Circuit design and system error analysis based on MR / GPS combination measuring projectile roll angle

CAO Peng
Nanjing University of Science and Technology
Nanjing, China
e-mail: suke.cp@gmail.com

WANG Xiao-ming,JIA Fang-xiu, WU You-long
Nanjing University of Science and Technology
Nanjing, China

***Abstract*—In the control process of trajectory correction projectile, a real-time accurate measurement of projectile roll angle information is required. Geomagnetic and GPS measurement principle is applied for the establishment of the projectile measured roll angle combinations mathematical calculation model, the designing of MR and GPS measuring circuits, and derivation of the singular points of the system and error resolution type. Numerical simulation methods are applied to verify the location of singular points of the combination of measurements and the linear spline combination of interpolation method of compensation the position of the magnetic vector error and the ellipsoid fitting calibration algorithm compensate for magnetic measurement error. The geomagnetic error has less effects on the combination of measured roll angle error, while the pitch angle and yaw angle error has greater impact on the roll angle error. Remove the singular point area, projectile roll angle error is less than 2°when measured by the combination of MR / GPS .**

Keywords-trajectory correction projectile; MR/GPS; roll angle

I. INTRODUCTION

The measurement of the projectile attitude angle is one of key technologies of trajectory correction projectile. At present ,there are so many methods of measuring the projectile attitude angle ,including GPS, Gyroscope, accelerometer and the Magnetic detection etc.[1]-[4]However ,single measuring type has limits on the measurement of the projectile attitude angle and accuracy of measurement as a result of own problems. For example, the update frequency of GPS is low and the measurement of the roll angle is disabled. The system error of Gyroscope cumulates with time and it cannot be resistant to the high overloading. Accelerometer can't measure high dynamic projectile attitude angle one or two external known attitude angles should be introduced in Magnetic detection. GPS can provide velocity ballistic angle and the ballistic angle, and positional information compensation magnetic measurement the geomagnetic information can finish the calculation of roll based on it. Therefore, the projectile attitude measuring system based on the triaxial magnetic resistance sensor and GPS combination, which can enhance strong points and avoid weaknesses, with characteristics of the work as not cumulative error, over time, all-weather and high frequency, is a reliable and efficient whole attitude measuring scheme.

At present, in the research about the platform that magnetic and GPS combination measure projectile attitude Angle, [3] derived the nonlinear observation equation while the equivalent angle error is a state parameter, and used extended kalman filtering to posture parameters of state estimation, [4] analyzed the feasibility of this scheme and guidance accuracy, and used quasi Newton method for calculating attitude in a follow-up study. But, in view of the system error of which geomagnetic and GPS combination measure the attitude Angle, the literature [4] takes no consideration; while literature [3] only considering the angle error. Therefore, according to the combination measurement principle, the article completely deduced mathematics calculation formula of the combined measurement, and designed hardware circuit for MR and GPS combination measurement, and analyzed the system error by using numerical simulation method.

II. MR/GPS COMBINATION MEASUREMENT PRINCIPLE AND CIRCUIT DESIGN

The projection value of magnetic vector in the navigation system is the initial magnetic value of the integrated navigation. While in flight process the projectile measures magnetic data through the magnetic survey unit loaded on the bomb , then magnetic and projectile attitude Angle relationship equation can be get, such as formula (1) shows.

$$B_i = C_n^b B_0 \qquad (1)$$

1. National Natural Science Foundation of China , No. 61201391
2. Supported by “the Fundamental Research Funds for the Central Universities”, No. NUST2011YBXM49

where

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} = \begin{pmatrix} \cos\theta\cos\psi & \sin\theta & \cos\theta\sin\psi \\ -\sin\theta\cos\psi\cos\gamma - \sin\psi\sin\gamma & \cos\theta\cos\gamma & -\sin\theta\sin\psi\cos\gamma + \cos\psi\sin\gamma \\ \sin\theta\cos\psi\sin\gamma - \sin\psi\cos\gamma & -\cos\theta\sin\gamma & \sin\theta\sin\psi\sin\gamma + \cos\psi\cos\gamma \end{pmatrix} \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix}$$

Magnetic survey unit is installed in the projectile, and the direction of sensitive axis of magnetic resistance sensor and direction of the projectile coordinate are consistent.

