Electromagnetic articulograph based on a nonparametric representation of the magnetic field

Tokihiro Kaburagi
Department of Acoustic Design, Kyushu Institute of Design, 4-9-1, Shiobaru, Minami-ku, Fukuoka 815-8540, Japan and CREST, Japan Science and Technology Corporation, Japan

Masaaki Honda
Human and Information Science Laboratory, NTT Communication Science Laboratories, 3-1, Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan and CREST, Japan Science and Technology Corporation, Japan

(Received 20 August 2001; accepted for publication 27 November 2001)

Electromagnetic articulograph (EMA) devices are capable of measuring movements of the articulatory organs inside and outside the vocal tract with fine spatial and temporal resolutions, thus providing useful articulatory data for investigating the speech production process. The position of the receiver coil is detected in the EMA device on the basis of a field function representing the spatial pattern of the magnetic field in relation to the relative positions of the transmitter and receiver coils. Therefore, the design and calibration of the field function are quite important and influence the accuracy of position detection. This paper presents a nonparametric method for representing the magnetic field, and also describes a method for determining the receiver position from the strength of the induced signal in the receiver coil. The field pattern in this method is expressed by using a multivariate spline as a function of the position in the device’s coordinate system. Because of the piecewise property of the basis functions and the freedom in the selection of the rank and the number of the basis functions, the spline function has a superior ability to flexibly and accurately represent the field pattern, even when it suffers from fluctuations caused by the interference between the transmitting channels. The position of the receiver coil is determined by minimizing the difference between the measured strength of the received signal and the predicted one from the spline representation of the magnetic field. Experimental results show that the error in estimating the receiver position is less than 0.1 mm for a 14×14-cm measurement area, and this error can be further reduced by using a spline-smoothing technique. © 2002 Acoustical Society of America. [DOI: 10.1121/1.1445785]

PACS numbers: 43.70.Aj, 43.70.Jt [AL]

I. INTRODUCTION

By observing the dynamically changing behavior of the speech articulators, we can deepen our understanding of the motor process in the production of speech utterances. Electromagnetic articulograph (EMA) devices have been studied as tools for providing useful information about the position and movement of fixed points inside and outside the vocal tract with a high degree of spatial and temporal resolution (Hixon, 1971; Sonoda, 1974; Schönle et al., 1987; Schönle et al., 1989; Tuller et al., 1990; Perkell et al., 1992; Kaburagi and Honda, 1994). Because the EMA device uses static or alternating magnetic fields, it is much less invasive than x-ray techniques (Fujimura et al., 1973; Kiritani et al., 1975) to obtain a large amount of articulatory data. Although the problem of invasiveness to the subject can be completely avoided with ultrasonic imaging techniques (Morris et al., 1984; Shawker et al., 1985; Stone et al., 1988; Stone, 1990; Stone and Lundberg, 1996), such techniques are limited by their relatively slow frame rate. The EMA device is also effective for studying dynamic models of articulatory movements (Kaburagi and Honda, 2001), articulatory-based speech synthesis (Kaburagi and Honda, 1998), and acoustic-to-articulatory inversion problems (Suzuki et al., 1998).

The two-dimensional EMA device with alternating magnetic fields (Schönle et al., 1987) uses three transmitter coils driven by currents of different frequencies. It simultaneously measures the electromagnetically induced currents in multiple receiver coils attached to the articulators and detects their positions in the midsagittal measurement plane. To obtain spatial information from the received signal, the spatial pattern of the magnetic field is represented as a voltage-to-distance function (VDF) incorporating the distance of a given receiver from any one of the three transmitter coils. Schönle et al. (1987) proposed a VDF in which the received signal was inversely proportional to the transmitter–receiver distance cubed. The position of the receiver coil is then determined as the crossing point of three circles, the center and radius of each given by the transmitter position and corresponding transmitter–receiver distance estimated using the VDF from the received signal.

