Overall Design of Fine Guidance Sensor in Attitude Determination for the SVOM Satellite

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Abstract. SVOM is a Sino-French cooperation project aiming at Gamma Ray Burst observation. From the top level requirement, during the observation period, the satellite platform should provide a stability of better than 1.6 arcsec/100s. Based on this severe requirement, a high precision attitude measurement device is strongly demanded. This article describes the overall design of a novel optical sensor, called Fine Guidance Sensor, for the SVOM Satellite. First, the functional and performance requirements are presented, including the extremely high measuring precision of 0.3 arcsec in y/z-axis. Second, FGS composition, including hardware and software, and processing flow design are described. Then, working mode switching logic is introduced. Next, attitude determination method and simulation result are shown. The conclusion is obtained and all the required indexes are fulfilled by current FGS design.

1. Introduction
SVOM mission is a Sino-French satellite project. The main objective of the SVOM mission is to detect and study gamma-ray bursts (GRBs). These powerful phenomena are attributed to massive star explosions (more than 20 times the mass of the Sun) and the merger of compact objects such as neutron stars or black holes[1]. Under the scientific mode, in order to satisfy the observation requirement driven by the payload, called Visible Telescope (VT), the satellite is generally in inertial pointing mode and the stability must reach a severe level, which is better than 1.6 arcsec/100s. Consider that the satellite’s stability can be allocated to several components, such as the thermal-elastic and micro vibration, the stability requirement attributed to Attitude and Orbital Control Subsystem (AOCs) is less than 0.8 arcsec/100s for y/z-axis [2]. In order to achieve such a high stability, the attitude measurement accuracy should be 0.3 arcsec for y/z-axis at least.

Astronomical observation spacecraft usually take advantage of optical system of telescopes to increase the attitude determination accuracy [3–5]. By designing a fine detector on the focus plane of the telescope, the star image can be obtained, and the difference between the detector and the telescope can be neglected. As a result, the stability of the spacecraft can be greatly increased to lower than 1 arcsec during a large time scale.

VT of SVOM satellite is designed and developed by Xi’an Institute of Optics and Precision Mechanics of CAS [6]. Two special Fine Guidance Sensor (FGS) CCDs are added on the VT’s focus plane, above and below VT’s CCD, as shown in Figure 1. By using the attitude information provided
from the same focus plane with the telescope, the payload information is involved in control loop, and the thermal-elastic affect can be prevented.

2. Functional and performance requirements

FGS system autonomously provides high accurate 3-axis attitude information with regard to the J2000 inertial reference frame. High quality images of the celestial sphere are acquired from the autonomous FGS FOV by means of an optical system and two CCD detectors. The digital signal processing, performed in hardware and software, realizes the star acquisition and attitude determination. FGS also have the ability of calibration in orbit.

The main characteristics of FGS are shown in the table below.

| Item                          | Characteristic                        |
|-------------------------------|---------------------------------------|
| Focus                         | 3600mm                                |
| Effective calibre             | 400mm                                 |
| FOV (each CCD)                | 12.7arcmin×12.7 arcmin                |
| Detector                      | CCD47-20                              |
| Spectrum range                | 400–650 nm                            |
| Stars                         | > 15 magnitude range                  |
| Guide star catalogue          | No                                    |
| Number of stars (each CCD)    | ≥ 1 (over 98% cases)                  |
| Window size                   | 60×60 pixel²                          |
|                                | 15×15 pixel²                          |
| Measurement accuracy          | 0.3arcsec (X/Y axis, 3 sigma)         |
|                                | 5arcsec (Z axis, 3 sigma)             |
| Mode                          | Standby mode                          |
|                                | Full frame mode                       |
|                                | Big window mode                       |
|                                | Small window mode                     |
|                                | Calibration mode                      |
| Data frequency                | 1Hz, 2Hz                              |

From Table 1, we can find that the required measuring accuracy of FGS must reach one order lower than 1 arcsec, which is better than the traditional Star Trackers.

Figure 2 shows the optical layout and path of VT and FGS channels. Figure 3 shows two typical images obtained by FGS.
3. FGS composition and processing flow design

3.1. FGS composition

The FGS is not off-shelf equipment, but a newly designed and developed system, which is of the greatest importance for AOCS [7]. The FGS’s hardware are not realized in a single box, but distributed in VT, Satellite Management Unit (SMU) and Payload Data Processing Unit (PDPU).

FGS system includes hardware and attitude determination software, and the main components and their locations are shown in table below.

| No. | Hardware item               | Location   | Software function                                      |
|-----|-----------------------------|------------|--------------------------------------------------------|
| 1   | Baffle                      | VT         | Star image obtain                                      |
| 2   | Optics                      | VT         |                                                        |
| 3   | Detector                    | VT         |                                                        |
| 4   | Front Electronics           | VT         |                                                        |
| 5   | Cooler                      | VT         |                                                        |
| 6   | Mechanical structure        | VT         |                                                        |
| 7   | Image processing board      | PDPU       | Image pre-processing, Image calibration                |
|     |                             |            | Star acquisition and centre calculating                  |
|     |                             |            | Star quality sequencing and matching                     |
| 8   | Attitude processing computer| SMU        | Mode management                                         |
|     |                             |            | Window size and position calculating                     |
|     |                             |            | Attitude Determination                                   |
3.2. Processing flow design
FGS performs the following functions using the described hardware:

- Star image obtain
- Image pre-processing
- Image calibration
- Star position calculation
- Attitude Determination

As the data and information are transferred among different part of FGS system, and the commands come from several units, the processing and information flow is complicated. The processing flow diagram of FGS is shown in Figure 4.

