A Study on the Improvement of Measurement Accuracy of the Three-dimensional Electromagnetic Articulography

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Abstract

The alignment of the transmitter coils for the three-dimensional electromagnetic articulography (3D-EMA), an instrument used to measure articulatory movements, was studied. The receiver coils of the 3D-EMA are used as position markers and are placed in an alternating magnetic field produced by multiple transmitter coils. The estimation of state (the position and orientation) of each receiver coil is based on the minimization of signal error between the measured and predicted receiver signals using a model of the magnetic field. Previous studies report a noticeable increase in the position estimation error at a specific portion of the measurement region irrespective of small signal error values. The existence of non-uniqueness in the position estimation problem is hypothesized to be the cause of this problem. To resolve the problem, we optimized the alignment of the transmitter coils by maximizing the difference between the receiver signals at any two states in the measurement region and evaluated the alignment using a computer simulation and an experiment. As a result, a measurement accuracy of approximately 0.4 mm was obtained.

Index Terms: three-dimensional electromagnetic articulography, alignment of transmitter coils, position estimation

1. Introduction

Observing the movements of the articulatory organs is important for estimating articulatory states and understanding the underlying mechanisms engaged in during speech production. Various observation techniques used to measure the articulatory organs have been studied such as magnetic resonance imaging (MRI) \cite{1} and X-rays \cite{2}. However, it is difficult for these techniques to record the movement of articulatory organs during continuous speech because in MRI the frame rate is not high enough and radiation exposure cannot be avoided when using X-rays. Conversely, electromagnetic articulography (EMA) has sufficiently high temporal resolution for observing dynamic articulatory behavior without being overly invasive \cite{3}. The principles of two-dimensional electromagnetic articulography have been studied by Schöle \textit{et al.} \cite{4}, and Perkell \textit{et al.} \cite{5}. The system estimates the position of the receiver coils on a measurement plane using three transmitter coils. Three-dimensional electromagnetic articulography (3D-EMA) extends the measurement region from the sagittal plane to three-dimensional space using six transmitter coils \cite{6,7}. In some recent studies, an application to control the articulatory movement model \cite{8} and a speech training method \cite{9} using the observed data from the 3D-EMA system was investigated.

The electromagnetic articulography consists of transmitter coils that generate the magnetic field, and receiver coils that act as position markers placed on the articulatory organs. At the receiver coil, the receiver signal is induced by the magnetic field, and the position of the receiver coil can then be estimated from the signal. The system estimates the position and orientation of the receiver coils by minimizing the signal error between the measured and predicted receiver signals. Here, the predicted signal is calculated using a model of the magnetic field, and the position and orientation of the receiver coils.

Hoole \textit{et al.} \cite{11} reported that the existence of the receiver position whose estimation error had noticeable increased though the signal error is small. Stella \textit{et al.} \cite{12} investigated the position estimation error after eliminating any hardware or electromagnetic source of disturbance, and clarified that a noticeable increase in the error had occurred in certain regions. It was concluded that the cause of the error is not due to any physical problem but a wrong convergence of the calculation method for the position estimation in the study. However, we think the cause is also due to a combination of magnetic field distribution and receiver position, because the error had occurred in certain regions repeatedly. The combination leads to the situation that the receiver signals from receiver coils at different positions are the same. In this situation, the state of the receiver coil cannot be uniquely determined from the measured receiver signal. In this paper, we call this problem the non-uniqueness problem. To resolve the issue, we will define the problem’s criterion as the difference between receiver signals at any two states in the measurement region. We will optimize the alignment of the transmitter coils using the criterion, and evaluate the measurement accuracy of this alignment using the computer simulation and an experiment.

In this study, we first describe the measurement principles of three-dimensional electromagnetic articulography. Then, we discuss the optimization of the alignment of the transmitter coils. Finally, we investigate the measurement accuracy using the receiver signals for the optimal alignment of the transmitter coils.

2. Three dimensional electromagnetic articulography

2.1. Outline of the three-dimensional electromagnetic articulography and the coordinate system

The three-dimensional electromagnetic articulography (3D-EMA) consists of six transmitter coils and several receiver coils as position markers. The transmitter coils are placed on the surrounding of the measurement region and generate alternating magnetic fields at different frequencies from each other. The receiver signals from the receiver coils are induced by the mag-
The alignment of the transmitter coils and the coordinate system of 3D-EMA

The magnetic field at the various receiver positions.

