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Attitude-Independent Magnetometer Calibration Considering Magnetic Torquer Coupling Effect

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I. Introduction

THREE-AXIS magnetometer (henceforth TAM) is widely used as a component of spacecraft attitude sensors. During the launch and on-orbit period, TAM is affected by mechanical distortion, thermal gradients, and internal magnetic moment disturbance of magnetic actuator. The typical purpose of calibration is to estimate factors that affect raw measurements in the magnetometer frame. Over the past several years, many studies have been conducted pertaining to attitude-independent calibration [1–3]. Generally, these studies were focused on the computation of calibration parameters without including magnetic torquer (MTQ) coupling effect. However, as an example, TAM measurement was found to be contaminated by MTQ activation according to the first Korea Multipurpose Satellite (KOMPSAT-1) flight data. If the several preceding methods take KOMPSAT-1 TAM data, the outcome could be an incorrect calibration. In this study, the proposed calibration method can estimate the MTQ coupling effect together with bias, scale factor, and nonorthogonality terms. The particle swarm optimization (PSO) algorithm is used to estimate 18 calibration parameters. The PSO algorithm is known to be a powerful algorithm that searches for a solution to minimize nonlinear cost functions with a simple structure for computer implementation [4].

II. Problem Statement

KOMPSAT-1 was developed by the Korea Aerospace Research Institute and launched in December 1999. KOMPSAT-1 is a small satellite with 450 kg mass, and it is located in a sun-synchronous circular orbit with a 685 km altitude. The TAM of KOMPSAT-1 measures magnetic field in the range of ±600 mG in any direction relative to the local sensor frame. MTQ assembly consists of three torque rods aligned in three axes of the spacecraft body frame. The amount of torque each torque rod can deliver depends on the state of the Earth's magnetic field. The magnetic moment for each torque rod can vary from 17 to 25 Am^2 due to temperature and driving voltage variations. While in its Earth-pointing attitude mode, the KOMPSAT-1 attitude control system uses a reaction wheel assembly to perform three-axis stabilization. The function of the MTQ assembly is to remove unwanted momentum from the reaction wheel assembly. MTQ activation during the momentum dumping contaminates raw TAM measurements every orbit. TAM-MTQ coupling effect is related to the distance and the magnetic permeability between TAM and MTQ. Moreover, the coupling term depends on the magnetic dipole moment among magnetic torque bars of three axes, and it was not measured on the KOMPSAT-1 ground test. This TAM-MTQ coupling effect of KOMPSAT-1 can be estimated using the MTQ dipole moment as sampled by an onboard computer.

III. Measurement Model and Cost Function Formulation

The magnetometer measurement model can be defined as in Eq. (1):

$$\begin{aligned} B_k &= (I_{3\times3}+D)^{-1}(A_kH_k+b+GM_k+n_k) \quad \text{magnetic torque on} \\ &= (I_{3\times3}+D)^{-1}(A_kH_k+b+n_k) \quad \text{magnetic torque off} \end{aligned} \tag{1}$$

where B_k is geomagnetic field measurement in the TAM sensor frame at time t_k, H_k is the corresponding true field in the Earth-fixed frame usually obtained from the International Geomagnetic Reference Field model [5], A_k denotes an unknown attitude matrix of the magnetometer, b is the unknown constant bias, D is an unknown symmetric matrix of scale factors (the diagonal elements) and nonorthogonality corrections (the offdiagonal elements), and n_k represents the measurement noise with covariance Σ_k. M_k is dipole moment vector by MTQ, and G is a 3×3 coupling matrix between TAM and MTQ, which depends on a distance from dipole moment and a mean permeability of material.

An effective measurement that eliminates the attitude dependence can be derived as follows from the residual of a magnetometer measurement norm and a reference geomagnetic field vector norm [3]:

$$\begin{aligned} z_k = |B_k|^2 - |H_k|^2 &= -B_k^T(2D+D^2)B_k + 2B_k^T(I+D)b - |b|^2 \\ &+ 2B_k^T(I+D)GM_k - 2b^TGM_k - (GM_k)^TGM_k + \nu_k \end{aligned} \tag{2}$$

where the measurement index is $k = 1, 2, 3, \cdots, m$, and the effective measurement noise, which is expressed as

$$\nu_k = 2[(I+D)B_k - b - GM_k]^T n_k - n_k^2 \tag{3}$$

can be considered as Gaussian, where u_k denotes the mean and σ_k^2 is the variance. This results in the following relationships:

$$u_k = E\{\nu_k\} = -tr(\Sigma_k) \tag{4}$$

$$\sigma_k^2 = E\{\nu_k^2\} - u_k^2 \tag{5}$$

where $E\{\}$ represents expectation.