![Figure 4. The processing flow diagram of FGS.](image)

4. Mode switching design
The modes switching logic diagram of FGS can be simplified, shown in Figure 5.

After power-on or system reset, FGS automatically enter Standby mode. As seen from the mode switching diagram, the mode can be commanded either in the nominal operational branch or in the Calibration mode. The Calibration mode provides background field calibration, dark field calibration and flat field calibration. The nominal operational branch can be entered by sending command from the standby mode to the Full frame mode. The Full frame mode performs autonomously the full field and multi-image matching. The switch between the Full frame mode and the Window mode is judged by the matching result. After successful matching, switch to the Big window mode is performed automatically. After the stability reach a certain value, assumed to be 1 arcsec/10 s, the Small window mode is performed automatically. Small window mode is the nominal operating mode of the FGS providing valid attitude quaternion measurements.

The software has been developed, implemented and tested by now.
5. Attitude determination method and simulation result

As there is no star catalogue storage budget, FGS cannot determine the absolute attitude. After the initial stability is achieved, the initial attitude has been acquired by Star Tracker in the form of quaternion, and the attitude is kept internally as a-priori absolute information initialization with regard to the J2000 inertial reference frame. The star position variation between two continuous frames are calculated and transferred to the form of delta quaternion. Based on the absolute attitude quaternion obtained by Star Tracker and the relative delta quaternion obtained by FGS, a new quaternion of extremely high accuracy is finally got. As the high stability is driven by VT’s exposure time, only the relative stability is severely required.

Assume the deviation quaternion between \( t_1 \) and \( t_n \) is \( \Delta Q_{FGS} \), we can get the quaternion under the satellite body coordinate \( Q_{FGS} \),

\[
dQ_{FGS}^b = dQ_{FGS}^b \otimes Q(A_{VT})
\]

where \( A_{VT} \) is VT’s assembling matrix and \( Q(A_{VT}) \) is VT’s assembling quaternion. \( \otimes \) is the quaternion multiplication and is defined as

\[
q' \otimes q = \begin{bmatrix}
q_4' & q_3' & -q_2' & q_1' \\
-q_3' & q_4' & q_1' & q_2' \\
q_2' & -q_1' & q_4' & q_3' \\
-q_1' & -q_2' & -q_3' & q_4'
\end{bmatrix} \begin{bmatrix}
q_1 \\
q_2 \\
q_3 \\
q_4
\end{bmatrix}
\]

(2)

where \( q = [q_1, q_2, q_3, q_4]^T \), \( q' = [q_1', q_2', q_3', q_4']^T \).

Assume the quaternion at \( t_1 \) obtained by Star Tracker is \( q_{STR}^1 \), the high accuracy absolute attitude quaternion at \( t_n \) is

\[
q_{FGS}^n = q_{STR}^1 \otimes Q_{STR}^F \otimes dQ_{FGS}^b
\]

(3)

where \( Q_{STR}^F \) is the transfer quaternion from Star Tracker coordinate to FGS coordinate.

As a result, the following attitude information would be all calculated by the variation quaternion and can reach the required accuracy of 0.3 arcsec for y/z-axis.
The following simulation gives an example of the satellite attitude from one pointing to another pointing, and the AOCS mode keeps in High Stability Pointing Mode.

The simulation results of the attitude quaternion, Euler angle, the angular rate, the stability, FGS mode switching and AOCS mode switching curves are shown in Figure 6 ~ Figure 11.

From the simulation results we can see, the FGS mode transfer from Full frame mode to Big window mode and lock in Small window mode at last. This guarantees an attitude determination.
accuracy of 0.3 arcsec. The attitude quaternion and Euler angle convergent in a short time. The angular rate of 3-axis is better than 0.0002 deg/s and the stability in 100s can reach 0.6 arcsec in y/z axis, which fulfils the requirement of 0.8 arcsec/100s well.

6. Conclusion
This research was driven by the high stability requirement during GRB observation period of SVOM satellite. This article is focus on the overall design of the novel attitude determination sensor system, FGS. FGS is not integrated in a single box, but separate in payload and satellite platform instrument. Based on the functional and performance requirements described at first, FGS’s composition and processing flow design are presented. The mode switching design is detailed introduced. The attitude determination method and simulation result are shown at last. According to the simulation results, we can get the conclusion that, the attitude determination precision can reach 0.3 arcsec for y/z-axis, and the mode switching logic is reasonable. The overall stability can be guaranteed by the FGS design.

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