Coordinate System Alignment using Single Camera for Functional Brain Imaging

Yung-Cheng Cheng¹, Yong-Sheng Chen², Jen-Chuen Hsieh¹,³,⁴,⁵, and Li-Fen Chen³,⁶,*

¹Institute of Health Informatics and Decision Making, National Yang-Ming University, Taipei, Taiwan
²Department of Computer Science and Information Engineering, National Chiao Tung University, Hsinchu, Taiwan
³Lab. of Integrated Brain Research, Dept. of Medical Research and Education, Taipei Veterans General Hospital, Taiwan
⁴Institute of Neuroscience, ⁵Faculty of Medicine, ⁶Center for Neuroscience, National Yang-Ming University, Taipei, Taiwan

Abstract—In this work, we propose a novel method to align the coordinate systems between the neuromagnetometer device (functional space) and the subject’s head (structural space). Conventionally, coordinate system alignment is performed by locating a set of coils attached to the subject’s head in both the coordinate systems by means of electromagnetic manners. However, such electromagnetic approach may cause instability of functional source mapping when the estimated coil positions are not stable due to external noise or when the coils are not tightly attached. This paper presents a new coordinate system alignment technique without using coils. Instead, the proposed method utilizes a calibrated camera to monitor feature points attached to the subject’s face. Coordinate system alignment is then achieved by determining the head pose in neuromagnetometer device coordinate system. According to the phantom experiments, we demonstrate the better noise immunity, better stability, and less electromagnetic interference of the proposed alignment method.

I. INTRODUCTION

Magnetoencephalography (MEG) [1] is a powerful method for in vivo noninvasive imaging of cortical source. Estimation of neuronal source requires the information of coordinate transformation between the MEG device and the subject’s head coordinate systems. The conventional way of coordinate system alignment is to attach a set of coils, also called head position indicator (HPI), to the subject’s scalp. The coordinates of HPI coils in the head coordinate system can be measured with 3D digitizer in the preparation stage. During the data acquisition stage, small currents are supplied for these coils and their positions in MEG device coordinate system can be determined by dipole fitting from the measured magnetic signals. The transformation between the head and MEG device coordinate systems can then be obtained [2]. Then the structural data can be mapped to the functional data.

Unfortunately, the fitted HPI positions in MEG device coordinate system may be unstable. If the HPI coils are not tightly attached to the scalp, their positions may change during the signal acquisition stage because the HPI coils touch the dewar when the subject sits in the MEG system. The HPI is an electromagnetic method, so it is sensitive to external noise. According to our experience, the measured positions via source localization are not stable even the HPI coils are fixed. Furthermore, this kind of HPI-based method encounters another problem in detecting and correcting head movements in neuromagnetic measurements [3]. The signal made by the HPI coils interfere the original brain signal, so HPI can not be executed during MEG experiment; moreover, the signal made by HPI coils may interference baseline of MEG sensor. Thus degrades accuracy and correctness of the functional brain imaging from MEG measurements.

In this work, we develop a new coordinate system alignment technique using a CCD-camera, instead of HPI coils, as a medium. This camera is first calibrated so that the transformation between the camera and MEG device coordinate systems is known and fixed. Then, the subject wears several feature points on her/his face (these feature points will not touch the dewar) during the signal acquisition stage. The camera observes these feature points and the head pose in camera coordinate system can then be determined. Combining the head pose in camera coordinate system and the transformation between the camera and MEG device coordinate systems yields the desired coordinate system alignment between the head and MEG coordinate systems. To have the ground-truth of source positions for accuracy and stability assessment, we performed experiments using phantom data. According to the experiment results, we clearly demonstrate the feasibility, stability, and accuracy of the proposed camera-guided alignment method.

II. METHODS

This section describes the procedures of the proposed method for coordinate system alignment in detail. We start with the description of the notations used in this paper.

A. Notations

\( C_{\text{MEG}} \), \( C_{\text{CAM}} \), \( C_{\text{IMG}} \), \( C_{\text{OBJ}} \), and \( C_{\text{HEAD}} \) represent the coordinate systems of the MEG device, the camera, the image plane in the camera, calibration object, and the subject’s head, respectively (Fig. 1) In this work, we use a phantom as the calibration object. \( \text{sup} \rightarrow \text{sub} \) denotes the transformation from the \( \text{sub} \) coordinate system to the \( \text{sup} \) coordinate system; for instance, \( \text{OBJ}_{\text{sup}} \rightarrow \text{MEG} \) stands for the transformation from the MEG device to calibration object coordinate systems. Here \( \text{sub} \) and \( \text{sup} \) could be any one of the above defined five coordinate systems.