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The effective measurement model in Eq. (2) can be defined as in Eq. (6):

$$z_k \equiv f_k(b, D, G) + v_k \equiv f_k(x) + v_k \tag{6}$$

Equation (6) is clearly a nonlinear equation with respect to the 18 unknown calibration parameters denoted by x. As in Alonso and Shuster [1], a negative log-likelihood cost function is used as a cost function in Eq. (7). Finally, TAM calibration parameters can be determined by minimizing the cost function; see Eq. (7):

$$J = \frac{1}{2}\sum_{k=1}^{m}\left[\frac{1}{\sigma_k^2}(z_k - f_k - u_k)^2 + \log\sigma_k^2 + \log 2\pi\right] \tag{7}$$

It is possible to employ the nonlinear least-squares method based on a gradient approach to seek the parameters through linearization and an iterative computation approach, as Alonso and Shuster [2]. In such a case, one principal disadvantage is the fact that the derived Jacobian and Hessian functions take complicated forms with respect to the parameters. Also, an 18×18 Hessian matrix has to be inverted for gradient-based approaches. Therefore, computing the Hessian of a cost function may be a formidable task, especially since the inverse of Hessian matrix can easily degenerate into an ill-conditioned matrix. Classical gradient-based optimizations suffer a weakness, as they do not guarantee a global minimum in multimodal optimization problems. For this reason, the PSO algorithm is used for attitude-independent TAM calibration considering magnetic torque coupling effect and has been considered highly efficient for nonlinear and multiparameter problems [4].

IV. Particle Swarm Optimization Algorithm

The PSO algorithm is a stochastic population-based evolutionary computer algorithm. Its mechanism can be classified as an adaptive and robust parameter search technique that is based on the conceptual model of bird foraging [4]. In addition, the principal advantages of the PSO algorithm are a very simple concept and the fact that its key routines can be implemented easily in a few lines of computer code.

Essentially, the PSO algorithm consists of three steps: positioning of the particles and initialization of the velocity, an evaluation of the cost function in Eq. (7), and updating of the position and velocity. Initialization is the step in which the position and velocity of all particles are randomly assigned within predefined ranges. Next, at the current kth iteration, the best position of particles with optimum fitness is selected through an evaluation of the cost function. Finally, the position and velocity of each particle for the next $k+1$th iteration are updated by Eqs. (8) and (9). The updated position and velocity are used to evaluate the fitness for the next iteration. This process is repeated until a user-defined cycle number is reached or until there is no improvement in the best fitness:

$$v_i^{k+1} = w v_i^k + c_1 R_1 (P_i^k - x_i^k) + c_2 R_2 (P_g^k - x_i^k) \tag{8}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{9}$$

where x_i and v_i correspond to the position and velocity of the ith particle; and P_i and P_g are the positions with the best fitness value found so far by the ith particle and by all particles, which are called the individual and the global best positions, respectively. Note that x_i represents the parameters to be estimated. Also, the individual position represents the best previously estimated parameter of the ith particle, whereas the global position represents the best particle of the whole swarm. The inertia weight coefficient w serves to control the impact of the previous velocity. The acceleration coefficients c_1 and c_2 play the role of moving particles toward the best individual position and the best global position. The balance among these coefficients determines the performance of global and local search ability. Two random vectors R_1 and R_2 are selected as uniform random numbers between 0 and 1.

V. Simulation Study

A. Simulated Calibration Test

In this section, magnetometer calibration results of the PSO algorithm are presented in terms of simulated data. It is assumed that the simulated spacecraft is controlled at a launch separation tipoff rate of 2 deg/s with its axis at a sun-pointing attitude. Once the spacecraft attains its correct attitude, the spacecraft rotates at an angular rate of 5 deg/s in the sun-pointing direction to stabilize its attitude. During this simulation scenario, attitude is controlled via MTQ. The dipole moment of MTQ is limited to 20 Am^2, and the moment of inertia of the spacecraft is $[27, 17, 25]\ \mathrm{kg \cdot m^2}$. The spacecraft orbit is approximated as a circular orbit with an altitude 450 km, an inclination of 87 deg, and the corresponding orbit period of approximately 5600 s. The magnetometer measurement noise is assumed to be Gaussian white noise. The covariance is isotropic with a standard deviation per axis of 2 mG. The simulated measurements are sampled every 30 s over a span of 24 h. The PSO algorithm for the simulation test uses a linearly varying inertia weight over generations that vary from 0.9 at the beginning of the search to 0.4 at the end. The number of the particle swarm is equal to 80, and the acceleration coefficients c_1 and c_2 are equal to 2 for almost all applications. The maximum velocity update is constrained to 20% of the dynamic range of each parameter. This method is called the inertia weights approach to ensure the improved performance in many applications [6]. The initial dynamic range of the calibration parameters is set to ± 4 times of truth values along the dimension.

