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Bio-Motivated Geomagnetic Navigation Based on Leading Angle Technique and Parameters

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ABSTRACT. This paper takes into account the matter of approach towards working on a navigation system based on geomagnetism, inspired by a concept found in biology, named as Geomagnetic Bionic Navigation. Firstly, the deserved significance and the need for the above-mentioned system is discussed, which motivates the researchers towards its development. The discussion elaborates on the fact that it goes beyond the point where other navigation systems reach their limits. What follows is a brief introduction to the applications of the geomagnetic field. Secondly, all ideas of methodologies have been introduced. The choice of method has been discussed, taking into consideration the behavior of animals concerning the geomagnetic field. Lastly, the most feasible way of achieving the system has been complemented with a mathematically-supported discussion.

Keywords: Geomagnetism; Navigation; Bionic.

INTRODUCTION

The geomagnetic field, a product of the Dynamo effect, taking place in the Earth's interior core, functions as a shield that prevents hazardous solar winds and cosmic rays from entering the Earth, thus making the Earth habitable. The geomagnetic field is also useful in other developments across the globe. These developments include the storage of information regarding planets residing in rocks, providing geological researchers with plenty of facts, details, and directions, magnetic levitation in electric trains,[1] etc. The most common application of the magnetic levitation is, however, navigation.[1] For centuries, navigation has facilitated people, from compass navigation to modern-day navigation including, satellite navigation, inertia or celestial navigation, etc. Both civil and military spheres apply these systems, with the Global Positioning System, or GPS, being the most sought-after navigation system. The GPS offers long-term accuracy with an error of some meters.[2, 3] In the improved GPS, the error is around 10 meters or so,[3] although GPS signals are still unreliable in environments such as urban gorges and forest canopies.[2, 5] The Inertial Navigation System, or INS, faces time-dependent errors. The time function depends on the sensors quality. The product will turn out to be incompatible even if improvements are made.[6, 8] Also, the weather conditions limit the accuracy of the INS.[7]

While each of the above systems has its weaknesses and limitations, the geomagnetic navigation system is not affected by any external disturbance, since this means of navigation employs a field of force extending over 98% of the Earth's surface, including areas that are covered in water.[8] According to achievements of researchers, two methods have been worked upon, namely, geomagnetic matching and geomagnetic filtering.[2, 11] Different matching techniques, including MAD, MSD, and ICCP, and filtering methods, including EKF and UKF,[2] have been employed. Various studies have proven that geomagnetic matching is more accurate.

UNATTAINABILITY OF A PRIOR MAP

It is, however, not possible to achieve a map of geomagnetic anomalies due to its complications. These complications are because even the accurate measurements of satellites equipped with highly-sensitive magnetometers do not necessarily capture the sign of magnetic anomalies. Assuming if capturing is

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successful, variations exist in the field when measured from a level as high above as the satellites compared to that of near the Earth's surface.[8] Solar winds also create variations in the magnetic field, causing a disturbance in satellite measurements. Hence, a method that does not involve the map is preferred.

INSPIRATION FROM BIOLOGY

Researches have been conducted, claiming that animals use the geomagnetic field to navigate.[12] It is conspicuous from their motion[13] that bacteria, insects, many vertebrates, turtles,[14] salmon,[15] and birds[1] such as pigeons,[13] obtain directions by manipulating the information acquired from their destination's geomagnetic field.[20] This manipulation comprises determining their position.[17]

POSSIBLE TECHNIQUES

In the 1960s, E-systems used geomagnetic matching through MAGCOM, which required a map, making it infeasible. Therefore, the US Navy put forward the idea that geomagnetic cues were the desired solution that directed navigators from the present to the target location.[21] Furthermore, according to Todd et al., the intensity and inclination of the geomagnetic field and its field lines can describe the geomagnetic field.[14] While Brain K. Taylor believes that the field's leading angle from the local horizontal can describe the geomagnetic field.[23] An approach comprising the intensity, leading angles, the strength of the geomagnetic field, and three parameters of the geomagnetic data is therefore needed. Geomagnetic bionic navigation, a bio-inclined technique, is one such approach.

