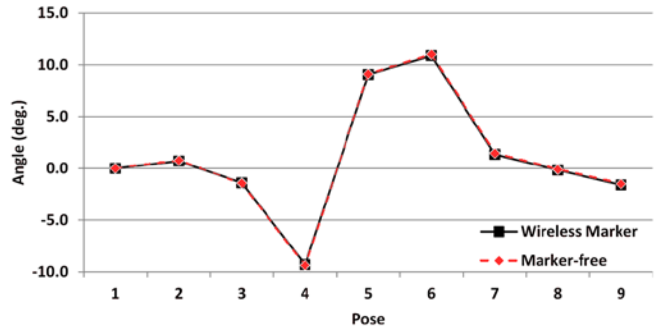

Fig. 4. In-bore experimental results. Out-of-plane rotation estimate for the in-bore phantom at each pose using the marker-free approach with a small feature patch (red) and the wireless MR markers (black, ground truth).