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The use of D.O.A. estimate in communication satellite attitude determination

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Abstract

This work offers a unique attitude determination approach that uses direction of arrival (DOA) estimate of a terrestrial signal source for three-axis stabilized communication satellites. There are differences between this method and others, such as those used for optical measurement, magnetic field measurement, inertial measurement, and GPS attitude determination. The suggested technique is distinguished by its acquisition of attitude information through DOA estimation and its use of the ground signal source as the attitude reference. Attitude is measured by deriving an equation that estimates the angle of attack. We next examine the measurement equation's inaccuracy. Finally, the dynamic model, the attitude measurement equation, and measurement errors are used to propose an attitude determination method. Using a magnetometer, reaction wheels, and three-axis magnetorquer rods, a developing low Earth orbit (LEO) satellite may be stabilized in three axes so that mobile communication technology with smart antennas can be tested. The simulation results prove the efficiency of the approach based on the communication satellite. If the satellite's attitude determination system were to fail, this approach may be used as a fallback. With DOA estimation, accuracy is determined by the input signal-to-noise ratio (SNR) and the number of snapshots taken.

Key words : ***low Earth orbit (LEO); direction of arrival (DOA) prediction; antenna orientation determination.***

Introduction

Measurements from attitude sensors [1-3] define the orientation of communication satellites, which should be as precise as possible for the best possible data connection. The projection of the reference vector in the attitude-sensitive direction is what attitude sensors give out [3, 5]. Common vector definitions include the stars, Sun, Earth, geomagnetic field, inertial space, and global positioning system (GPS) satellites [3-6]. Due to the aforementioned sensors' unique characteristics, most communication satellites perform attitude determination by the coordinated use of several attitude references, which eliminates the risk of a catastrophic system failure [1-2]. For instance, Iridium satellites utilize attitude references such a three-axis gyroscope, a three-axis magnetometer, and a coarse horizon sensor [1]. Satellites equipped with Globalstar use four Sun sensors, a horizon sensor, a three-axis magnetometer, and global positioning system (GPS) to calculate their orientation [2]. This paper's research is grounded on ongoing work on a low Earth orbit (LEO) satellite that uses stationary intelligent antennas to evaluate mobile communication technologies. Using array signal processing, we can learn about the temporary physical gap between a ground signal source and the smart antennas. The smart array's collected data is used for DOA estimation, which attempts to pinpoint the signal's origination point [7-8]. Direction-of-arrival (DOA) estimate techniques are now used in signal source direction estimation [9-12]. It was claimed in Ref. [13] that a dipole triad antenna aboard an airplane might be used to more accurately estimate the aircraft's attitude.

Using the DOA estimate of a ground source and the electric ellipse orientation angle described in Ref. [13], a pilot may calculate the aircraft's attitude angle. However, instead of using smart antennas, this technique relies on the conventional dipole triad antenna found on aircraft. Attitude determination on communication satellites has never before relied on the DOA of a terrestrial signal. Smart antenna orientation with respect to a ground station's signal source is recorded in the DOA. Therefore, a satellite's attitude can be further referenced by a ground signal source at a known location. In order to determine the attitude of a communication satellite, this work is interested in employing the DOA estimate of a ground signal source (a ground station or a ground mobile user) as the observation of the extended Kalman filter (EKF). Using data on the position of the signal source on the ground, the location of the satellite in orbit, and the geometry of the area between the source and the smart antennas, we can derive an equation for measuring the direction of arrival of a signal. We conduct a comprehensive study on the inaccuracy of the attitude measurement equation while considering DOA. The satellite dynamics, the attitude measurement equation with DOA estimation, and the measurement errors are then used to propose an attitude determination method. Finally, the stability, convergence time, and estimation accuracy of the proposed approach to attitude determination are analyzed by looking at the effects of the number of snapshots and the input signal-to-noise ratio (SNR). The following is the outline for this paper. In Section 2, we provide the fundamental attitude model for satellites. Section 3 explains how to get DOA from an attitude measurement. In Section 4, we examine how DOA influences the attitude measurement equation's inaccuracy.