PROBLEM INTERPRETATION

The geomagnetic field is a vector field comprising its component parameters. The navigation is governed by parameters of geodetic datum and leading angles measured between field lines and the Earth's surface. Therefore, the field can be represented by following formula:

$$B = \{B_1, B_2, B_3, \ldots\ldots, B_n\} \quad (1)$$

Here, The B_i indicates the i[th] perimeter of the field vector; i= 1, 2, 3, …, n.
The geodetic equation of motion in the Cartesian plane is given as:

$$x_m = x_{m-1} + v\cos Ø_{m-1}$$
$$y_m = y_{m-1} + v\sin Ø_{m-1} \quad (2)$$
$$f = (Ø, v)$$

Here, the coordinates (x, y) indicate the object's location in the geodetic system. f is the parameter as the function of the leading angle (Ø) and velocity (v) of the object. The output function (f) depends on Ø, i.e., f=Ø. However, this is only in the case of constant velocity. Therefore, the field vector can be calculated using the location and the leading angle (Ø). An objective function (G) is introduced to determine the pathway of navigation. This function governs the object's motion from the initial to the final position with instantaneous positions along the path. Hence, g depends on the field, angle, and m. Here, m represents the instant parameter.

$$G(B, m, Ø) = (g_1, g_3, g_3 \ldots g_n) \to 0, \quad i = 1, 2, 3 \ldots n \quad (3)$$

At every instant and angle $Ø_m$, the value of the function is given as:

$$g_{i,m}(Ø_m) = |B^a_i - B_{i,m}(Ø_m)| \quad (4)$$

Where $B_{i,m}$ is final position; and B^a_i is the value of B at the required instant and angle. The difference between them indicates the value of the function. As the object reaches the final position, this value decreases and approaches zero.

$$Gm(Øm) = \frac{\sum_{i=1}^{n} gi, m\,(Øm)^2}{\sum_{i=1}^{n} gi^2, 0} = \frac{\|B^a - B_m(Ø_m)\|^a}{\|B^a - B_0\|} \to 0 \quad (5)$$

GEOMAGNETIC BIONIC NAVIGATION STRATEGY

The field lines are considered to vary smoothly across the surface. Therefore, to measure the ratio of variation to determine the leading angle, we introduce two terms, $\Delta B_{i,m}$ and $\Delta B_{i,a}$.
Where

$$\Delta B_{i,m} = |\Delta B_{i,m,\lambda}|\cos\phi_m + |\Delta B_{i,m,\psi}|\sin\phi_m \quad (6)$$

This represents the difference in the geomagnetic field parameter at time instant m, which depends on $\Delta B_{i,m,\lambda}$

and $\Delta B_{i,m,\psi}$, the difference in B along the longitude and latitude, respectively.
And,

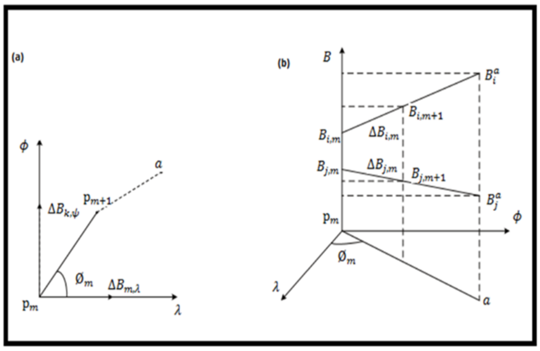
$$\Delta B_{i,a} = B_i^a - \Delta B_{i,m} \tag{7}$$

This represents the difference between the instantaneous values of B and the final position of the target. The ratio is then given by:

$$M_{i,m} = \frac{\Delta B_{i,m}}{\Delta B_{i,a}}, \qquad i = 1, \dots, n \tag{8}$$

The problem discussed here is the determination of the leading angle Øm, so that differences in different geomagnetic field values $\Delta B_{i,m}$ approach in parallel to the corresponding geomagnetic field value at the destined location, i.e., $M_{i,m} = M_m$, (i=1, ..., n).
Thus, variations in the geomagnetic field can be written as:

$$\Delta B_{i,m,\lambda} = q_{i,m,\lambda} . |\lambda\hat{}| \tag{9}$$



$$\Delta B_{i,m,\psi} = q_{i,m,\psi} . |\Psi\hat{}| \tag{10}$$

Where $q_{i,m,\lambda}$ and $q_{i,m,\psi}$ are the longitude and latitude components of the geomagnetic gradient, respectively.| |λ^| and |Ψ^| are unit lengths in the longitude and latitude directions, respectively.
The geomagnetic gradient $q_{i,m}$ is presented by Zhenchang,[21] based on the Gaussian theory of magnetic fields.

