A Sensor Positioning System for Functional Near-Infrared Neuroimaging

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Abstract. In cognitive studies using functional near-infrared (fNIR) techniques, the optical sensors are placed over the scalp of the subject. In order to document the actual sensor location, a system is needed that can measure the 3D position of an arbitrary point on the scalp with a high precision and repeatability and express sensor location in reference to the international 10-20 system for convenience. In addition, in cognitive studies using functional magnetic resonance imaging (fMRI), the source location is commonly expressed using Talairach system. In order to correlate the results from the fNIR study with that of the fMRI study, one needs to project the source location in Talairach coordinates onto a site on the scalp for the placement of the fNIR sensors. This paper reports a sensor positioning system that is designed to achieve the above goals. Some initial experimental data using this system are presented.

Keywords: 10-20 system, brain mapping, fNIR, neuroimaging, Talairach.

1 Introduction

Recent advancements in the functional near-infrared (fNIR) technique have expanded its potential applications in mapping the human brain's hemodynamic response to various cognitive tasks. In most studies reported in the literature, the optical sensors were placed over the forehead [1-3]. However, in many functional neuroimaging studies, the location nearest to the activation area in the brain may not be on the forehead [4]. In such cases, the optical sensors need to be placed at various locations on the scalp in order to optimize the reception of fNIR signals. In order to document the actual sensor location in a study, a device is needed that can measure the 3D position of an arbitrary point on the scalp with a high precision and repeatability. In addition, in cognitive studies using functional magnetic resonance imaging (fMRI), the source location is commonly expressed using the Talairach coordinate system. In order to correlate the results from the fNIR study with that of the fMRI study, one needs to project the source location in Talaraich coordinates onto a site on the scalp and then place the fNIR sensors over that site. Finally, since the most recognized standard for scalp electrode localization is the international 10-20 system used in the EEG studies [5], it may be convenient to express the fNIR sensor location in reference to the international 10-20 system, but a much higher spatial resolution is required (the typical 10-20 system has only 19 electrode locations). This paper reports a sensor

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positioning system that is designed to achieve the above goals. Some initial experimental data using this system are presented.

2 Method

2.1 The Three-Dimensional (3D) Sensor Positioning System

The sensor positioning system is built upon an electromagnetic tracking device manufactured by Polhemus (3SPACE® FASTRAK®, Colchester, Vermont). The device has a system electronics unit, a transmitter, and four receivers numbered as Receiver 1 to Receiver 4. Receiver 1 is a hand-held stylus which is used to point to a location for position measurement. Receivers 2, 3, and 4 have the same shape of a small cube that will be attached to the subject's head to form a reference coordinate system. Upon receiving a reading command, each receiver reports its real-time position and orientation with reference to the transmitter. For the current application, only the 3D position coordinates are used.

Since the head of the subject can move during an experiment, the goal of the sensor positioning system is to define the location of a point in a head system (HS) that is unique to a particular subject, a method similar to EEG channel localization in the 10-20 system. This goal is achieved by establishing three coordinate systems and suitable transformations of coordinates between the systems. The following is a description of the three coordinate systems as shown in Fig. 1.

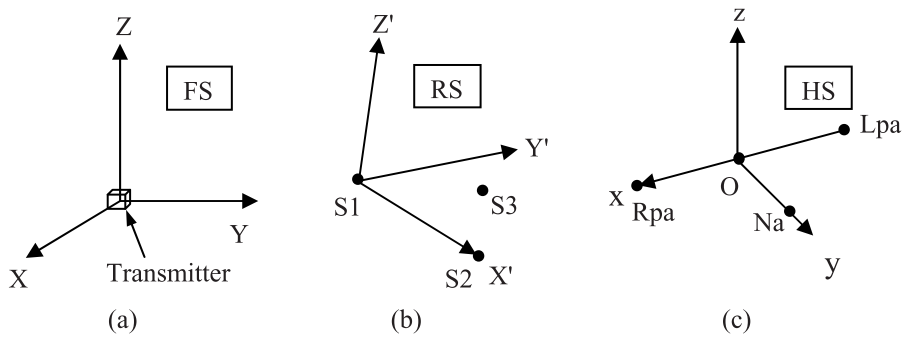


Fig. 1. (a) The fixed coordinate system (FS). (b) The reference coordinate system (RS) where S1, S2, S3 are three reference receivers which form the X'-Y' plane of RS. (c) The head system (HS) where Na is the nasion, and Lpa and Rpa are left and right pre-auricular points. These three points define the x-y plane of HS.