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In Section 5, we develop the attitude determination method that accounts for DOA. The Section 6 analysis and visualization of the simulated outcomes of the procedure. Section 7 proposes some last thoughts and suggestions for moving ahead.

Conceptual framework

Fig. 1 depicts the relationship between the satellite and the attitude reference of the ground signal source d S in an effort to solve the attitude determination issue of a satellite equipped with intelligent antennas. We focus on the situation of a single ground source for attitude determination and assume that the smart antennas have access to a line-of-sight (LOS) signal component from the ground to the satellite. In Fig.1 we see three reference frames, and they are all right-hand orthogonal triads. Where O represents the mass center of the satellite, Z represents the center of the Earth, and H represents the direction of flight, Fo represents the orbital frame OHXZ. Where x is parallel to x' body axis and y to y' body axis, and R is the center of the smart antennas which is located in the x y plane, we have the satellite body fixed frame, denoted by Fb, and the receiving smart antennas frame, denoted by Fr, where z is parallel to z' body axis and x, y, and z are all in the same plane.

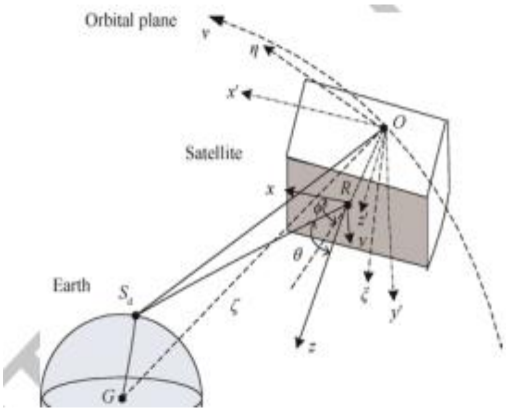

Fig.1. DOA and attitude of reference frames for the communication satellite In Fig.1, the DOA vector is defined by (,) Q F in Fr , where Q is the polar angle which is measured from the signal source vector RSd v to z axis, and F is the azimuth angle that corresponds to Q in the same spherical coordinate system. Then, the unit vector of the reference vector RSd v denoted as

$$\boldsymbol{S}_{dr} = [S^r_{dx}, S^r_{dy}, S^r_{dz}]^T \text{ in } F_r$$

in Fr is calculated as

$$\boldsymbol{S}_{dr} = [\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta]^T$$

The satellite attitude is defined by the orientation of the satellite body fixed frame Fb with respect to the orbital frame Fo . The attitude matrix Cbo is defined as the transfer matrix from Fo to Fb and T C Cobbo is the attitude matrix from Fb to Fo . Since the smart antennas frame Fr parallels to Fb , the attitude matrix Cro from Fo to Fr is given by

$$\boldsymbol{C}_{ro} = \boldsymbol{C}_{bo}$$

The attitude from Fo to Fb is described by quaternion parameterization

$$\dot{q}_{bo} = (q_{bo_0}, \boldsymbol{q}_{bo})$$

Attitude measurement equation with DOA

The basic model of DOA estimation

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The DOA estimation is based on the relative arrival times of a source signal at the array elements and the second-order statistics [7,9]. Assume that there are M elements in the antenna array located at the x-y plane. A steering vector a(,) Q F characterizes the relative phase with the DOA (,) Q F . The received input data vector

$$\boldsymbol{X}(t) = [x_1(t),\ x_2(t),\ \ldots\ ,x_M(t)]^{\mathrm{T}}$$

can be expressed as

$$\boldsymbol{X}(t) = \boldsymbol{a}(\theta,\phi)s(t) + \boldsymbol{N}(t)$$

where s t( ) is the received signal and

$$\boldsymbol{N}(t) = [n_1(t), n_2(t), \ldots, n_M(t)]^{\mathrm{T}}$$

is the noise vector. The spatial covariance matrix Rxx is defined in

$$\boldsymbol{R}_{xx} = E[\boldsymbol{X}(t)\boldsymbol{X}(t)^{\mathrm{H}}]$$

where H X( )t is the complex conjugate transpose of X( )t [9]. In practice, this matrix is estimated by L snapshots of the actual antenna array output, as shown in