The alignment of the transmitter coils and the coordinate system of 3D-EMA is defined as shown in Fig. 1. The axes of the transmitter coils are parallel to $x_1$, $x_2$, and $x_3$ for $S_1$, $S_3$, and $S_5$, respectively; for $S_2$, $S_4$, and $S_6$, however, the axes are parallel to the lines $S_2S_6$, $S_4S_2$, and $S_6S_1$, respectively, in the same way as the AG500 system (Carstens, Germany). The state of the receiver coil is represented as

$$s = (x_1, x_2, x_3, \theta_1, \theta_2),$$

where $(x_1, x_2, x_3)$ and $(\theta_1, \theta_2)$ denote the positions of the coordinate system and the rotational angles with respect to the axes $x_2$ and $x_3$, respectively.

### 2.2. The modeling of the magnetic field

The accuracy of the magnetic field model directly influences the position estimation accuracy. In this study, we regard the transmitter coils as magnetic dipoles and use a magnetic field model based on Coulomb’s law. We denote the positions of both poles of the transmitter coil $S_i$ as $x_p$ and $x_n$, and define these poles, $x_p$ and $x_n$, as having electrical charge $+q$ and $-q$ respectively. The magnetic field created by the transmitter coil at an arbitrary position $x$ is represented as

$$y(x) = \frac{q}{4\pi\mu_0} \left( \frac{r_p(x)}{|r_p(x)|^3} - \frac{r_n(x)}{|r_n(x)|^3} \right),$$

where $r_p(x) = x - x_p$, $r_n(x) = x - x_n$, and $\mu_0$ is the magnetic permeability of air. Denote that $g = \frac{\pi}{\mu_0} \Delta r(x)$ and $\Delta r(x) = |r_p(x)|^3 - |r_n(x)|^3$; Eq. (2) can be rewritten using gain and position variables as

$$y(x) = g \Delta r(x).$$

When we use the vector that represents the orientation of the receiver coil, $e(\theta_1, \theta_2)$, the predicted receiver signal $\hat{z}(s)$ at state $s$ is calculated as

$$\hat{z}(s) = Lg(y(x))e(\theta_1, \theta_2),$$

where $L$ is a gain constant that relates to the properties of each transmitter coil and receiver coil, and $\bullet$ is the dot product. We substitute Eq. (3) into Eq. (4), and rewrite $Lg$ to $g$. Then, we can represent $\hat{z}(s)$ as

$$\hat{z}(s) = g\Delta r(x)e(\theta_1, \theta_2).$$

From this equation, we know that if the gain parameter is known, then a predicted receiver signal $\hat{z}(s)$ can be calculated.

### 2.3. Determination of the gain parameter

The gain parameter, $g$, is determined by calibration data that produces receiver signals at $m$ calibration points $s_i (i = 1, 2, \ldots, m)$. We define the residual calibration error as the difference between the measured and predicted receiver signals for all the calibration points:

$$E_g = \sum_{i=1}^{m} (z_i - \hat{z}(s_i))^2.$$

The gain parameter $g$ is determined by minimizing this residual error, $E_g$.

### 2.4. Position estimation method

The position and orientation of each receiver coil is determined by minimizing the difference between the measured and the predicted signals. Here we defined the difference between the measured and predicted receiver signals for all of the transmitter coils’ receiver signal components as $E_s$:

$$E_s = \sum_{l=1}^{6} (z_l - \hat{z}(s_l))^2,$$

where $l$ is the index of the transmitter coil. The estimation result for the state of the receiver coil is determined by minimizing $E_s$. Since the relationship between $z_l$ and $s$ is non-linear, we employ the Gauss-Newton method to find the optimal state of the receiver coil.