1) The fixed system (FS, the X-Y-Z system): which is defined by the fixed Polhemus transmitter. The real-time positions of the four receivers are all expressed in this fixed system (Fig. 1(a)).
2) The reference system (RS, the X'-Y'-Z' system): which is defined by the three cubic receivers. The centers of these three receivers (S1, S2, S3 in Fig. 1(b)) form the X'-Y' plane of RS. The origin is the position of Receiver 2. The line

from Receiver 2 to Receiver 3 defines the X'-axis. The position of Receiver 4 indicates the positive direction of the Y'-axis. The Z'-axis and the actual Y'-axis are defined by the right hand rule of convention (Fig. 1(b)).

3) The head system (HS, the x-y-z system): which is established using the following three points of the subject's head: the left pre-auricular point (Lpa), the right pre-auricular point (Rpa), and the nasion (Na). These three points form the x-y plane of HS. The origin O is the middle point of the line connecting Lpa and Rpa. The line from O to Rpa defines the x-axis. The Na indicates the positive direction of the y-axis. The z-axis and the actual y-axis are defined by the right hand rule of convention (Fig. 1(c)).

Notice that RS and HS both move with respect to FS during an experiment, but the relation between these two systems is fixed as long as the three receivers attached to the subject's head do not move relatively to the subject's head.

The position of a location pointed by the stylus receiver is originally expressed by the 3D coordinates in FS. These coordinates are first transformed to the coordinates in RS, and then to that in HS. The general method of transformation of coordinates involving translation and rotation can be described by the following matrix equation:

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{pmatrix} \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} \tag{1}$$

where: X-Y-Z are the coordinates in the old system; X'-Y'-Z' are the coordinates in the new system that has an origin O' whose coordinates in the old system are X_0, Y_0 and Z_0; T_{11}, T_{12} and T_{13} are the direction cosines of the X' axis which are the cosines of the angles between the X' axis and the X, Y, Z axes, respectively; T_{21}, T_{22}, and T_{23} are the direction cosines of the Y' axis; and T_{31}, T_{32}, and T_{33} are the direction cosines of the Z' axis. For a coordinate system defined by three points, as shown in Fig. 1(b) and 1(c), a MATLAB program <points2cosines>, which is available upon request, was written to calculate the T-matrix of the direction cosines.

Prior to actual position measurement in an experiment, the above three coordinate systems need to be established according to the following procedures.