Table 1 shows the mean with 3σ bounds of the estimated values after 50 runs of 200 generations each. Figures 1 and 2 present mean estimates and 3σ bounds for the bias and TAM-MTQ coupling effect. Calibration parameters converge through 200 generations with large initial guess. The simulation results, as shown in Table 1 and Figs. 1 and 2, indicate that the proposed algorithm provides correct solutions and convergence.

B. Three-Axis Magnetometer Calibration Using Flight Data

The flight measurements for the computation are sampled every 32 s over 16 orbits and in the Earth-pointing mode, where TAM measurements are corrupted by MTQ activation. Since the TAM-MTQ coupling effect occurs at about 20% of one orbit period, calibration using flight data is performed within narrow search range for better observability of the coupling effect estimation. Table 2 represents the calibrated parameters with a minimum cost value. The coupling effect is estimated as the only terms depending on the Y-axis aligned magnetic torque bar. This comes from the Y-axis momentum dumping operation of the magnetic torque bar to maintain the Earth-pointing attitude.

A plot for the residual between the magnitude of the adjusted observation using the calibrated parameters and the magnitude of the

Table 1 Results of simulated data

Parameter	Truth	Estimated with 3σ
b_1	50 mG	49.69 ± 4.79
b_2	30 mG	29.49 ± 5.62
b_3	60 mG	59.79 ± 5.87
D_{11}	0.05	0.0512 ± 0.0127
D_{22}	0.10	0.1005 ± 0.0303
D_{33}	0.05	0.0504 ± 0.0301
D_{12}	0.05	0.0489 ± 0.0172
D_{13}	0.05	0.0492 ± 0.0175
D_{23}	0.05	0.0466 ± 0.0209
G_{11}	20	15.38 ± 6.09
G_{12}	10	10.00 ± 1.50
G_{13}	20	20.28 ± 1.80
G_{21}	20	19.31 ± 4.55
G_{22}	10	6.28 ± 2.72
G_{23}	20	19.16 ± 1.88
G_{31}	20	20.51 ± 4.15
G_{32}	10	10.65 ± 1.80
G_{33}	20	16.23 ± 2.76

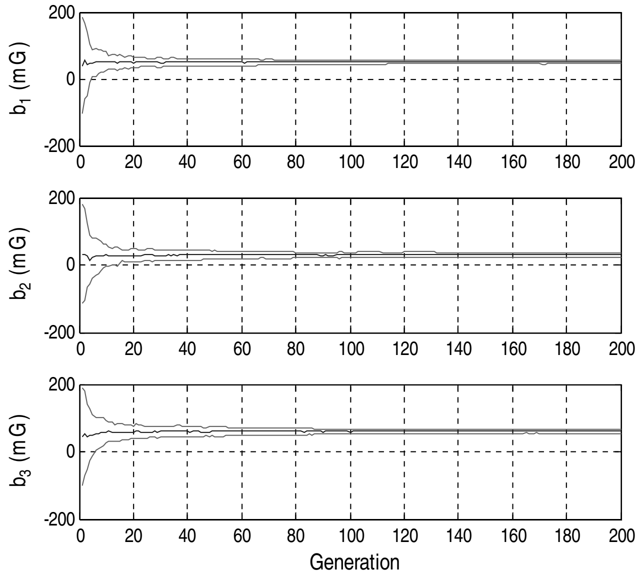

Fig. 1 Result of bias estimates.

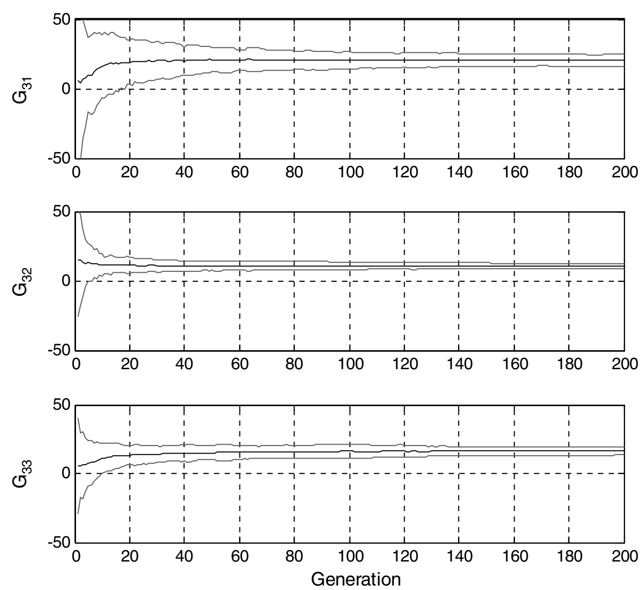

Fig. 2 Result of TAM-MTQ coupling effect estimates (third row of *G*).