### 3. Optimization method for the alignment of transmitter coils

The non-uniqueness problem indicates that the position and orientation of the receiver coil cannot be determined uniquely from the measured receiver signal, resulting in a large measurement error. The non-uniqueness problem takes place when $z_l(s_1) \approx z_l(s_2)$ for all transmitter coils and, at the same time, the position $s_1$ is different from $s_2$. This irregular situation may occur because of an ineffective spatial magnetic field pattern, and therefore we search for the optimal alignment of the transmitter coils. For the optimization, we define the following criterion to express the minimum signal difference between two points in the measurement region:

$$C(\varphi) = \min_{i,j=1,2,\ldots,N} \left\{ \frac{1}{6} \sum_{l=1}^{6} (z_l(s_i) - \hat{z}_l(s_j))^2 \right\} \left\{ \frac{1}{6} \sum_{l=1}^{6} (z_l(s_i) - \hat{z}_l(s_j))^2 \right\},$$

where $l$ is the index of the transmitter coil, and $i$ and $j$ are the index of sampling points. Here $N$ is the number of samples and $\varphi$ is the transmitter coils’ angle, $\{\varphi_1, \varphi_2\}(l = 1, 2, \ldots, 6)$. If $C(\varphi)$ takes a small value, it indicates that there are different sampling points for which the receiver signals are almost the
4. Experiment

4.1. Optimal alignment of transmitter coils

In this study, we defined the measurement region as a rectangular parallelepiped with a size of $80 \times 80 \times 80$ mm as shown in Fig. 2(a). The range of the region was set as the most important articulatory movements of the tongue were included. We assumed that the range of the orientation of a receiver coil was $-30^\circ \leq \theta_1 \leq 30^\circ, -30^\circ \leq \theta_2 \leq 30^\circ$. The range was decided as the movable range for the orientation of the receiver coil when the receiver coil was placed on the tongue as illustrated in Fig. 2(b). We optimized the transmitter coils' angles, $\phi$, by maximizing the criterion for the region.

We used a GA (genetic algorithm) based on combinational methods to optimize the transmitter coils’ angles. First, we prepared for the update angle candidate, $\phi'$, which added a normal random vector to the current transmitter coils’ angle, $\phi$:

$$\phi' = \phi + N(0, \sigma^2),$$  \hspace{1cm} (9)

where $N(0, \sigma^2)$ is a normal random vector with 0 mean and variance $\sigma^2$. Then, we calculated $C(\phi')$ and $C(\phi)$ using Eq. (8). If $C(\phi')$ was larger than $C(\phi)$, the transmitter coil’s angle $\phi$ was updated to $\phi'$. After the update, the variance $\sigma^2$ was increased and a new candidate for the updated angle was prepared. However, if $C(\phi')$ was not larger than $C(\phi)$, then the transmitter coil’s angle was not updated, and the preparation of a new candidate was repeated. When an update did not happen five times consecutively, the variance $\sigma^2$ was decreased. Repeating this procedure until convergence, the optimal angle of transmitter coils, $\phi$ could be found.

The set of sample states, $S = \{s_i(x_1, x_2, x_3, \theta_1, \theta_2) | i = 1, 2, \ldots, N\}$, is defined by the combination variables, $x_{1,2,3} = \{0, \pm 10, \pm 20, \pm 30, \pm 40, \pm 50\}$, and $\theta_{1,2} = \{0, \pm 5, \pm 10, \pm 15, \pm 20, \pm 25, \pm 30, \pm 35\}$ for the calculation of $C(\phi)$. The range of each variable was extended outside of the measurement region by 10 mm, and $5^\circ$, respectively.

As a result of the optimization, we obtained the optimal transmitter coils’ angle $\phi_{\text{opt}}$, whose $C(\phi_{\text{opt}})$ was 2.11. It exceeded twice the value of the criterion before optimization. When the transmitter coils’ angle was set to the original angle, $C(\phi_{\text{org}})$ was 0.79. From this result, we expect that the non-uniqueness problem hardly occurs using the optimal transmitter coils’ angle. We show the criterion, $C(\phi)$, and transmitter coils’ angle before and after optimization in Table 1. In this table, we know that almost transmitter coils’ angle had a lot of difference, but the $S_2$ angle had no difference.