$$\boldsymbol{R}_{xx} = \frac{1}{L}\sum_{l=1}^{L} \boldsymbol{X}(lT)\boldsymbol{X}(lT)^{\mathrm{H}}$$

where T is the sampling interval [9]. An eigenvalue decomposition of Rxx can be used to form a noise subspace matrix VM containing the noise eigenvectors [7,9]. Multiple signal classification (MUSIC) is a high-resolution estimation method of DOA using the steering vector [7, 14,15]. The DOA ˆˆ (,) Q F of the signal can be estimated by locating the peaks of an MUSIC spatial spectrum [14]

$$P_{\mathrm{MUSIC}}(\theta,\phi) = 1\Big/\boldsymbol{a}^{\mathrm{H}}(\theta,\phi)\boldsymbol{V}_M\boldsymbol{V}_M^{\mathrm{H}}\boldsymbol{a}(\theta,\phi)$$

The precision of the DOA ˆˆ (,) Q F is limited by the input SNR and the number of snapshots on condition that the difference between the elements and the mutual coupling between the antennas array are compensated [9, 16,17]

Error analysis of attitude measurement

Smart antennas model

In our study, the LEO satellite we are developing will run in a Sun-synchronous circular orbit with an altitude of 800 km and a local time of descending node of nominal 8:00 AM [18]. The LEO satellite tests mobile communication technology with a uniform circular array (UCA) which is composed of 12 quadrifilar helix antennas (QHAs). The uplink signal wavelength is L 150 mm. Figure 2 represents the smart antennas model of the satellite

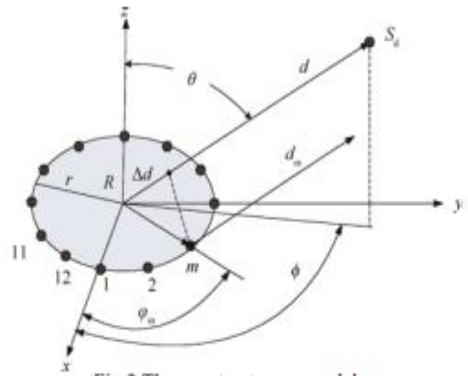

Fig.2 The smart antennas model In Fig.2, the UCA radius is r 150 mm. d and md are the distance from the signal source d S to center of array R and the element . The element phase angle is 2ʌ(1) /12 J m mfor m 1, 2,...,12 . The unit vector of Rm v denoted as

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$$\boldsymbol{M}_{\mathrm{r}} = [M_x^{\mathrm{r}}, M_y^{\mathrm{r}}, M_z^{\mathrm{r}}]^{\mathrm{T}} \text{ in } F_{\mathrm{r}}$$

is given by

$$\boldsymbol{M}_{\mathrm{r}} = [\cos\varphi_m, \sin\varphi_m, 0]^{\mathrm{T}}$$

$$\begin{aligned}\Delta d &= d - d_m \\ &= r\boldsymbol{S}_{\mathrm{dr}}\boldsymbol{M}_r \\ &= r\sin\theta\cos(\phi - \varphi_m)\end{aligned}$$

The difference between the elements and the mutual coupling of the antenna array can be compensated by array calibration methods [9, 16,17]. From this, the steering vector is given by

$$\boldsymbol{a}(\theta,\phi) = \begin{bmatrix} \exp(\mathrm{j}\frac{2\pi}{\lambda} r\sin\theta\cos(\phi - \frac{2\pi}{12}\cdot 0) \\ \exp(\mathrm{j}\frac{2\pi}{\lambda} r\sin\theta\cos(\phi - \frac{2\pi}{12}\cdot 1) \\ \vdots \\ \exp(\mathrm{j}\frac{2\pi}{\lambda} r\sin\theta\cos(\phi - \frac{2\pi}{12}\cdot 11) \end{bmatrix}$$