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*Corresponding author.
B. Overview of the Proposed Method

The goal of this work is to obtain the transformation $\text{HEAD}_T\text{MEG}$ used for MEG source imaging. In other words, we need $\text{HEAD}_T\text{MEG}$ to translate the structural data obtained in MEG device coordinate system into subject’s head coordinate system for functional study.

The transformation $\text{HEAD}_T\text{MEG}$ can be decomposed as follows:

$$\text{HEAD}_T\text{MEG} = \text{HEAD}_T\text{CAM} \cdot \text{CAM}_T\text{MEG}. \quad (1)$$

Once the relative positions between the MEG device and the camera are fixed, the $\text{CAM}_T\text{MEG}$ will be invariable.

Based on this concept, the proposed method is composed of two working stages as shown in Fig. 2. All the invariant parameters such as camera intrinsic parameters and $\text{CAM}_T\text{MEG}$ can be obtained in the first stage. Camera intrinsic parameters can be estimated by camera calibration techniques. By utilizing the concept of transformation decomposition once more, $\text{CAM}_T\text{MEG}$ can be decomposed into the form $\text{CAM}_T\text{OBJ} \cdot \text{OBJ}_T\text{MEG}$. The calibration object is used as a medium for computing $\text{CAM}_T\text{OBJ}$ and $\text{OBJ}_T\text{MEG}$. A set of camera-visible feature points on the calibration object can be used to estimate $\text{CAM}_T\text{OBJ}$ by using pose determination technique. Furthermore, HPI coils attached on the calibration object are used to compute $\text{OBJ}_T\text{MEG}$ by using MEG source localization technique. Since subjects are not involved in this stage at all, we refer this stage as calibration, subject-independent stage.

In the second stage, $\text{HEAD}_T\text{CAM}$ can be determined by using pose determination technique based on a set of camera-visible feature points on the subject’s head. The computation of $\text{HEAD}_T\text{CAM}$ is totally device-independent. Once both $\text{HEAD}_T\text{CAM}$ and $\text{CAM}_T\text{MEG}$ are estimated, $\text{HEAD}_T\text{MEG}$ is then obtained.

Among the above mentioned techniques, we describe the process of camera calibration, feature point detection, and pose determination below.

1) Camera Calibration: Camera intrinsic parameters are required to determine the 3-D projection line for each feature point on the captured image. These 3-D projection lines can then be used for pose determination in the following stage. In this work, we adopt the camera calibration method proposed in [4] due to its simplicity, robustness, versatility, and accuracy. Its widely used implementation in OpenCV library was used to obtain accurate intrinsic camera parameters, including effective focal length, aspect ratio, skew factor, lens distortion, and image center.

As can be seen in Fig. 3(a), the calibration plane contains 9 16-mm radius circles, and 11 images of the plane under different positions were taken for camera calibration. The calibration plane was printed on an A4 paper with a 600 DPI laser printer and attached to a glass board.

2) Feature Point Extraction: To reduce the labor of manual feature selection, we use the block matching algorithm to automatically detect the black circles in the image, as shown in Fig. 4. For efficiency, we adopt a fast block matching technique [5] in this work. Once a circle is located, the feature
points can be extracted by thresholding [6] the image followed by estimating the centroid.

3) Pose Determination: For a rigid set of 3-D points in the head coordinates, their corresponding feature points projected on the image plane, as well as the intrinsic camera parameters, can be used to determine the pose of the head in the camera coordinate system. In this study, we use OI post estimation [7] to estimate the head pose, $\text{CAM}_T \text{HEAD}$, by using the coordinate pairs of the feature points both in head coordinate system, $C_{\text{HEAD}}$, and in image coordinate system, $C_{\text{IMG}}$.

C. System Procedures

Following shows how to use those techniques described above to estimate $\text{HEAD}_T \text{MEG}$. The detailed steps of the procedures are listed as follows:

1) Set up the camera calibration plate as shown in Fig. 3(a) and perform camera calibration for intrinsic parameter estimation.
2) Set up the calibration object as shown in Fig. 3(b) for the first stage.
3) Get the coordinates of HPIs and those of a set of camera-visible feature points in the calibration object coordinate system, $C_{\text{OBJ}}$, respectively, by using 3D digitizer.
4) Perform location estimation of HPI in the MEG device coordinate system by using MEG dipole fitting technique.
5) Obtain $\text{OBJ}_T \text{MEG}$ by using the coordinates of HPIs in both the coordinate systems, $C_{\text{OBJ}}$ and $C_{\text{MEG}}$.
6) Perform pose determination to obtain $\text{CAM}_T \text{OBJ}$ by using the 3D coordinates of the feature points in the object coordinate systems, $C_{\text{OBJ}}$.
7) $\text{CAM}_T \text{MEG} = \text{CAM}_T \text{OBJ} \times \text{OBJ}_T \text{MEG}$.
8) Get the coordinates of camera-visible feature points in the subject’s head coordinate system, $C_{\text{HEAD}}$, by using 3D digitizer.
9) Start MEG data acquisition.
10) Perform pose determination to obtain $\text{HEAD}_T \text{CAM}$ by using the 3D coordinates of the feature points in the subject’s head coordinate systems, $C_{\text{HEAD}}$.
11) $\text{HEAD}_T \text{MEG} = \text{HEAD}_T \text{CAM} \times \text{CAM}_T \text{MEG}$.

III. EXPERIMENTS

We use simulate all conditions as real experiment will happened, and a phantom was employed as a subject. Following shows the properties of experiment environment.

A. System Setup

1) Camera: In this study, we used a CCD camera (Marlin, ALLIED Vision Tech. GmbH) with lens of focal length 35 mm and image size of 1280×1024 pixels, which is located around 2.1 meters away in front of the MEG device.

2) Calibration object: A calibration object (Fig. 3(b) is to be a medium for estimating $\text{CAM}_T \text{MEG}$. Base on the phantom supplied by the manufactory (Neuromag Ltd., Finland), we fixed a smaller calibration plane which has 9 13-mm radius circles. The calibration plane was printed on a A4 paper with a 600 DPI laser printer and attached to a plastic board. Once the calibration object has been putted in a MEG device, we can estimate $\text{OBJ}_T \text{MEG}$ by HPI and $\text{CAM}_T \text{OBJ}$ by pose determination, then the $\text{CAM}_T \text{MEG}$ can be formed by above result.

3) Phantom Data: The phantom was used to demonstrate the accuracy of the present work without human intervention. The signal source with stationary locations and two-cycle sine waves of duration 120ms were activated individually to generate the electromagnetic field. The peak-to-peak current strength of each dipole was set to 100nAm. Four head position indicator (HPI) coils (fixed on the phantom) were used to obtain the position of the phantom with respect to the sensor array. After well-positioning, the phantom was assumed to keep still within a session. For each session, 100 trials were recorded at a sampling rate of 1000Hz with bandpass filtering 0.1Hz to 333Hz. The preprocessed data were then used for further localization analysis.

4) Related result: The re-projection error of the camera calibration (intrinsic parameters and extrinsic parameters) is under 0.15 pixel. For verifying the stability of the digitizer, we obtain a position of a point by ten times through the digitizer, and the standard deviation of the digitizer is [0.0568, 0.04830, 0.0667] in mm, by x, y, and z axis. The re-projection error of the pose determination in data acquisition id under 0.38 pixel. The feature point extraction has sub-pixel accuracy.

B. Performance Evaluation

A stability test and a accuracy test will verify the proposed method’s performance in the experiment.

1) The Stability of $\text{CAM}_T \text{MEG}$ and $\text{HEAD}_T \text{MEG}$: In the stability test, according to the method in Section II to estimate
The MEG data acquisition stage will estimate subject’s pose and form the $\text{CAM}_\text{T}_{\text{MEG}}$ by all the estimated results in both stage.

![Diagram of the proposed method schema. The calibration stage is used to estimate all the invariant parameters of the equipments and environment. The MEG data acquisition stage will estimate subject’s pose and form the $\text{CAM}_\text{T}_{\text{MEG}}$ by all the estimated results in both stage.](image)

**Fig. 2.** Illustration of the proposed method schema. The calibration stage is used to estimate all the invariant parameters of the equipments and environment. The MEG data acquisition stage will estimate subject’s pose and form the $\text{CAM}_\text{T}_{\text{MEG}}$ by all the estimated results in both stage.

