PROPOSED DESIGN OF A FAULT-TOLERANCE ATTITUDE ESTIMATOR FOR SMALL EARTH OBSERVATION SATELLITE

Ngo Duy Tan
Space Technology Institute, Vietnam Academy of Science and Technology, 18, Hoang Quoc Viet, Cau Giay, Ha Noi, Vietnam

Thai Quang Vinh
Institute of Information Technology, Vietnam Academy of Science and Technology, 18, Hoang Quoc Viet, Cau Giay, Ha Noi, Vietnam

Bui Trong Tuyen
Space Technology Institute, Vietnam Academy of Science and Technology, 18, Hoang Quoc Viet, Cau Giay, Ha Noi, Vietnam

ABSTRACT
Attitude Determination and Control Subsystem (ADCS) is considered as the most complex subsystem on-board on-board an Earth observation satellite. The subsystem functions to point the satellite to the desired target especially for earth imaging task. Its performance is certainly decided by the accurate and reliable data provided by the attitude estimator. However, the estimator which is the fusion of multiple sensors data such as gyroscope and star tracker is heavily impacted by uncertain parameters such as the system noise, measurement noise and sensor unavailability delivering unreliable attitude outputs. This paper will describe a fault-tolerant gyro-stellar estimator (GSE) to effectively fuse the measurements from gyroscope and star tracker and for small Earth observation satellite.

Key words: attitude sensor fusion, fault-tolerance estimator, gyro-stellar estimator, fuzzy-tuning filter.

http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=1

1. INTRODUCTION
Generally, the term “sensor fusion” refers to the process of combining measurements from several different sensors in order to obtain a better result than considering each sensor separately. It is especially useful for such system equipped with different types of sensors
Proposed Design of a Fault-Tolerance Attitude Estimator for Small Earth Observation Satellite

having distinctive characteristics in output data, sampling rates and level of accuracies. Common attitude sensors for earth observation satellite are:

- Inertial sensor: accelerometers, gyroscope …
- Reference sensor: sun sensors, Earth sensor, magnetometers, star trackers…

Each type of the above sensors has its own advantages and disadvantages. Particularly, inertial sensors are of high accuracy (typically to the one hundredth of a degree) but suffering from drift over time and may contain moving parts; reference sensors do not provide high accuracy (one to several degrees) and depend on the reference frame, but are low cost, robust and containing no moving parts. In practice, an in-orbit satellite is a non-linear system due to influences by unwanted factors including:

- External forces: perturbation forces, solar pressure, gravity gradient…
- Internal forces: vibration effects by solar panel mechanism, momentum wheels,
- Sensor inaccuracy and unavailability.
- Sensor misalignment.

Kalman filter (KF) functions well as a filter for satellite attitude by fusion of gyroscopes and star tracker. This type of filter (KF-GSE) is relatively simple and especially effective for low-Earth orbit satellites with certain level of estimation error and fault-tolerance. However, unwanted circumstances such as star tracker unavailability due to bright object (Sun and Moon) or high drift of gyroscope will lead to unreliable attitude determination. This situation may be more severe during period of target imaging. Therefore, it is necessary to propose a fault-tolerance algorithm for gyro-stellar estimator. The operation of the proposed estimator is mainly relied on the traditional Kalman filter with fault-detection and fuzzy-based gain tuning. This fault-tolerance filter will be simulated with 02 typical on-board circumstances which are faulty sensor during imaging and noisy measurement during earth pointing. The next section will describe the modeling of gyroscope, star tracker and the basic Kalman filter for attitude estimator (KF-GSE).

2. MODELLING OF ATTITUDE SENSOR AND KALMAN FILTER FOR GSE

2.1. Modelling of Gyroscope

Gyroscope is considered as an orientation measuring device with relatively good accuracy. Mechanical sensors operating on the principle of conservation of angular momentum, usually consists of a rotating wheel or disk around its shaft. One of the main disadvantages of these sensors is its moving parts, leading to the declining in their usage. They are being replaced by optical fiber or laser gyroscope. Both of them operate on the Sagnac effect. They are of high accuracy; containing no moving parts and high reliability. However they are suffering from drifts and noises. In particular, the commonly used optic gyroscopes’ drifts are highly susceptible to the Earth’s magnetic field. This needs to be seriously considered when using gyroscopes for attitude determination.

For a 3-axis attitude controlled satellite, each axis will be equipped with a gyroscope for its attitude prediction. As such, there will be error resulted from the mechanical misalignment of the mounting of the gyroscopes on the satellite platform.