On the other hand, Perkell et al. (1992) expressed the exponent part of the VDF as a polynomial function of the transmitter–receiver distance, and also described the importance of calibrating the VDF parameters in the local region in which the receiver coil would be located during the experiment. It has been recognized that the parameter calibration is of importance as well as the field representation problem
(Gracco and Nye, 1993; Hoole, 1993), and Kaburagi and Honda (1997) extended the idea of the local calibration to propose an adaptive method of the parameter calibration. This method was performed by selecting calibration data samples neighboring the receiver position during the experiment, which was a priori unknown, resulting in a higher measurement accuracy.

The effectiveness of local and adaptive calibration methods indicates that the global pattern of the actual magnetic field deviates from the theoretical field based on the assumption that a transmitter coil functions as a dipole source, and hence a VDF with fixed parameters only holds for a restricted region. A possible source of this pattern deviation is interference among the transmitting channels of the EMA device, which would affect the strength of the magnetic fields with each other. For example, the transmitter coils could be mutually inductive. Then, for any given transmitter coil, currents would be induced by neighboring transmitters so that the resulting reproduction of magnetic field attenuates the surrounding fields of the corresponding frequencies.

In this paper, we present a novel approach for representing the spatial pattern of the magnetic field and describe how the receiver position can be calculated using the proposed field function. Instead of using the voltage-to-distance function, the field pattern in our method is expressed by multivariate B-spline functions (Schumaker, 1981; Dierckx, 1993), which can depict a smooth curved surface as a linear combination of piecewise basis functions. The position and orientation of the receiver coil is then determined by minimizing the difference between the measured and predicted signal strengths.

The spline function has the following advantageous characteristics when used to represent the magnetic field. First, each basis function is defined locally and there are freedoms in the selection of the rank and the number of the basis functions. These flexibilities allow the spline function to accurately represent the desired curved surface. Second, the field pattern is expressed as a function of the x and y axes of the device, whereas the VDF only takes the transmittance–receiver distance into account. Therefore, our method explicitly accommodates the field function to the actual magnetic field even when it has location-dependent fluctuations. Third, the spline function provides a closed-form representation of the entire field pattern. Therefore, the proposed method circumvents the computationally inefficient pattern matching used in the adaptive calibration method to discover the local calibration data (Kaburagi and Honda, 1997). In calculating the receiver position, the optimal values of three unknown parameters, i.e., the positional variables x and y and the orientation θ, are simultaneously determined so that the prediction error with respect to the receiver signal is minimized. This problem becomes nonlinear, because the basis functions of the splines are piecewise polynomial functions. Therefore, a procedure based on the Gauss–Newton method is used to solve the nonlinear optimization problem.

This paper is organized as follows. Section II explains the spline-based representation of the magnetic field, and Sec. III presents the method for estimating the receiver position from the strength of the induced signal. Experimental results are then presented in Sec. IV to show the accuracy of the proposed method in representing the magnetic field and estimating the receiver position. The effect of smoothing the calibration data samples is also considered. Finally, Sec. V summarizes this work and gives our conclusions.

II. MAGNETIC FIELD REPRESENTATION

This section explains the coordinate system and measurement area of the EMA device, and presents the method for representing the spatial pattern of the magnetic field using the multivariate spline functions. Then, it describes the calibration method to determine the values of weighing parameters included in the spline function. The explanations of the spline function given in this section are based on Schumaker (1981) and Dierckx (1993).