<table>
<thead>
<tr>
<th>Item</th>
<th>STD $\sigma$ of Rotation (degree)</th>
<th>STD $\sigma$ of Translation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{OBJ}<em>\text{T}</em>{\text{MEG}}$</td>
<td>$[0.2706, 0.1300, 0.0536]$</td>
<td>$[0.1153, 0.1691, 0.2680]$</td>
</tr>
<tr>
<td>$\text{CAM}<em>\text{T}</em>{\text{OBJ}}$</td>
<td>$[0.0041, 0.0030, 0.0012]$</td>
<td>$[0.0067, 0.0108, 0.0609]$</td>
</tr>
<tr>
<td>$\text{CAM}<em>\text{T}</em>{\text{MEG}}$</td>
<td>$[0.2700, 0.0714, 0.1207]$</td>
<td>$[0.1181, 0.2427, 0.2253]$</td>
</tr>
</tbody>
</table>

**TABLE I**

THE STABILITY OF THE $\text{CAM}_\text{T}_{\text{MEG}}$.

<table>
<thead>
<tr>
<th>Item</th>
<th>$\text{HEAD}<em>\text{T}</em>{\text{HPI}}$</th>
<th>$\text{HEAD}<em>\text{T}</em>{\text{MEG}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation $[\alpha, \beta, \gamma]$ (°)</td>
<td>$[0.2706, 0.1300, 0.0536]$</td>
<td>$[0.0004, 0.0009, 0.0031]$</td>
</tr>
<tr>
<td>Translation $[x, y, z]$ (mm)</td>
<td>$[0.1153, 0.1691, 0.2680]$</td>
<td>$[0.0101, 0.0544, 0.0289]$</td>
</tr>
</tbody>
</table>

**TABLE II**

THE STABILITY OF THE MEG HPI AND THE PROPOSED METHOD. $^1$STD $\sigma$ OF MEG HPI’s $\text{HEAD}_\text{T}_{\text{MEG}}$. $^2$STD $\sigma$ OF $\text{HEAD}_\text{T}_{\text{MEG}}$ OF THE PROPOSED METHOD.

the $\text{CAM}_\text{T}_{\text{MEG}}$, we put the simulation object (Fig. 4) in a fixed position, and estimate the $\text{HEAD}_\text{T}_{\text{MEG}}$ with ten trials through HPI and the proposed method. Then calculate the standard deviation of these ten results of each method.

The $\text{CAM}_\text{T}_{\text{MEG}}$ is a important transformation in our work, because it affects the accuracy and the stability of $\text{HEAD}_\text{T}_{\text{MEG}}$ estimated by our work. We execute the calibration stage by ten times, and calculate the standard deviation of $\text{HEAD}_\text{T}_{\text{MEG}}$. Ideally, the $\text{CAM}_\text{T}_{\text{MEG}}$ should be the same with the related position of the camera and the MEG device fixed. Table I shows that $\text{CAM}_\text{T}_{\text{MEG}}$ has a little variation (rotation in degree: $[0.2700, 0.0714, 0.1207]$), translation in mm: $[0.1181, 0.2427, 0.2253]$), but the variation of our work is quite small (rotation in degree: $[0.0041, 0.0030, 0.0012]$), translation in mm: $[0.0067, 0.0108, 0.0609]$). In detail, we divided $\text{CAM}_\text{T}_{\text{MEG}}$ into $\text{CAM}_\text{T}_{\text{OBJ}}$ and $\text{OBJ}_\text{T}_{\text{MEG}}$. Table I shows that most variation is affected by the instability of $\text{OBJ}_\text{T}_{\text{MEG}}$ estimated from HPI.

Next, we execute the MEG data acquisition stage by ten times, and calculate the standard deviation of $\text{HEAD}_\text{T}_{\text{MEG}}$. we take the average value of the ten $\text{CAM}_\text{T}_{\text{MEG}}$ as a ideal value. As the Table II shows, because the pose determination of our work is very stable, the standard deviation of our $\text{HEAD}_\text{T}_{\text{MEG}}$ is more stable than HPI’s.

2) The Accuracy of $\text{HEAD}_\text{T}_{\text{MEG}}$: In the accuracy test, the phantom signal source are activated to verify the accuracy of the source localization under the original $\text{HEAD}_\text{T}_{\text{MEG}}$ through the HPI and another $\text{HEAD}_\text{T}_{\text{MEG}}$ which is estimated by the proposed method.

After calibration stage, we position the phantom (Fig. 4) in the MEG device, and execute MEG data acquisition to estimate $\text{HEAD}_\text{T}_{\text{MEG}}$. Then we activate eight signal sources of phantom to demonstrate the accuracy of dipole fitting under five different $\text{HEAD}_\text{T}_{\text{MEG}}$.

As Fig. 5 shows, there are average errors of each of eight dipoles under five different positions. The average fitting error of HPI and the proposed method are 2.3767 mm and 3.0329 mm, respectively. Although the error of the proposed method
Fig. 4. The simulation object for accuracy evaluation.