Mathematical model of a gyroscope can be represented as following [1]:

http://www.iaeme.com/IJMET/index.asp 135  editor@iaeme.com
\[ \dot{\omega} = (I_{3 \times 3} + S)\omega + \beta + \eta_v \]
\[ \dot{\beta} = \eta_u \]
\[ \dot{s} = \eta_s \]
\[ \dot{k}_U = \eta_U \]
\[ \dot{k}_L = \eta_L \]
\[ S = \begin{pmatrix} s_1 & k_{U1} & k_{U2} \\ k_{L1} & s_2 & k_{U3} \\ k_{L2} & k_{L3} & s_3 \end{pmatrix} \]

Where: \( \dot{\omega} \) as the measured velocity, \( \beta \) as the drift, \( S \) as the scale factor matrix
\[ s, k_U \text{ and } k_L \] as the misalignment error;
\[ \eta_u, \eta_s, \eta_U \text{ and } \eta_L \] as the Gaussian white noises with the zero mean value and:
\[ E \{ \eta_u(t) \eta_u^T(t) \} = \sigma_u^2 \delta(t-t) I_{3 \times 3} \]
\[ E \{ \eta_s(t) \eta_s^T(t) \} = \sigma_s^2 \delta(t-t) I_{3 \times 3} \]
\[ E \{ \eta_U(t) \eta_U^T(t) \} = \sigma_U^2 \delta(t-t) I_{3 \times 3} \]
\[ E \{ \eta_L(t) \eta_L^T(t) \} = \sigma_L^2 \delta(t-t) I_{3 \times 3} \]

Where \( E \{ \} \) denotes the expectation and \( \delta(t-t) \) denotes the Dirac pulse function.

### 2.2. Modelling of star tracker

A star tracker (SST) is a high-accuracy sensor. The sensor images the stars and compares the captured pictures with a star map on board, the differences then be used to calculate the satellite orientation. The sensor’s accuracy depends on several factors such as the number of stars it can track, its star map and the quality of its optical components. Its accuracy is usually in the range of several arc seconds.

Star tracker is modeled as [1]:
\[ q_s = \mathcal{E} q \otimes q \]

Where:
\[ q_s \] is the quaternion measured attitude,
\[ q \] is the quaternion real attitude,
\[ \delta q \] is the sensor noise.

http://www.iaeme.com/IJMET/index.asp editor@iaeme.com
2.3. General structure of kalman filter gyro-stellar estimator

General structure of the KF-GSE to fuse data from gyroscope and star tracker is described as follows.

The chosen state vector is \([q \, \beta]\)

Where \(q\) is the attitude quaternion and \(\beta\) is the gyroscope drift.

The estimation process is divided into three phases:

- Prediction of the state vector: a predicted quaternion is calculated based on the estimated quaternion at the previous time step and the gyro measurement. The predicted drift is equal to the estimated drift at the previous time step.

- Calculation of innovation: The angular difference between star tracker measured quaternion and predicted quaternion is calculated.

- Correction: The predicted attitude quaternion and drift is corrected by the innovation, previously multiplied by the filter gain.

The KF-GSE operation is illustrated in the following table:

| Initialize | \(q(0) = q_0\) |
| State prediction based on quaternion kinematics equation. \(\omega_{k,\text{Gyr}} \cdot \text{gyro measurement} \) | \(\hat{\omega}_{k-1} = \omega_{k,\text{Gyr}} - \hat{\beta}_k\) |
| Calculation of innovation through multiplication of star tracker measurement and predicted attitude \(q_{k,\text{SST}} \cdot \text{SST measurement} \) | \(\Delta z_{k+1} = 2q_{k,\text{SST}} \otimes \hat{q}_{k+1}\) |
| Correction of attitude and gyro drift Correction factor for attitude \(q_{k,\text{Cor}}\) Correction factor for gyro drift \(d_{k,\text{Cor}}\) | \(X_{k,\text{Cor}} = \begin{bmatrix} q_{k,\text{Cor}} \\ d_{k,\text{Cor}} \end{bmatrix} = K_{\text{GSE}} \Delta z_{k-1}\) |
| | \(\hat{q}_{k-1,\text{Cor}} = \hat{q}_{k-1} \otimes q_{k,\text{Cor}}\) |
| | \(\hat{\beta}_{k-1,\text{Cor}} = \hat{\beta}_k - d_{k,\text{Cor}}\) |