A. Hardware system

Figure 1 illustrates the two-dimensional EMA device used in this study (Carstens Articulograph AG100, Germany), which has three transmitter coils positioned at vertices $T_1$, $T_2$, and $T_3$ of a regular triangle with side lengths of 64.18 cm. They are driven at carrier frequencies of 12, 12.5, and 13 kHz, respectively, and generate alternating magnetic fields. The measurement area of articulatory movements is expressed as the induced signal. The number of the data samples for each side of the rectangular is denoted as $N$. The measurement area specified for the observation of the articulatory organs. Calibration and test data samples are taken by using the receiver coil placed at known positions, i.e., the crossing points of the grid drawn to cover the entire measurement area, and by measuring the strength of the induced signal. The number of the data samples for each side of the rectangular is denoted as $N$. The measurement area specified for the observation of the articulatory organs. Calibration and test data samples are taken by using the receiver coil placed at known positions, i.e., the crossing points of the grid drawn to cover the entire measurement area, and by measuring the strength of the induced signal. The number of the data samples for each side of the rectangular is denoted as $N$. The measurement area specified for the observation of the articulatory organs. Calibration and test data samples are taken by using the receiver coil placed at known positions, i.e., the crossing points of the grid drawn to cover the entire measurement area, and by measuring the strength of the induced signal. The number of the data samples for each side of the rectangular is denoted as $N$. The measurement area specified for the observation of the articulatory organs. Calibration and test data samples are taken by using the receiver coil placed at known positions, i.e., the crossing points of the grid drawn to cover the entire measurement area, and by measuring the strength of the induced signal. The number of the data samples for each side of the rectangular is denoted as $N$.
fixed to the transmitter coils. Note that the axes of the transmitter coils are parallel to one another and perpendicular to the measurement plane.

B. Spline-based representation of the magnetic field

The strength of the electromagnetically induced signal in the receiver coil can be expressed as \( e_i = u_i(x, y) \cos \theta \), where \( u_i(x, y) \) is the field function representing the strength of the magnetic field, and \( \theta \) is the tilt angle of the receiver coil relative to the magnetic flux, identical for every transmitter channel. The induced signal is then reduced by a factor of \( \cos \theta \). An index to the transmitters is represented as \( l \).

We express the logarithm of the field function \( u(x, y) \) using a multivariate B-spline function such that

\[
\log\{u(x, y)\} = \sum_{p=1}^{P} \sum_{q=1}^{Q} c_{pq} N_p(x) N_q(y),
\]

where \( N_p(x) \) and \( N_q(y) \), respectively, represent piecewise polynomial functions, the basis functions of the spline representation, with respect to the \( x \)- and \( y \)-axes. The rank of these basis functions is assumed to be \( m \). \( P \) and \( Q \) indicate the number of basis functions to represent the entire field pattern, and \( c_{pq} \) denotes the weighting parameter in summing combinations of the basis functions.

Equation (1) forms a curved surface over the \( x-y \) plane as the tensor product of the basis functions. For given data samples \( u_{ij} = u(x_i, y_j) \) \( (i = 1, 2, ..., N; j = 1, 2, ..., M) \), the weighting parameters \( c_{pq} \) can be determined so that the curved surface interpolates these samples. Another possible selection of the weighting parameters is the spline smoothing in which the curved surface is made to approximate the data samples by minimizing an error criterion. The basis function takes zero outside a certain interval along the axis. By virtue of this piecewise property, the spline function generally provides a good result when used for interpolating or smoothing given data samples and reproducing the overall shape of a curved surface. In addition, the smoothness of the surface can be controlled by parameter \( m \), which determines the polynomial order of the basis function. From these properties, the spline function is applicable for a fine representation of the magnetic field.

C. Construction of the basis functions

By setting the number and the positions of the internal nodes, the basis functions \( N_p(x) \) and \( N_q(y) \) are uniquely determined regardless of the data samples to be interpolated or smoothed. Internal nodes of the two-variate spline function [Eq. (1)] can be arranged in a rectangular region \( R = [a, b] \times [c, d] \) as follows:

\[
a = \xi_{1-m} = \cdots = \xi_1 = \xi_0 < \xi_1 < \cdots < \xi_p < \cdots < \xi_{p-m+1} = b,
\]

and

\[
c = \xi_{1-m} = \cdots = \xi_1 = \xi_0 < \xi_1 < \cdots < \xi_q < \cdots < \xi_{q-m+1} = d,
\]

where \( \xi_p \) and \( \xi_q \) represent the positions of the nodes along the \( x \)- and \( y \)-axes, respectively. Note that \( m \) nodes overlap on both sides, and the number of nonoverlapping nodes \( n \) equals \( P - m \) and \( Q - m \).