Fig. 5. Accuracy of source estimation. There are 8 dipoles under different position. The average error of HPI and the proposed method are 2.3767 mm and 3.0329 mm, respectively.

is bigger than HPI, but it is possible to improve accuracy of the proposed method, and it will be discussed in the next section.

IV. DISCUSSION

In the proposed method, the estimated transformation, \( \text{HEAD}^T_{\text{MEG}} \), is formed by \( \text{HEAD}^T_{\text{CAM}} \) in data acquisition stage and \( \text{CAM}^T_{\text{MEG}} \) in calibration stage. Because of the limitation of MEG device, a calibration object is utilized for a medium, the \( \text{CAM}^T_{\text{MEG}} \) is formed by \( \text{OBJ}^T_{\text{MEG}} \) estimated by conventional method and \( \text{CAM}^T_{\text{OBJ}} \) estimated by vision method. The stability and accuracy of these two methods directly affect the final result of the proposed method.

Although the accuracy of the proposed method is not better than the conventional method, there are some methods to improve the accuracy:

- Visible reference points for \( \text{C}_{\text{MEG}} \):
  Recently, there are no reference points which are in known positions in \( \text{C}_{\text{MEG}} \) can be captured by camera, so the proposed method utilize a home-made calibration object to be a medium for estimating \( \text{CAM}^T_{\text{MEG}} \) in calibration stage, and HPI accuracy will affect the accuracy of calibration stage because of \( \text{CAM}^T_{\text{MEG}} \) is formed by \( \text{CAM}^T_{\text{OBJ}} \text{OBJ}^T_{\text{MEG}} \). Perfectly, if there are some visible reference points (Fig. 6) in known positions on MEG device, and they can be captured by camera, the \( \text{CAM}^T_{\text{MEG}} \) can be estimated directly be vision method. Therefore, it will avoid the inaccuracy of HPI to affect the accuracy performance of calibration stage.

- Well-calibrated calibration object:
  The coordinates in the \( \text{C}_{\text{HEAD}} \) and \( \text{C}_{\text{OBJ}} \) of feature points are defined through the 3D digitizer manually, we can use a well-calibrated calibration object which has accurate positions of all feature points for decreasing this artificial error.

- Stereo vision:
  It is able to directly estimate 3D position of feature points through stereo vision, and that can improve efficiency of the proposed method. Besides, it can obtain more information by stereo vision than single camera, so that will improve accuracy of the proposed method.

- More HPI coils attached on calibration object:
  In calibration stage, it needs HPI to estimate \( \text{OBJ}^T_{\text{MEG}} \). More HPI coils attached on calibration object can obtain more information of calibration object position, and that can help us to estimate accurate \( \text{OBJ}^T_{\text{MEG}} \).

- MRI visible marker:
  If MRI device is available, we can replace feature points by MRI visible markers. After MRI scanning, it is able to obtain \( \text{C}_{\text{OBJ}} \) and the coordinates of visible markers from 3D MRI data. Therefore, we can overlay the source position with MRI data and obtain functional information directly. This directly mapping will avoid the artificial error made by defining \( \text{C}_{\text{HEAD}} \) manually.

- Attachment of feature points:
  One of difficulty of the proposed method is attachment of feature points with subject. In reality, the fixed places of the subject’s face are not too much, for example, nose tip, forehead. It can use a glass frame which has feature points attached on it, and subject wears the glass frame, instead of attaching feature points on subject face. Using this equipment can also decrease the preparing time of experiment.

V. CONCLUSION

This paper presents a new coordinate system alignment technique without using HPI coils. According to the experi-
Fig. 6. Illustration for visible reference points setup: The gray circles are the visible reference points, and it are for directly estimating $\text{CAM}_{\text{MEG}}$ by vision method.

...ment results, we clearly demonstrate the better noise resilience, better stability, and less interference of the proposed camera-guided alignment method.

Comparing the conventional method with the proposed method, the location estimation of HPI is sensitive to the external noise, so the result of $\text{HEAD}_{\text{MEG}}$ will be affected by external noise. The illumination of environment is easier to control than external noise, so the proposed method has less interfering noise. According to our experience, we have to redo many times to look for a better HPI fitting results. From the results of Table II, our work is more stable than HPI, and is more resistible to the external noise.

The proposed method can estimate the position of the subject’s head in the MEG device coordinate system during experiments without interfering with brain signals. In other words, we are able to do the online motion estimation such that we may monitor the status of the subject’s head online. It is possible for compensating head movement for correcting brain signal positions.

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