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<th>Angle difference</th>
<th>Position error (mm)</th>
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4.2. Simulation experiment

We estimated the position and orientation of each receiver coil using a computer simulation before and after optimization of the transmitter coils’ angle. In the simulation, a pseudo receiver signal was used instead of the measured receiver signal. The pseudo receiver signal was calculated by adding white Gaussian noise with the variance of the actual measurement noise to the predicted receiver signal calculated using the magnetic field model. The pseudo receiver signals are calculated for the sample states of the receiver coil, and the states for the simulation were used by combining $x_{1,2,3} = \{0, \pm 10, \pm 20, \pm 30, \pm 40\}$ and $\theta_{1,2} = \{0, \pm 5, \pm 10, \pm 15, \pm 20, \pm 25, \pm 30\}$, 5103 points in total.

Figures 3 and 4 show the estimation result for before and after the optimization of transmitter coils’ angle and Fig. 5 shows the extended neighborhood origin of Fig. 4. In these figures, the position errors are plotted as a function of residual signal error for all sample states, where the position error means the distance between the estimated and correct positions and the signal error was used instead of the measured receiver signal. The pseudo receiver signal was used instead of the measured receiver signal. The pseudo receiver signals were calculated using the magnetic field model. The pseudo receiver signals are calculated for the sample states of the receiver coil, and the states for the simulation were used by combining $x_{1,2,3} = \{0, \pm 10, \pm 20, \pm 30, \pm 40\}$ and $\theta_{1,2} = \{0, \pm 5, \pm 10, \pm 15, \pm 20, \pm 25, \pm 30\}$, 5103 points in total.

4.3. Experiment

Since the simulation results show the efficiency of the optimization of the transmitter coils’ angle, we changed the transmitter
coils’ angle of the system from the original angle, $\varphi_{\text{org}}$, to the optimal angle, $\varphi_{\text{opt}}$, and estimated the real receiver coil position. The receiver signals were measured at the grid points of the measurement region. The grid points are the combination of $x_{1,2,3} = \{-40, 0, +40\}$. We measured receiver signals for 10 orientations of the receiver coil. The range of orientations was $-30^\circ \leq \theta_1 \leq 30^\circ, -30^\circ \leq \theta_2 \leq 30^\circ$. The data set whose receiver coil orientation was almost equal to $(\theta_1 = 0^\circ, \theta_2 = 0^\circ)$ by sight was used to calibrate the gain parameters. We estimated the position for all of the receiver signal data, with a total number of estimated points of 270.

Figure 6 shows the position estimation error as a function of the signal residual error. In this figure, we can see that if the signal error is small, the position error is also small and the position error is not larger than 2.5 mm. It is clear that the estimation error caused by the non-uniqueness problem is resolved.

Figure 7 demonstrated the position error as a function of the receiver coil angle. The receiver coil angle is the angular difference from $x_1$ axis. The dots represent the average position error for the same orientation. Figure 7 shows that the estimation accuracy tends to deteriorate when the angular difference increases. The average position error of all estimated samples is 0.40 mm. That of the estimated sample whose angular difference from $x_1$ axis is smaller than $20^\circ$ is 0.37 mm. From this result, it is clear that we can estimate the receiver positions more accurately if we place the receiver coils at the articulatory organs with their orientation equal to the orientation when we gathered the calibration data.

5. Conclusions

In this study, we optimized the alignment of transmitter coils by maximizing the criterion $C(\varphi)$, defined as the difference between receiver signals at any two different points in a measurement region using a genetic algorithm to resolve the non-uniqueness problem. The result of the optimization shows that the criterion $C(\varphi)$ becomes more than twice as large before optimization. This result means that the non-uniqueness problem hardly occurs using this alignment $\varphi_{\text{opt}}$.

The computer simulation results indicated that the non-uniqueness problem can be resolved by optimizing the transmitter coils’ angles based on the criterion $C(\varphi)$. Taking these results, we changed the transmitter coils’ angles in the real system from the original $\varphi_{\text{org}}$ to the optimal $\varphi_{\text{opt}}$, and estimated the receiver coil positions. The results show that the non-uniqueness problem can be resolved and that the estimation accuracy tends to deteriorate when the receiver coil angles increase. The average position error of all estimated samples and the estimated samples whose receiver coil angles were smaller than $20^\circ$ were 0.40 mm and 0.37 mm, respectively. For future work, we will consider the combination of the number of transmitter coils, transmitter coil positions, and transmitter coils’ angles.

6. Acknowledgement

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7. References