Then, the B-spline basis function can be constructed from the positions of successive \( m+1 \) nodes as

\[
N_p(x) = (\xi_p - \xi_{p-m}) M_p(x; \xi_{p-m} \cdots \xi_p),
\]

and

\[
N_q(y) = (\xi_q - \xi_{q-m}) M_q(y; \xi_{q-m} \cdots \xi_q)
\]

for \( 1 \leq p \leq P \) and \( 1 \leq q \leq Q \), where \( M_p(x; \xi_{p-m} \cdots \xi_p) \) and \( M_q(y; \xi_{q-m} \cdots \xi_q) \) are divided difference of truncated power function \( M(x; z) = (x-z)^{p-1} + 1 \) with respect to \( z = \xi_{p-m} \cdots \xi_p \) and \( z = \xi_{q-m} \cdots \xi_q \), respectively. These basis functions have the following piecewise properties:

\[
N_p(x) = \begin{cases} 1, & \xi_{p-m} < x < \xi_p, \\ 0, & \text{otherwise}, \end{cases}
\]

and

\[
N_q(y) = \begin{cases} 1, & \xi_{q-m} < y < \xi_q, \\ 0, & \text{otherwise}, \end{cases}
\]

indicating that the basis functions take a nonzero value only for a limited interval along the axis. The values of these basis functions can be effectively evaluated for a specific value of \( x \) or \( y \) using de Boor’s iterative algorithm (de Boor, 1972). Figure 2 illustrates examples of the B-spline basis functions \( N_p(x) \), where the rank is set at three and internal nodes are placed at 0.0, 0.25, 0.5, 0.75, and 1.0 along the \( x \) axis. Three nodes are overlapped on both sides at 0.0 and 1.0, and the number of nonoverlapping nodes is three. Six basis functions are constructed from this node assignment.

D. Determination of the weighting parameters

The weighting parameters in Eq. (1) can be determined so that the spline function forms a curved surface interpolat-
ing or smoothing a given set of calibration data samples. The field strength in a given location is obtained by positioning a receiver coil parallel to the magnetic field and then measuring the induced signal. For the purpose of obtaining a spline representation of the magnetic field, the calibration data are measured at the points of intersection of lines drawn at equal intervals in the horizontal and vertical directions, as shown in Fig. 1. Every calibration datum stores the measured field strength \( v_{ij} \) sampled at the position \( (x_i, y_j) \) for \( 1 \leq i \leq N \) and \( 1 \leq j \leq N \), where \( N \) gives the number of samples in each axis.

The equations specifying the spline interpolation condition can be derived by substituting the calibration data samples into Eq. (1) as

\[
\log v_{ij} = \sum_{p=1}^{P} \sum_{q=1}^{Q} c_{pq} N_p(x_i) N_q(y_j). \tag{2}
\]

The values of the unknown parameters \( c_{pq} \) are calculated by solving these \( N \times N \) linear equations simultaneously. \( N = m + n \) must be satisfied for the number of nodes \( n \) and the rank of the basis functions \( m \) so that the number of equations is coincident with that of the unknown parameters. On the other hand, the weights in the spline smoothing are determined under the condition \( N > m + n \) so that a criterion \( C \), the total square error between the measured and predicted field strengths, is minimized, where

\[
C = \sum_{i=1}^{N} \sum_{j=1}^{N} \left( \log v_{ij} - \sum_{p=1}^{P} \sum_{q=1}^{Q} c_{pq} N_p(x_i) N_q(y_j) \right)^2. \tag{3}
\]

If the partial derivative of \( C \) with respect to \( c_{pq} \) is set to zero, the resulting normal equation can be used to determine the optimal values of the weighting parameters.