Attitude determination algorithm

The satellite dynamic model

The satellite can be stabilized in three axes by corporately using reaction wheels and three-axis magnetorquer rods [18]. Therefore, the dynamic equation is given by

$$\boldsymbol{I}_{3\times3}\dot{\boldsymbol{\omega}}_{\mathrm{bi}}(t) = -[\boldsymbol{\omega}_{\mathrm{bi}}(t)\times][\boldsymbol{I}_{3\times3}\boldsymbol{\omega}_{\mathrm{bi}}(t) + \boldsymbol{h}(t)] - \dot{\boldsymbol{h}}(t) + \boldsymbol{T}_{\mathrm{mt}}(t) + \boldsymbol{T}_{\mathrm{d}}(t)$$

$$\boldsymbol{\omega}_{\mathrm{bo}} = \boldsymbol{\omega}_{\mathrm{bi}} - \mathbf{C}_{\mathrm{bo}}\boldsymbol{\omega}_{\mathrm{o}}$$

where Wbi is the vector of inertial rotational velocity and h is the angular momentum of the wheels taken as a whole. Magnetorquer rods generate a torque denoted by the symbol Tmt.ˈTorques of disruption, denoted by Td; The angle of orientation toward fo, denoted by Wbo; What is the angular velocity of the satellite's orbit? The satellite's inertia matrix, denoted by

Calculational Outcomes

Two scenarios are shown here: The effectiveness of the suggested technique is shown by two simulations: 1) an attitude determination using DOA simulation, and 2) a Monte Carlo simulation demonstrating the effects of input SNR and the number of snapshots. All simulations follow the same flight plans as described in Section 4.2, and the satellite has access to at least one ground signal for every 5000 seconds in orbit. The initial inertial referenced angular velocity Wbi is T [0.5,0.5,0.5] °/s, and the initial Euler angles are o yaw 50, o roll 50, and o pitch 50. RW and Q are also selected in the same manner as described in Section 4.2 and Section In the first simulation, we set the input SNR to 0 dB and run 100 snapshots. The duration of the simulation is around 5000 s (one orbit). Figure 6 and Figure 7 show the estimated Euler angles and the inertial referenced angular velocity Wbi for this simulation instance, respectively, using the DOA estimation. The mistakes in the attitude angles are shown to converge to a value of 0.5 degrees after 1500 seconds, but the errors in the angular velocity take over a thousand seconds to reach 0.1 degrees per second in the simulation. The precision of the communication satellite's Earth-pointing estimate is satisfactory. Furthermore, the LEO satellite observes each station or mobile user for roughly 10 minutes (i.e., 600 s). To employ the approach, at least three ground stations or mobile users must maintain constant two-way communication with the satellite over the 1500 s required for the attitude determination convergence. The results show that satellite attitude estimates can be made using the suggested approach based on the DOA (,) Q F.

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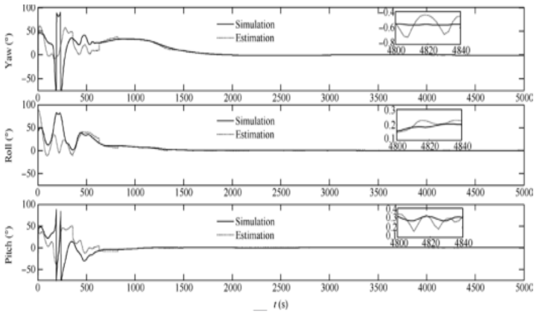

Fig.3 Estimation errors of attitude angles

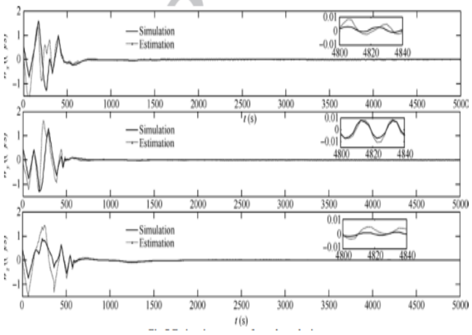

Fig.4 Estimation errors of angular velocity

The second simulation investigates the influences of the number of snapshots and the input SNR on performance. The precision of the DOA ˆˆ (,) Q F and the attitude determination can be described with the average root mean square error (RMSE) of estimates from 200 Monte Carlo trials