Table 2 Calibration results for KOMPSAT-1

Parameter	Estimated
b_1	−85.16 mG
b_2	32.59 mG
b_3	−88.85 mG
D_{11}	0.0104
D_{22}	−0.0303
D_{33}	0.0131
D_{12}	−0.0058
D_{13}	−0.0389
D_{23}	0.0152
G_{11}	——
G_{12}	−0.39
G_{13}	——
G_{21}	——
G_{22}	−3.93
G_{23}	——
G_{31}	——
G_{32}	−0.71
G_{33}	——

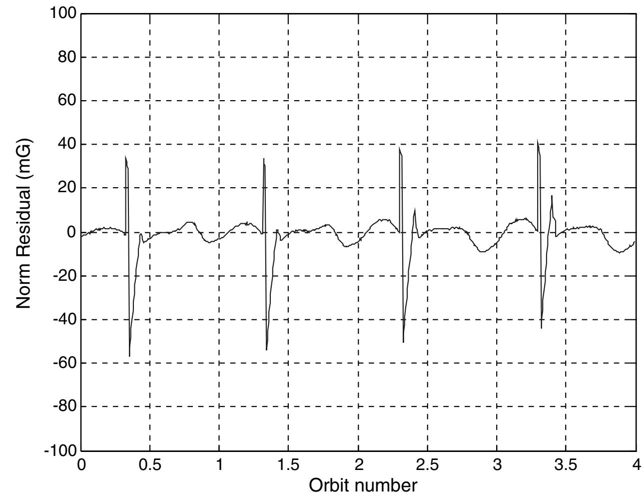

Fig. 3 Norm residual using different flight data.

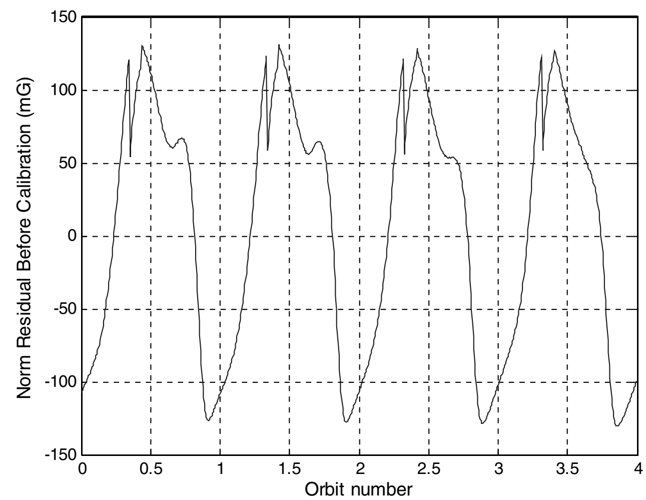

Fig. 4 Norm residual before calibration.

reference geomagnetic vector is presented in Fig. 3. Figure 4 shows the residual using the parameters before calibration. The adjusted observation is computed using a different flight data set from the one used to perform calibration. The postcalibration residual with the sinusoidal motions corresponding to a 98.6 min orbital period reduce from a too large precalibration residual. The mean and the standard deviation of the postcalibration residual are −1.38 and 10.19 mG, respectively. These are decreased from the mean 6.18 mG and the standard deviation 84.95 mG using precalibration parameters.

VI. Conclusions

The simulation test indicates that the PSO algorithm produces a converging estimation within a sufficiently rough initial boundary. For KOMPSAT-1 flight data, 12 calibration parameters of a magnetometer were successfully estimated. The estimated terms of the KOMPSAT-1 TAM-MTQ coupling effect matrix are dependent on the magnetic torque bar to align at the *Y* axis, because other torque bars did not activate. Residuals by a different flight data set and the calibrated parameters show improvement. Therefore, it can be concluded that the PSO algorithm is a viable tool for attitude-independent magnetometer calibration under the MTQ coupling effect.

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