The procedure for forming the spline representation can be summarized as follows. For the spatial alignment of the internal nodes, the rectangular region \( R \) is taken to coincide with the measurement area, and the node position is selected at the intersecting points of grids with equal intervals, just like the sampling points of the calibration data. The basis functions with respect to \( x \) and \( y \) axes are then constructed for given node positions under the condition \( P = Q = n + m \). Finally, as described above, weights used in summing the basis functions are calculated from the two-dimensional calibration data depending on the interpolating or smoothing condition.

### III. ESTIMATION METHOD OF THE RECEIVER POSITION

#### A. An error criterion of the signal prediction

This section describes the method for estimating the position of the receiver coil. The induced signal in the receiver coil is first separated in the frequency domain to obtain each component of the transmitting channels, which is expressed as \( e_j \), for \( j = 1, 2, \) and \( 3 \) below. On the other hand, the strength of the induced signal can be predicted as a function of the three unknown variables, positional variables \( x \) and \( y \) and the tilt angle \( \theta \), as

\[
\hat{e}_i(x, y, \theta) = v(x, y) \cos \theta, \tag{4}
\]

where the logarithm of the field strength is represented by the spline function as described in the previous section [Eq. (1)].

Therefore, the values of these variables can be determined so that the difference between the measured and predicted signal strengths is minimized. The criterion expressing the prediction error of the induced signal is defined as

\[
S(x, y, \theta) = \sum_{j=1}^{3} \left( \log e_j - \log \hat{e}_j \right)^2. \tag{5}
\]

This optimization problem becomes nonlinear since the magnetic field is represented by the piecewise polynomial functions, and we employ an iterative procedure based on the Gauss–Newton method (Dennis and Schnabel, 1983). The position of the receiver coil is estimated as the solution to this problem.

#### B. Derivation of the optimal solution

The values of the unknown parameters are incrementally optimized based on the Gauss–Newton method so that the prediction error \( S \) is minimized. This iterative step can be written as

\[
x^{k+1} = x^k + \alpha \Delta x^k, \tag{6}
\]

where vectors \( x \) and \( \Delta x \), respectively, represent the unknown parameters and their updating values

\[
x = (x, y, \theta)^t, \tag{7}
\]

and

\[
\Delta x = (\Delta x, \Delta y, \Delta \theta)^t. \tag{8}
\]

Here, \( \alpha \) is a reduction parameter \( (0 < \alpha \leq 1) \), \( k \) indicates the index of iterations, and \( t \) denotes the transposition. The values of the updating vector \( \Delta x \) can be determined by solving the normal equation

\[
A^t A \Delta x = A^t (e - \hat{e}), \tag{9}
\]

where \( A \) is the Jacobian matrix representing the sensitivity of the unknown parameters over the predicted signals

\[
A = \begin{pmatrix}
\frac{\partial \log \hat{e}_1}{\partial x} & \frac{\partial \log \hat{e}_1}{\partial y} & \frac{\partial \log \hat{e}_1}{\partial \theta} \\
\frac{\partial \log \hat{e}_2}{\partial x} & \frac{\partial \log \hat{e}_2}{\partial y} & \frac{\partial \log \hat{e}_2}{\partial \theta} \\
\frac{\partial \log \hat{e}_3}{\partial x} & \frac{\partial \log \hat{e}_3}{\partial y} & \frac{\partial \log \hat{e}_3}{\partial \theta}
\end{pmatrix}. \tag{10}
\]

Vectors \( e \) and \( \hat{e} \), respectively, represent measured and predicted logarithmic signals as

\[
e = (\log e_1, \log e_2, \log e_3)^t, \tag{11}
\]

and

\[
\hat{e} = (\log \hat{e}_1, \log \hat{e}_2, \log \hat{e}_3)^t. \tag{12}
\]

The procedure for determining the optimal values of the unknown parameters can be summarized as follows:

1. Given the measured signal \( e \) and the initial values of the unknown parameters \( x^0 \), set the counter \( k \) at zero.
2. Calculate the predicted signals \( \hat{e} \) and the value of each component of the Jacobian matrix \( A \) for \( x^k \). Then, solve the normal equation [Eq. (9)].
formed based on de Boor’s incremental algorithm.