$$\mathrm{RMSE} = \sqrt{\frac{1}{200J}\sum_{i=1}^{200}\sum_{j=1}^{J}(x_j^{\mathrm{true}} - \hat{x}_j^i)^2}$$

where J is the total step number in each trial; true j x is the actual value; and ˆ i j x is the estimation of true j x in the ith Monte Carlo trial. The RMSEs of the DOA estimation and the attitudedetermination versus the input SNR with L 100 are shown in Table 1. The RMSEs of the DOA estimation and the attitude determination versus the number of snapshots with an SNR of 0 dB are shown in Table 2.

Table 1 RMSE of the attitude determination versus the input SNR

Number of snapshots	SNR (dB)	RMSE of $\hat{\theta}$ (°)	RMSE of $\hat{\phi}$ (°)	RMSE of yaw (°)	RMSE of roll (°)	RMSE of pitch (°)
100	−14	11.118	68.128	7.397	3.662	1.732
100	−12	4.106	17.337	0.652	0.177	0.457
100	−10	1.518	1.307	0.130	0.079	0.215
100	−8	0.921	0.791	0.109	0.078	0.157
100	−6	0.595	0.534	0.094	0.071	0.111
100	−2	0.354	0.334	0.084	0.060	0.094
100	0	0.315	0.308	0.083	0.061	0.094
100	14	0.287	0.289	0.084	0.060	0.093

Table 2 RMSE of the attitude determination versus the number of snapshots

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Number of snapshots	SNR (dB)	RMSE of $\hat{\theta}$ (°)	RMSE of $\hat{\phi}$ (°)	RMSE of yaw(°)	RMSE of roll (°)	RMSE of pitch (°)
1	0	8.354	51.089	15.956	10.071	6.852
10	0	0.781	0.684	0.099	0.070	0.146
20	0	0.408	0.385	0.086	0.064	0.100
50	0	0.342	0.326	0.084	0.062	0.091
100	0	0.315	0.308	0.083	0.061	0.094
1000	0	0.287	0.289	0.084	0.062	0.093

Obviously as shown in Table 1 and Table 2, the DOA estimation is more accurate as the increases of the number of snapshots and the input SNR. It is consistent with the results in Section 4.2. In the same way, the performance of the attitude determination is much better. Especially, the RMSE of the attitude determination is better than 0.1° when the input SNR is greater than 6 dB or the number of snapshots is more than 50. In addition, we can see that the attitude determination accuracy is higher than that of the DOA estimation especially in the case of lower input SNRs and less number of snapshots in Table 1 and Table 2 (e.g., the case of one snapshot or 10 dB). The error of the DOA estimation W is injected into the attitude measurement equation Eq. (18) and its statistical properties are analyzed in Section 4.2. As a result of the attitude determination using the measurements as well as a prior knowledge about the time evolution of attitude and the statistical properties of the measurement error W , the precision of the attitude determination is improved. The simulation results also demonstrate the validity of the measurement error W analysis in Section 4.2. To sum up, the proposed method of attitude determination using DOAs estimation of ground terminals or stations could be an available method for communication satellites with smart antennas. Its accuracy depends on the input SNR and the number of snapshots. Thus, the above factors should be comprehensively considered for different situations in practical applications.

Conclusions

This paper introduces a novel approach to determine satellite attitude with DOA estimation. Based on the geometrical relationship between a signal source (a ground station or a ground mobile user) and an antenna array, an attitude measurement equation is derived and the error of the attitude measurement equation is analyzed in detail. By using this equation, the algorithm of attitude determination is obtained for communication satellites with smart antennas. Simulation results validate that this algorithm can estimate the attitude of a satellite effectively. The method could be a backup method of attitude determination to prevent a system failure. In addition, the influences of the SNR and the number of snapshots are explored on the performance of attitude determinationFor future studies, on conditions of several reference sources on the Earth for attitude determination and DOA estimation in presence of mutual coupling, the effects of attitude accuracy will be discussed in great detail in another paper.

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