In the formula (1):

$B_i = (X_i, Y_i, Z_i)^T$ —— projection value of the Magnetic vector in the bomb body coordinate system at any time respectively;

C_n^b ——matrix to transfer attitude from Navigation coordinate system to body coordinates;

(θ, ψ, γ) ——in flying process respectively , three attitude angles when the projectile pitch., yaw, and roll.

From the formula (1), the coordinate - transformation matrix C_n^b is not completely reversible. Therefore, only with magnetic survey unit to measure the real-time geomagnetic information under body coordinate, the calculation of attitude Angle is not feasible, so external auxiliary information or improved calculating method must be brought in.

From formula (1)

$$\gamma = arc\tan\left(\frac{bY_i - aZ_i}{aY_i + bZ_i}\right) \qquad (2)$$

In the formula (2), a, b is intermediate variable, as follows:

$$\begin{cases} a = -\sin\theta\cos\psi X_0 + \cos\theta Y_0 - \sin\theta\sin\psi Z_0 \\ b = -\sin\psi X_0 + \cos\psi Z_0 \end{cases}$$

Based on elastic load GPS equipment, we can measure the longitude, latitude, height, and also the velocity information in the flying process. In quasi speed coordinate system and navigation coordinates, path angle and ballistic angle calculation formula (3) can be deduced with the velocity information provided by GPS.

$$\begin{cases} \psi_V = a\tan\dfrac{V_{y_i}}{V_{x_i}} \\ \theta_V = a\tan\dfrac{V_{z_i}}{V_{x_i}} \end{cases} \qquad (3)$$

In the formula (3),

$V_i = \begin{bmatrix} V_{x_i} & V_{y_i} & V_{z_i} \end{bmatrix}^T$ ——three velocity component at the i moment under quasi speed coordinate system respectively;

$(\psi_V \quad \theta_V)$ ——path angle and ballistic angle.

From the analysis above, by the use of geomagnetic information, only the relation of projectile attitude angle can be established, while the attitude angle cannot be figured out completely. So, the velocity and position information provided by GPS can be introduced to complete combination of whole attitude measuring. MR/GPS combination measurement calculation principle block diagram (Figure 1) and the hardware circuit principle diagram (Figure 2) are obtained, as follows:

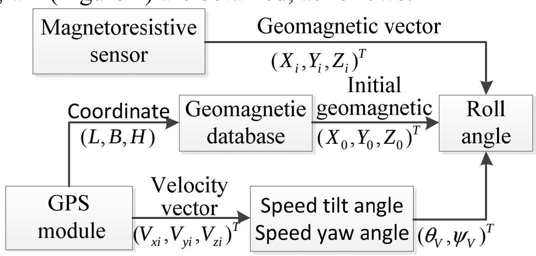

Figure 1. MR/GPS combination measuring calculation principle block diagram

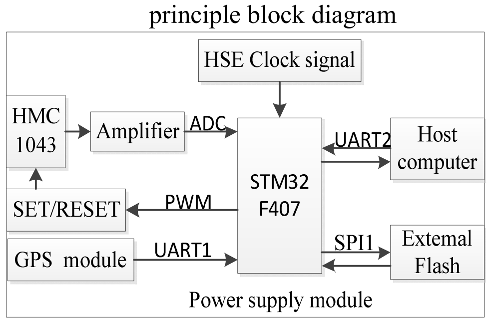

Figure 2. MR/GPS combination measurement hardware circuit principle diagram

III. SYSTEM ERROR ANALYSES

The formula (4) can be deduced from the formula (2):

$$a \bullet B_{y_i} + b \bullet B_{z_i} = (a^2 + b^2)\cos\gamma \qquad (4)$$

From the formula (4), when $\cos\gamma = 0$, the answer is normal; when $a = b = 0$, singular points (5) appear:

$$\begin{cases} -\sin\theta\cos I\cos(D-\psi) - \cos\theta\sin I = 0 \\ \cos I\sin(D-\psi) = 0 \end{cases} \qquad (5)$$

As value area of pitching Angle of the projectile θ and magnetic difference potential I are both (-π/2, π/2), so by (5) can work out:

$$\begin{cases} D-\psi = 0 \\ \theta + I = 0 \end{cases}, \quad \begin{cases} D-\psi = \pi \\ \theta - I = 0 \end{cases} \qquad (6)$$

From (6), singular point is seated in the position which projectile direction is parallel to geomagnetic direction. In this case, the projection of magnetic vector in the roll plane is 0, so the calculation of roll angle will be wrong. Then, in area nearby this position, a big deviation appeared. According to formula (2), the following variable is set:

$$\gamma = f(B_0, B_i) \tag{7}$$

It can be known from formula (7), the projectile roll error with magnetic and GPS combination measurement is generated by two parts: the change of navigation initial magnetic vector B0 caused by change in position; the measurement error of real-time magnetic vector Bi.