The experimental condition specifying the rank of the basis function is denoted as \( m \). The number of internal nodes and the weights are determined so that the spline function interpolates each set of calibration data.

3. Update the values of the unknown parameters [Eq. (6)].
4. When a convergence is obtained, quit the procedure. Otherwise, set the counter as \( k = k + 1 \) and repeat from the second step.

In computing components of the Jacobian matrix, the values of the basis functions and their partial derivatives \( \partial N_p(x) / \partial x \) and \( \partial N_q(y) / \partial y \), should be evaluated for a specific value of \( x \). These calculations can be effectively performed based on de Boor’s incremental algorithm (de Boor, 1972). In our study, the reduction parameter in Eq. (6) is expressed as \( \alpha = 0.1 L \), where \( L \) is an integer ranging from 1 to 10. \( L \) is selected, at each iteration, so that the prediction error of the received signal [Eq. (5)] is minimized.

IV. EXPERIMENTAL RESULTS

This section presents the results of experiments conducted to examine the accuracy of the proposed method in representing the magnetic field and estimating the receiver position. To perform the experiments, samples of calibration and test data were measured, as shown in Fig. 1, at equally spaced lattice points in the measurement area. The sample number \( N \) of calibration data was selected in the range from 3 to 10 in eight steps. The sample number was fixed at 15 for the test data, so that the interval between adjacent sampling points was 1 cm, and three sets were measured. Note that the rotational angle of the receiver coil was set at zero both for calibration and test samples. Results are first shown for experiments in which a spline interpolation is used to represent the field pattern. Next, the effect of smoothing the calibration data samples is examined, and the convergence of the iterative procedure in predicting the receiver position is presented.

A. Accuracy for representing the magnetic field

Experimental results plotted in Fig. 3 show the error between the predicted and actual field strengths as a function of the number of basis functions used to represent the magnetic field. The rank of the basis function \( m \) was set at three, four, and five, and the weights were determined so that the spline function formed an interpolated curved surface for each set of calibration data. Because the number of calibration data \( N \) must be equivalent to that of basis functions \( P \) and \( Q \), the number of nonoverlapping nodes \( n \) was set as \( n = N - m \) for specified \( N \) and \( m \). Then, the known position of each test sample \((x_i,y_j)\) was substituted into the spline function, and the relative error between the predicted \( v_i(x_i,y_j) \) and measured \( v_{ij} \) signal strengths was evaluated as \( 100 \cdot |v(x_i,y_j) - v_{ij}|/v_j \) \(%\). The ordinate of the figure represents the mean error of three trials, where errors for 15×15 test samples were also averaged in each trial.

The figure clearly indicates that the error is less than 0.06\% when the number of basis functions is greater than 3. The influence of the rank is relatively small, but an increase of the rank is observed for \( m = 5 \) when the sample number is greater than 7. The minimum error (0.04\%) is obtained when \( P \) and \( Q \) are greater than 6 for \( m = 3 \). These results suggest that the logarithm of the magnetic field is well represented by polynomial basis functions of the second order.

B. Accuracy in predicting the receiver position

Figure 4 shows the prediction accuracy of the receiver position. The spline interpolation of the calibration data was used to express the magnetic field as in the previous experiment, the receiver position \((x,y)\) was calculated from the signal strength of each test sample, and the prediction error of the receiver position was evaluated as \( \sqrt{(x-x_i)^2 + (y-y_j)^2} \) for the actual position \((x_i,y_j)\) included in the test sample. The iteration number of the position prediction procedure was fixed at 10. The mean of three trials is plotted along the ordinate.