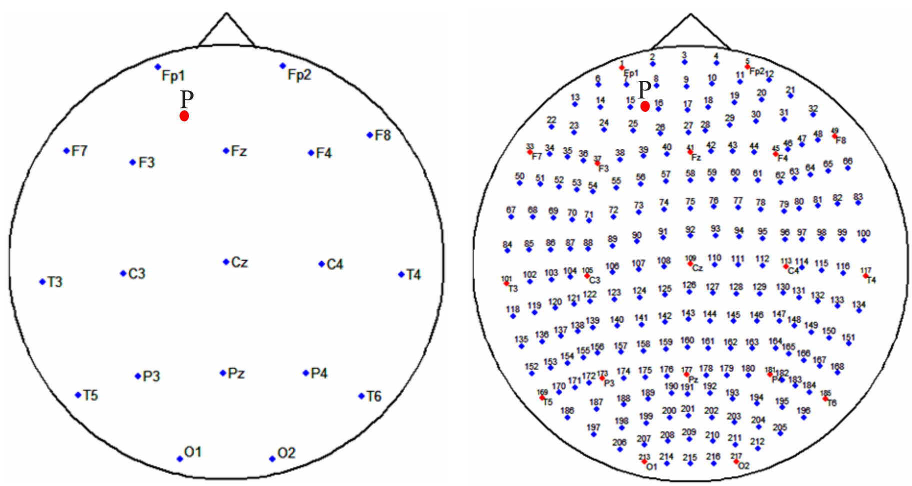
- Place the Polhemus transmitter to a fixed location near the subject's head.
- Attach Receivers 2, 3, and 4 to the subject's head using an elastic bandage near the line of the ears but not to cover any standard 10-20 channel locations.
- Using the stylus receiver (Receiver 1) to point to the left pre-auricular point (Lpa), and then send a reading command. The Polhemus system always provides the positions of all four receivers. Thus, at each reading, a real-time RS is formed, and the position of Lpa originally expressed in FS is mapped to a point in RS.
- The same procedure is repeated for the right pre-auricular point (Rpa) and nasion (Na). At each reading, a new, real-time RS is formed and a corresponding point of Rpa (or Na) in RS is determined.
- The HS can then be established and the transformation between RS and HS is established.

For every new subject, the positions (3D coordinates in HS) of the standard 19 channels are measured and saved according to the following procedures. The locations of the standard 19 channels of the subject are marked by an experienced operator according to the method described by Jasper [5]. After performing the procedures for establishing coordinate systems described above, the operator moves the stylus receiver to each of the 19 channels. At each location, the coordinates of that channel are first mapped to the real-time RS, and then to HS. In the end, the coordinates of all 19 channels in HS are stored in a file which will be used in future experiments with that subject.

2.2 Several Utility Programs for Use with the Above Sensor Positioning System

2.2.1 Display the 19 Channel Positions on a 2D Round Head Model

The locations of the standard 19 channels for a particular subject are originally expressed in three dimensions. To present this location information on a computer screen, one choice is to display a 3D head model with the 19 channels shown on the surface of the head [6]. A disadvantage of such an approach is that the operator usually cannot see all the channels at once and often needs to rotate the head model to see different channels. Since the purpose of model display is to observe the position of a particular point on the head in reference to the 10-20 system, we chose to display a 2D head model. A custom 3D to 2D conversion is written that maps Cz to the center of the head model and maps all other 18 channels proportionally. Fig. 2(a) shows an example of the displayed 19 channels for a particular subject. The figure also shows the position of an arbitrary point P measured by this system and consequently displayed on the model. Alternatively, the operator can enter the 3D coordinates of a reference point and display that point on the head model for sensor placement.



(a) (b)

Fig. 2. (a) 2D display of the 19 channel locations of the 10-20 system for a particular subject. P is an arbitrary point on the scalp. (b) 2D display of a dense grid containing 217 points that are expanded from the original 19 channel locations. P is the same point as in (a).

2.2.2 Generate a Dense Grid for Displaying Expanded 10-20 Channel Positions

In order to be able to express the location of a point in the 10-20 system more precisely, we expand the locations of the 19 channels by generating a dense grid using curvilinear interpolation. Fig. 2(b) shows the expanded 10-20 system based on the one shown in Fig. 2(a). For this particular expansion, a total of 217 points are generated, numbered, and displayed. This grid of points allows a more precise localization of a point on the scalp in reference to the 10-20 system.