A. Position error of $\boldsymbol{B_0}$

The earth's magnetic field is continuous distribution, changed with site. Therefore, during the process of the projectile in flight, navigation initial magnetic vector B0 is changed all the time. Using IGRF11 model, the varieties of earth's magnetic field X, Y and Z components in Nanjing area (N30°～N35°, E115°～E120°) are shown in Figure 3.

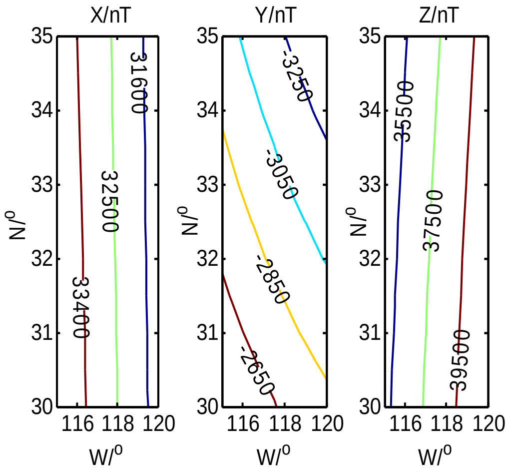

Figure 3. X, Y and Z component contour map

The position changing magnetic field information obtained by linear combination of spline interpolation method can limit relative errors of earth's magnetic field X, Y and Z components in 0.030%, 0.765% and 0.032% respectively. So, formula (8) can be deduced with formula (7) and definition of differential:

$$d\gamma_1 = \frac{1}{1+x^2}\left(\frac{\partial x}{\partial X_0}dX_0 + \frac{\partial x}{\partial Y_0}dY_0 + \frac{\partial x}{\partial Z_0}dZ_0\right)$$
$$= \frac{\left[\left(\frac{\partial b}{\partial X_0}a - \frac{\partial a}{\partial X_0}b\right)dX_0 + \left(\frac{\partial b}{\partial Y_0}a - \frac{\partial a}{\partial Y_0}b\right)dY_0 + \left(\frac{\partial b}{\partial Z_0}a - \frac{\partial a}{\partial Z_0}b\right)dZ_0\right](Y_i^2+Z_i^2)}{(aY_i+bZ_i)^2+(bY_i-aZ_i)^2} \tag{8}$$

B. Real-time measuring error of $\boldsymbol{B_i}$

During geomagnetic signal detection, there are error caused by three axial magnetic sensor itself, signal processing circuit and external environment interference etc. Especially, ferromagnetism material of the projectile brings soft hard magnetic interference in magnetic survey. And it is difficult to compensate soft iron magnetic field error accurately. By ellipsoid fitting algorithm which is based on space point magnetic vector invariant, the error can be reduced from 8% to 0.8%. So, formula (9) can be deduced with formula (7) and definition of differential.

$$d\gamma_2 = \frac{1}{1+x^2}\left(\frac{\partial x}{\partial Y_i}dY_i + \frac{\partial x}{\partial Z_i}dZ_i\right)$$
$$= \frac{(a^2+b^2)Z_i dY_i + \left[-(a^2+b^2)Y_i\right]dZ_i}{(aY_i+bZ_i)^2+(bY_i-aZ_i)^2} \tag{9}$$

From formula (8)-(9), system error based on magnetic and GPS combination measurement is formula (10).

$$\delta\gamma = d\gamma_1 + d\gamma_2 \tag{10}$$

IV. SIMULATION ANALYSIS

In order to analyze system error based on magnetic and GPS combination to measure projectile roll angle, In Nanjing (N32.03, E118.46) as the center, magnetic vector is calculated with the model of IGRF11, where B0 is the result of study in literature [5] and Bi gives compensation error of magnetic of the total amount in literature [6], while, in this article, it is be distributed to three component averagely; angle of pitch and yaw in the whole domain changes in the step of Δ. Then numerical simulation research about the combination method of measuring system error is carried on. Specific example simulation parameters are shown in TABLE I and TABLE II:

TABLE I. fundamental parameters of simulation

magnet vector						attitude angle			
B/nT	***D***/°	***I***/°	$\boldsymbol{X_0}$/nT	$\boldsymbol{Y_0}$/nT	$\boldsymbol{Z_0}$/nT	ψ/°	θ/°	γ/°	Δ/°
49625.3	-5.133	48.117	32996.9	-2964.5	36947	-2π/3~4π/3	-π/2~π/2	0	1

TABLE II. incremental parameter of simulation

$\boldsymbol{B_0}$ increment			$\boldsymbol{B_i}$ increment		
dX_0/nT	dY_0/nT	dZ_0/nT	dX_i/nT	dY_i/nT	dZ_i/nT
0.030%	0.765%	0.032%	0.46%	0.46%	0.46%

Formula (1), (2) and (8)-(10) are used to carry on numerical simulation to get contour map about θ, ψ and $\delta\gamma$, as shown in Figure 4. It can be seen from the chart, all Singular point positions are in accord with result of formula (6). $\delta\gamma$ There is larger error in the area where the projectile direction is parallel to the geomagnetic direction. Except these two positions, most of the measurement area meets the condition $|\delta\gamma| < 2^\circ$. Though there are two positions of large error, in an actual ballistic calculation, the error can be compensated by the way of interpolation.

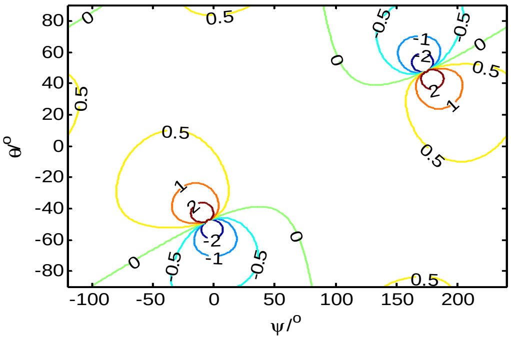

Figure 4. The whole contour map of roll angle error

V. CONCLUSION

Through derivation, measurement method based on the MR/GPS combination measuring projectile roll angle is established in the article. According to combination measurement principles, MR and GPS combination measurement hardware circuit is designed out. Finally, the analytic expression of combination measuring roll Angle error is given, and though simulation: measurement method of the projectile roll based on the MR and GPS combination, there is larger error in the area where the projectile direction is parallel to the geomagnetic direction. And through the linear combination of spline interpolation method to compensate position magnetic vector error and ellipsoid fitting algorithm compensation magnetic measurement error, roll error gets smaller, most of the measurement area meets the condition—— $|\delta\gamma| < 2^{\circ}$

REFERENCES

[1] ZHANG Min-quan, LIU Dong-fang, WANG Dong-mei, et al, A Summary for Trajectory Correction Projectiles, ACTA ARMAMENTARII, 2010, 32(2):127-130.

[2] LIU Ren-hao, XIA Jin-xiu, WANG Xue-bing, Study on Attitude Measurement of Gun-Launched Cruise Projectile with Geomagnetic Field, JOURNAL OF NORTH UNIVERSITY OF CHINA(NATURAL SCIENCE EDITION), 2009,30(6):630-633.

[3] ZHANG Da-yong, WU Wen-qi, WU Mei-ping, et al, Attitude Determination Algorithm Based on Combination of Attitude –GPS and Electronic Compass, NAVICATION OF CHINA, 2007,73(4):33-36.

[4] SHI Lian-yan, ZHANG Zi-bin, SONG Wen-yuan, Study of Rocket Body Attitude Solving Method Based on MR/GPS, Journal of System Simulation, 2010,22(12):2948-2951.

[5] LIU Jian-jing, ZHANG He, CHENG Xiang, Linear Spline Combination Interpolation of Geomagnetic Map for Attitude Detection, Journal of Detection & Control, 2010,32(5):69-73.

[6] HUANG Xue-gong, WANG Jiong, Error Analysis and Compensation Methods for Geomagnetic Signal Detection System, Acta Armamentarll, 2011, 32(1):33-36.