$$q_{i,m,\lambda} = (\partial B_{i,m,\psi})/\partial \lambda_m$$
$$q_{i,m,\psi} = (\partial B_{i,m,\psi})/\partial \psi_m \tag{11}$$

The specific steps and the calculation process of the geomagnetic gradient are explained by Zhenchang.[22]

LEADING ANGLE CALCULATION

Now that the ratio is defined, we further elaborate that, however, practically $\Delta B_{i,m}$ is taken to be $\tilde{B}_{i,m}$, a more accurate measurement of the field vector, which is given by:

$$\tilde{B}_{i,m} = B_{i,m} + \vartheta_{i,m} \tag{12}$$

Where the former term indicates the value of the field and the latter the noise. The ratio becomes:

$$M_{i,m} = \frac{\Delta\tilde{B}_{i,m} - \vartheta_{i,m}}{\Delta\tilde{B}_{i,a} - \vartheta_{i,m}}$$

Or

$$\Delta\tilde{B}_{im} = M_{im}\Delta\tilde{B}_{ia} + \gamma_{im} \tag{13}$$

Also,

$$\Delta\tilde{B}_{im} = |\Delta\tilde{B}_{im\lambda}| \cos Øm + |\Delta\tilde{B}_{im\psi}| \sin Øm$$
$$\Delta\tilde{B}_{ia} = B_i^a - \widetilde{B_{im}}$$
$$\gamma_{im} = (1 - M_{im})\gamma_{i,m}$$

Where γ_{im} is considered the noise in the measurement. We introduce a term:

$$e = [\alpha_{1,m}\alpha_{2,m}\alpha_{3,m\dots}\alpha_{n,m}]^S \tag{14}$$

Which gives all the noises at their respective instants, and solving its square will provide us with the leading angle.

$$e^2 = \sum_{i=1}^{n} \left(\Delta B_{im} - M_{im}\Delta\tilde{B}_{im}\right)^2 \qquad (n \leq 7)$$

$$e^2 = \sum_{i=1}^{n} \left[|\Delta\tilde{B}_{i,m,\lambda}| \cos Ø\, m + |\Delta B_{i,m,\Psi}| \sin Ø\, m - M_{i,n}\left(B_i^a - \tilde{B}\right)\right]^2 \tag{15}$$

Rewriting the equation:

$$A = \sum_{i=1}^{n} v_i e_i^2 \tag{16}$$
$$A = (BX - Mh)^S V(BX - Mh)$$

We solve this problem using matrices since doing so simplifies the equation:

$$X = \begin{bmatrix}\alpha \\ \beta\end{bmatrix}, h = \begin{bmatrix}B_i^a & \tilde{B}_{i,k} \\ B_n^a & \tilde{B}_{n,t}\end{bmatrix}$$

$$V = \begin{bmatrix}Vi,k \\ Vn.k\end{bmatrix}$$

$$J = \begin{bmatrix}|\Delta B_{i,m,\lambda}| & |\tilde{B}_{i,k}| \\ \vdots & \vdots \\ \Delta B_{i,m,\lambda} & \Delta B_{i,m,\lambda}\end{bmatrix} \quad (17)$$

$$M = \begin{bmatrix}M_{i,n} \\ M_{i,m}\end{bmatrix}$$

$$\alpha = \cos\phi_m \ , \qquad \beta = \sin\phi_m$$

Solving by differentiation gives:

$$X = \left(J^k V_j\right)^{-1} J^R V \begin{bmatrix} M_B(B_1^a - \tilde{B}_{1,m}) \\ M_{r,m}(B_n^a - \tilde{B}_{n,m})\end{bmatrix}$$

Since,

$M_{i,m} = M_n$ for i=1

And, (18)

$E(r) = 0$

$E(r^R r) = S \qquad V = S^{-1}$

Therefore,

$$\begin{bmatrix}\alpha \\ \beta\end{bmatrix} = (\nabla S^{-1} J) J^R S^{-1} M_m \begin{bmatrix} B_1^a - \tilde{B}_2 \\ B_X^n - \tilde{B}_{n,m}\end{bmatrix}$$

By solving the matrix, we get the leading angle:

$$\emptyset_m = \tan^{-1}\left(\frac{\propto}{\beta}\right) \quad (19)$$

CONCLUSION

It has been proved in this paper, both through mathematical statements and theoretical discussions the leading angle method under consideration is a feasible technique contrary to the map method, which is complicated and nearly impossible. This paper proves that through this and only this technique, the navigation is possible. Therefore, this technique is worth throwing light upon to enable future researches in this domain.

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