2.2.3 Convert the Position of a Point on the Cortical Surface from the Talairach System to the Head System

There is a rich literature of functional neuroimaging studies using fMRI. In these studies, the area of activation in the brain is often expressed in Talairach coordinates. In order to correlate the results from the fNIR study with that of the fMRI study, one needs to project the source location in Talairach coordinates onto a site on the scalp of a particular subject so that the fNIR sensor can be placed over that site for the fNIR study. A MATLAB program is written to perform a transformation from the given Talairach coordinates to the coordinates in the head system (HS) of a particular subject. This program uses the data provided by Okamoto et. al. [Table 3 in 6] that list the average Talairach coordinates of the cortical projection points of the 19 channels of the 10-20 system based on the measurements performed on 17 healthy subjects. The program first loads the coordinates of the 19 channels in HS of a particular subject that were previous measured and stored (see section 2.1). We now have two sets of the coordinates of the 19 channel locations: a set in Talairach and a set in HS. The operator is prompted to enter a set of Talairach coordinates that represents a particular point of interest on the cortical surface. The program then calculates the distance between this point to each of the 19 channels (in Talairach) and selects the three nearest channels to this point. For example, in Fig. 2(a), if the point of interest is P, then the three nearest channels will be Fp1, F3, and Fz. If we use **T** to represent a 3x3 transformation matrix that transforms the coordinates of Fp1, F3 and Fz from the Talairach system to HS:

$$AT = B \,. \tag{2}$$

where A and B are both a 3x3 matrix representing the coordinates of these three channels in Talairach and in HS, respectively, then T can generally be uniquely solved from the above matrix equation. This T is then used to transform the coordinates of P in Talairach to the coordinates in HS. Notice that, for the three points Fp1, F3, Fz, this T produces perfect transformation from Talairach to HS. Since P is nearest to these three points, such a 'local' T should provide an optimal mapping.

2.3 A Portable Continuous-Wave fNIR System

An fNIR system manufactured by Archinoetics (Honolulu, Hawaii) was used in this study to test the utility of the above sensor positioning system. The fNIR system uses an optical probe consisting of a photo-emitter and two photo-sensors. The miniature emitter and sensors are each installed on a slender, spring-loaded leg which can easily penetrate the subject's hair to reach the scalp surface. The system operates at three wavelengths (760, 810, and 850 nm) and provides relative changes in blood oxygenation.

3 Preliminary Test Results with the System

3.1 Repeatability of the System for Position Measurement

To test the practical repeatability of the sensor positioning system, we marked three sites on one subject's scalp near C_z, F_3 and F_4, and repeated five times the entire procedure of position measurement; that includes attachment of the three reference receivers to the subject's head, establishment of the three coordinate systems, and measurement of the positions of the three sites. During the measurements, the head of subject was free to move. The standard deviation of the measurement at each site is 0.85 mm, 1.09mm, and 1.05 mm, respectively.

3.2 Hemodynamic Response to Three Mental Tasks Measured Near F_7

It has been reported that the frontal cortex corresponding to Brodmann area 45 is often activated in response to an N-back working memory task [4]. In this experiment, we place the optical sensor near channel F_7 and let the subject to perform three kinds of cognitive tasks: silent number counting, a verbal N-back task in which a series of letters are used as the stimuli, and a spatial N-back task that used a set of four squares to form different spatial patterns. Fig. 3 shows an example of the relative change in oxygenation in a test where the three tasks were performed in the following sequence: number counting, spatial 3-back task, and verbal 3-back task. It is evident that, during each cognitive task, the blood oxygenation increases.

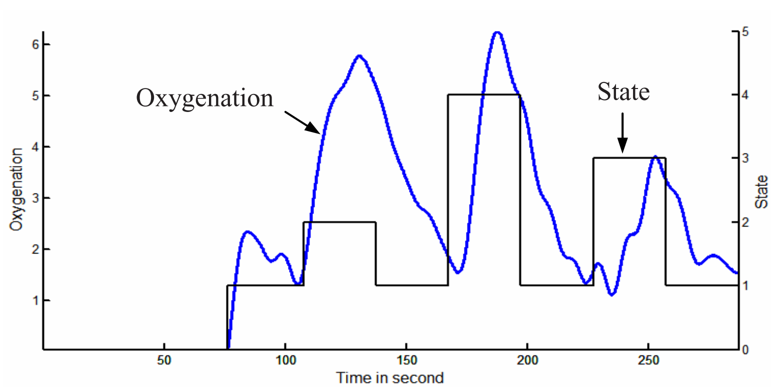


Fig. 3. Relative oxygenation level measured at a location near F_7. State indicator: 1. – relaxed, 2 – silent counting, 3 – verbal 3-back task, 4 – spatial 3-back task.