The results indicate that the prediction error is less than 0.1 mm when the number of basis functions is more than 3. The influence of the rank of the basis functions is more apparent than in the previous experiment: the prediction may...
be better performed for \( m = 3 \) if the number of basis functions is the same. When \( m \) is set at 3 and \( P \) and \( Q \) are greater than 5, the error is less than 0.07 mm. The errors shown in Figs. 3 and 4 appear to have a similar tendency and indicate that an accurate representation of the magnetic field can result in precise \( x \) and \( y \) measurements.

C. Effect of smoothing the calibration data

The weights of the spline representation can be determined, as described in Sec. II, so that given calibration data samples are smoothly approximated by the spline function. Estimation errors of the receiver position shown in Figs. 5 and 6 were obtained by using the smoothing spline technique in representing the magnetic field. The figures, respectively, indicate mean and maximum errors of the test data samples, as a function of the number of basis functions \( (P, Q) \). The rank \( (m) \) was fixed at 3, and the plotting symbols in these figures represent different numbers of calibration data samples \( (N) \), which ranged from 3 to 10. In addition, the symbols representing any given value of \( N \) are connected by straight lines. Together with the condition \( P = Q = n + m, N = P = Q \) holds for the spline interpolation and \( N > P \) and \( N > Q \) for the smoothing. Therefore, the extreme right-hand symbol in a connected sequence corresponds to the interpolating condition, while the other symbols in the sequence correspond to smoothing.

It is clear from Fig. 5 that the overall shape of every sequence of symbols shows the same tendency regardless of the sample number of the calibration data: the minimum error is obtained when five or six basis functions are used. In addition, the prediction error generally decreases when the calibration sample number increases, even when the number of basis functions is the same, suggesting that the data-smoothing technique can reduce the influence of random error components that occasionally arise during the measurement of calibration data. By combining both results, and using eight to ten samples of calibration data in each axis, a minimum error of approximately 0.06 mm is obtained. Figure 6 indicates the maximum prediction error in the measurement area calculated using 225 test samples. The result shows almost the same tendency as the previous one with respect to the number of calibration data samples and basis functions. It can be concluded from the figure that the maximum error is below 0.25 mm if the number of basis functions is set at 5 or 6.

D. Other considerations

Because the basis function of the spline representation is determined by the spatial alignment of the internal nodes, the alignment pattern may influence the accuracy of the proposed method. An experiment was performed in which the optimal node alignment was found by a search procedure, such that the mean estimation error of the receiver position was minimized. The rank and the number of the basis function was selected as 3 and 5, respectively, and spline smoothing was applied to the calibration data. The number of non-overlapping nodes, for which the search method was applied, was set at 2, and the experiment was repeated while changing the number of calibration data from 5 to 10. The results showed that the difference between the prediction errors with and without optimization is very small (approximately 0.003 mm), suggesting that the internal nodes can be placed at equal intervals.

Finally, Fig. 7 shows a plot of the receiver position prediction error as a function of the number of iterations. It is clear from the figure that the Gauss–Newton method converges rapidly and that three or four iterations are sufficient to reach a minimum prediction error.

V. SUMMARY AND CONCLUSIONS

The representation of the magnetic field is one of the central issues in constructing an electromagnetic position sensing device. Commonly, the voltage-to-distance function has been derived from the assumption that each transmission
coil behaves like an electromagnetic dipole (Raab et al., 1979; Schönle et al., 1987, 1989) or closely approximates dipole behavior (Perkell et al., 1992). This paper presented a novel method based on a nonparametric approach. A two-variate function is constructed by a linear sum of piecewise polynomial functions, i.e., B-spline basis functions, to represent the magnetic field of the two-dimensional articulographic device. The piecewise property of the basis functions makes it possible to accurately represent the spatial field pattern, even when it has local fluctuations. In addition, the spline function can provide a closed-form representation, which is computationally superior to the adaptive method we proposed before (Kaburagi and Honda, 1997) for calibrating unknown parameters included in the field function.