The above KF-GSE is simple but efficient enough for small earth observation satellite. This has been applied for various platforms and well-proven. The key issue of the estimator is the selection of the Kalman filter gain \(K_{\text{GSE}}\). The optimal gain is selected by thorough analysis, simulation and verification. This is also much dependent on the characteristic of the platform and mission requirements. The main issue of the above GSE is limited robustness especially in cases of sensor failure or unavailability. This fact leads to the necessity to propose specific adaptive mechanisms for the KF-GSE which will be demonstrated in the next sections.
3. DESIGN OF FAULT-TOLERANCE GYRO-STELLAR ESTIMATOR FOR SMALL EARTH OBSERVATION SATELLITE

3.1. Design of adaptive KF-GSE

Some innovation based tuning strategies have been proposed such as in [1] and [3] for Extended Kalman filter GSE. The mechanism described in [1] has been applied for this article with KF-GSE and for measurement noise covariance $R_k$ with the following approach:

$$R_k = R_0a^{2(k+1)}$$  \hspace{1cm} (4)

The estimator gain is adapted as given below:

The KF-GSE is adapted as follows:

Table 2 Structure of the Adaptive KF-GSE

| Initialize | $q(0) = q_0$ |
|           | $\beta(0) = \beta_0$ |
|           | $P(k_0) = P_0$ |
|           | $R(k_0) = R_0$ |

State prediction based on quaternion kinematics equation.
$\omega_{k,Gyro}$: gyro measurement

$$\hat{\omega}_{k+1} = \omega_{k,Gyro} - \hat{\beta}_k$$
$$\hat{\beta}_{k+1} = \hat{\beta}_k$$
$$\hat{\mathbf{q}}_{k+1} = \hat{\mathbf{q}}_k \otimes \mathbf{q}(\omega_{k+1})$$

Calculation of innovation through multiplication of star tracker measurement and predicted attitude
$q_{k,SST}$: SST measurement.
FLO: evaluation function on innovation

$$\Delta \mathbf{z}_{k+1} = 2q_{k,SST} \otimes \hat{\mathbf{q}}_{k+1}$$
$$\alpha = FLO(\text{var}(\Delta \mathbf{z}_{k+1}), \text{mean}(\Delta \mathbf{z}_{k+1}))$$
$$P_{k+1} = (I - K_{k,GSE})P_k$$
$$R_k = R_0a^{2(k+1)}$$
$$K_{k+1,GSE} = P_{k+1} / (P_{k+1} + R_k)$$

Correction of attitude and gyro drift
Correction factor for attitude $q_{k,Cor}$
Correction factor for gyro drift $d_{k,Cor}$

$$X_{k,Cor} = \begin{bmatrix} q_{k,Cor} \\ d_{k,Cor} \end{bmatrix} = K_{k-1,GSE} \Delta \mathbf{z}_{k-1}$$
$$\hat{q}_{k-1,Cor} = \hat{q}_{k-1} \otimes q_{k,Cor}$$
$$\hat{\beta}_{k-1,Cor} = \hat{\beta}_k - d_{k,Cor}$$

The weighting factor $a$ is evaluated by a Fuzzy Logic Observer (FLO) which is described in [4]. The FLO takes the innovation mean and variance as its inputs to evaluate the tuning factor $a$. The proposed block diagram is shown in the following figure:

Figure 1 Structure of the Fuzzy Logic Observer
The Membership Function of the Observer is designed as follows:

![Figure 2 Membership function for input mean value](image)

![Figure 3 Membership function for output](image)

For the output $a$, 4 levels are the range of $[1; 1.2]$ as: zero, small, average and large. The fuzzy referring rules are proposed as bellows [3]:

<table>
<thead>
<tr>
<th>Value of $a$</th>
<th>Input 1: value of the mean</th>
<th>Input 2: standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Small</td>
<td>Large</td>
<td>Zero</td>
</tr>
<tr>
<td>Large</td>
<td>Average</td>
<td>Small</td>
</tr>
</tbody>
</table>

### 3.2. Satellite Model and Attitude Control

For earth observation satellite, it should be noted that, the attitude control strategy is different from mode of operation. For example, in Earth-pointing mode, the satellite shall keep the spacecraft body pointing toward the Earth, that means the angular rate is kept at $\frac{2\pi}{T_o}$ (rad/s) with $T_o$ is the orbital period of the satellite around the earth ($T_o$ is around 90 minutes for Sun-synchronous low earth orbit). When being tasked in imaging mode, a guidance profile shall be followed in orientation and angular rate trajectory.