3.3 Topographic Map of Hemodynamic Response to a Mental Task

In this study, the locations of the standard 19 channels of a subject were first measured, and a dense grid of 217 points was generated. The fNIR sensor was systematically moved to each of the points located in the front half of the head to record the relative change in tissue oxygenation during a verbal 3-back task and a spatial 3-back task. For each task, a color-coded topographic map was derived that showed the level of activation (increase in oxygenation, red color) and deactivation (decrease in oxygenation, blue color) over the front half of the scalp. The results of the verbal task are presented in Fig. 3(a) and the results of the spatial task are presented in Fig. 3(b). Both figures show that the strongest activation takes place near F_7 and F_8.

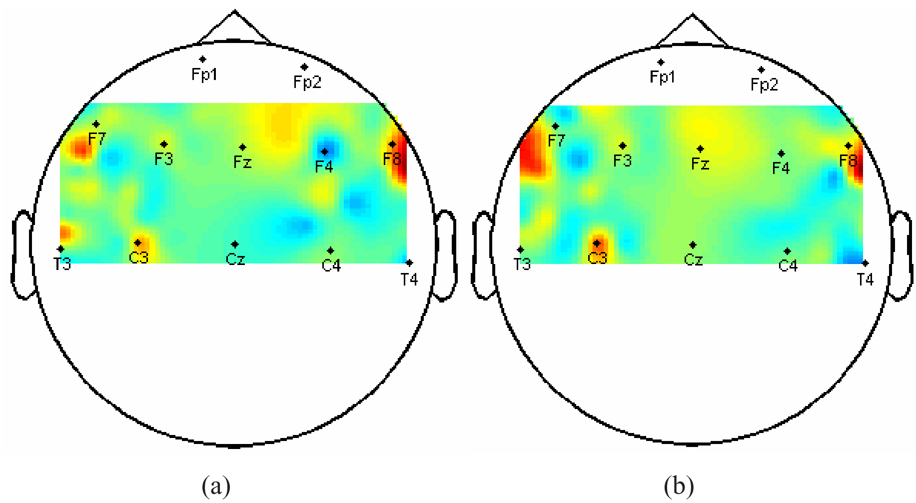


Fig. 4. (a) Topographic map of hemodynamic response in verbal 3-back test. (b) Topographic map of hemodynamic response in spatial 3-back test.

4 Conclusion and Discussion

Our preliminary experiences indicate that the above sensor positioning system can precisely and reliably determine the 3D position of a site on the scalp. By displaying a background head model with either standard 19 channel locations or a dense grid of expanded channel locations, the sensor position can be conveniently described with reference to the standard 10-20 system. This system could be used for sensor re-positioning in repeated experiments with multiple subjects.

The transformation from the Talairach coordinates to the coordinates in the head system allows for correlating the source location in the fNIR study on a particular subject with that reported in the fMRI literature. The numerical values used for deriving the transformation matrix in this study are solely based on the data provided by Okamoto et. al. [Table 3 in 6], which have not been corroborated by other studies.

Due to the variation in the coordinates reported in the fMIR literature, the result of transformation may also show some degree of variation. For example, Okamoto et al. gave Talairach xyz coordinates (in mm) of the cortical projection point of Fp1 as (21.3, 68.0, -3.0). But in Table II of [4], three different sets of Talairach coordinates are given for the region of the frontal pole (Brodmann area 10 corresponding to Fp1): (-36, 44, 20), (-38, 44, 20), and (-32, 42, 10). If one enters these three sets of coordinates, our program will produce three points that are all closer to F_3 than to Fp1. We are currently investigating the source and scope of this discrepancy. We also plan to conduct more experiments with several subjects to fully test the capability and limitations of the system.

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