Based on a spline representation of the magnetic field, it is possible to predict the strength of the received signal for three unknown parameters of the receiver coil, i.e., the position and the tilt relative to the magnetic field, while incorporating the influence of the tilt angle. The position of the receiver coil can be then determined by minimizing the difference between the measured and predicted signal strengths. This framework produces a nonlinear optimization problem, which is solved here using a Gauss–Newton-based iterative procedure.

Experiments were performed to examine the accuracy of the proposed method. A receiver coil was placed at each crossing point of a grid drawn in a 14×14-cm measurement area of the magnetic device, and the received signal was measured to obtain several calibration and test data sets. Calibration data were used to determine the values of the weighting coefficients of the spline function, while test data were used to compute errors in predicting the strength of the magnetic field and the position of the receiver coil.

The main experimental results and related considerations are as follows:

1. Experiments showed that the relative error in predicting the magnetic field strength is less than 0.06%, when the spline function is constructed to interpolate four or more samples of calibration data in each axis. The influence of the rank of the basis function is relatively small, but the results are generally better at 3 than at 4 or 5.

2. If the same number of calibration data samples are used as in (1), the error in predicting the receiver position is less than 0.1 mm. It was revealed that this error can be further reduced by using the data smoothing technique. The error generally decreases when the number of calibration data samples increases for the same number of basis functions. The optimal number of basis functions is 5, and the minimum prediction error (approximately 0.06 mm) can be obtained by using more than six calibration data samples along each axis.

3. About the spatial alignment of the internal nodes, the experimental results indicated that nodes can be placed at points separated by equal intervals on each side of a rectangle that covers the entire measurement area.

4. The iterative procedure was revealed to converge quickly. Three or four iterations are enough to obtain an accurate prediction of the receiver position.

Kaburagi and Honda (1997) showed that the measurement accuracy of an articulograph device, the same one used in this study, is 0.230 mm when the voltage-to-distance function is calibrated globally, and this error decreases to 0.106 mm when a local or adaptive calibration is performed. Experimental results presented in this paper indicate that the spline function is slightly superior to the ordinal field representation method when an equivalent number of calibration data samples is used: the measurement error decreases from 0.106 to 0.084 mm for 4×4 calibration samples.

However, the two-dimensional articulograph device still has the problem of off-sagittal misalignment and rotation of the receiver coil that causes significant measurement errors. An informal experiment indicated that the influence of the off-sagittal misalignment can be compensated if the rotation angle is zero: the increase of the measurement error is approximately 0.1 mm as long as the misalignment is less than plus or minus 6 mm. However, the error rapidly increases when the rotation angle increases. It reaches about 3 mm when the rotation angles with respect to the x and y axes are both 20 deg and the misalignment is 6 mm.

To overcome this problem, the proposed method should be extended to measure the receiver coil position in three-dimensional space as well as the rotational angle relative to the three-dimensional pattern of the magnetic field. The principle and architectural design of the three-dimensional articulograph have been extensively investigated (Zierdt, 1993; Tillmann et al., 1996; Zierdt et al., 1999, 2000), resulting in the construction of an actual measurement system (Carstens Articulograph AG500, Germany). The spline function is expected to be useful for representing the field pattern of the three-dimensional system as well, because the magnetic fields are generated using six transmitting channels and hence the interference problem might be more apparent than in two-dimensional systems. To investigate the three-dimensional field pattern representation, experimental results obtained in the present study would be useful to determine...
the values of several parameters included in the construction of the spline representation.

ACKNOWLEDGMENT

This research was partly supported by the Grants for Incentive Research from the Nissan Science Foundation.