![Figure 4 Sample guidance profile for satellite angular rate.](image)
The following PID simple control law is used for the purpose of study [2]:

\[ u = -K_p q_e - K_d \omega \]  

(5)

Where: \( u \) is the commanded torque to be applied on the satellite reaction wheel as actuator  
\( K_p, K_d \) are the control gain matrices  
\( q_e, \omega \) are errors in orientation and angular rates

For the purpose of analysis and simulation, the satellite is considered as a rigid body and its model of dynamics and kinematics are linearized around the nominal angular rate \([0, -\omega_0, 0]\) (\(\omega_0 = \frac{2\pi}{T_o}\), earth pointing rate) described by the following state equation [2]:

\[ \dot{x}(t) = Ax(t) + B_a N_c(t) + B_{dist} N_{\text{dist}} \]  

(6)

Where: \( x(t) \) is the state vector as \([\omega, q, h]\) and \( h \) is the angular momentum of the reaction wheels  
\( N_c \) is the commanded torque  
\( N_{\text{dist}} \) is the disturbance forces  
\( A, B \): state space matrices

3.3. Proposed strategy for fault-tolerance GSE for small earth observation satellite

Three practical scenarios are considered in order to propose the fault-tolerance GSE, which are:

Nominal mode: the GSE innovation is acceptable then the normal KF-GSE is used to estimate the satellite attitude and angular rates based on the reliable measurements of gyroscope and star tracker.

Sensor degradation due to high level of noise or unavailability: Adaptive KF-GSE algorithm is applied to adapt the Kalman gain in order to improve the reliability of the estimator.

During the imaging phase and noisy gyroscope measurement, if the AKF-GSE innovation is high, the angular rates are calculated from star tracker measurement and are used for the GSE. In the worst case if the innovation is very high, the commanded rates shall be used as the angular rates input instead of the actual gyro measurement.

The above scenarios and performance of the proposed fault-tolerance strategy will be simulated and evaluated with a typical earth observation satellite in the next part of the article.

4. SIMULATION AND RESULTS

The simulation is done in MATLAB with the following inputs:

Satellite specifications:
- Inertial matrix:
Proposed Design of a Fault-Tolerance Attitude Estimator for Small Earth Observation Satellite

\[
J = \begin{pmatrix}
13.5 & 0 & 0 \\
0 & 12.8 & 0 \\
0 & 0 & 18.8 \\
\end{pmatrix} \text{ kg.m}^2
\]

- Star tracker noise: [96° 16° 16°] (on X, Y and Z axis respectively) (3σ)
- Gyroscope drift: 6°/h drift,
- Gyroscope angular rate walk (ARW): 0.15°/√h.
- Satellite nominal rate (earth pointing): 2π/(90*60) rad/s (T_0=90 minutes)
- Commanded angular rates during imaging phase: [-0.0036  -0.0074  0.0032] rad/s
- Imaging phase: To+200 to To+300 (second).
- Earth pointing: To+350 onwards.
- The simulation results are shown as followings:

4.1. Nominal Mode
In case of reliable measurements from gyroscope and star tracker, the basic KF-GSE is applied.

![Figure 5 Outputs from KF-GSE](image)

As seen from the simulation output, the KF-GSE performs well in the normal mode of operation, following reliably the guidance profile and earth pointing requirement.

4.2. Degraded gyroscope measurement
In this scenario, noise is injected to the gyroscope measurements and Adaptive KF-GSE behavior is simulated with the following results:

4.2.1. Normal KF-GSE

![Figure 6 KF-GSE output (uncompensated)](image)
4.2.2. Fault-tolerance estimator (AKF-GSE)

Figure 7 Attitude and angular rates is compensated by star tracker measurements during imaging phase and Adaptive KF_GSE is applied in earth pointing phase.

The fault-tolerance has been simulated and show great improvement of the estimator in phase of imaging and earth pointing as compared to the pure KF-GSE. These results demonstrate the compactness and robustness of the proposed estimator.

5. CONCLUSIONS

Fault-tolerance is a key requirement for on-board attitude estimator due to its harsh operating environment such as noise, sensor failure and unavailability. Additionally reliable and compact processing performance should also be considered for any on-board software due to its limited resources in memory and processing power. The proposed fault-tolerance estimator in this article inherits a very compact and efficient KF-GSE and introduces an adaptive mechanism to avoid the degraded performance of the satellite due to unexpected impacts.

REFERENCES


Proposed Design of a Fault-Tolerance Attitude Estimator for Small Earth Observation Satellite


