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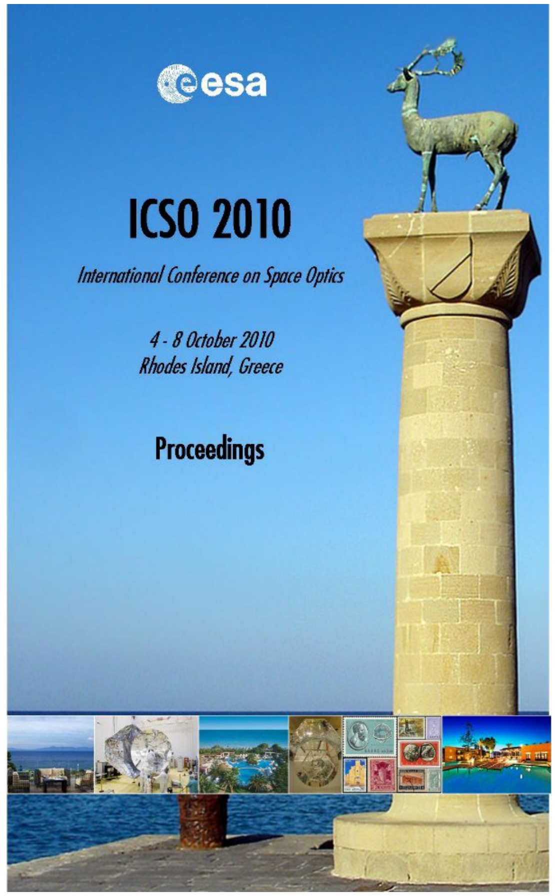

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COMPACT AUTONOMOUS NAVIGATION SYSTEM (CANS)

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I. INTRODUCTION

Autonomous navigation of Satellite and constellation has series of benefits, such as to reduce operation cost and ground station workload, to avoid the event of crises of war and natural disaster, to increase spacecraft autonomy, and so on. Autonomous navigation satellite is independent of ground station support. Many systems are developed for autonomous navigation of satellite in the past 20 years. Along them American MANS (Microcosm Autonomous Navigation System) [1] of Microcosm Inc. and ERADS [2]、[3] (Earth Reference Attitude Determination System) of Honeywell Inc. are well known. The systems anticipate a series of good features of autonomous navigation and aim low cost, integrated structure, low power consumption and compact layout. The ERADS is an integrated small 3-axis attitude sensor system with low cost and small volume. It has the Earth center measurement accuracy higher than the common IR sensor because the detected ultraviolet radiation zone of the atmosphere has a brightness gradient larger than that of the IR zone. But the ERADS is still a complex system because it has to eliminate many problems such as making of the sapphire sphere lens, birefringence effect of sapphire, high precision image transfer optical fiber flattener, ultraviolet intensifier noise, and so on. The marginal sphere FOV of the sphere lens of the ERADS is used to star imaging that may be bring some disadvantages., i.e. , the image energy and attitude measurements accuracy may be reduced due to the tilt image acceptance end of the fiber flattener in the FOV. Besides Japan, Germany and Russia developed visible earth sensor for GEO [4]、[5]. Do we have a way to develop a cheaper/easier and more accurate autonomous navigation system that can be used to all LEO spacecraft, especially, to LEO small and micro satellites? To return this problem we provide a new type of the system—CANS (Compact Autonomous Navigation System) [6].

II. RATIONALE AND CONFIGURATION

CANS is an integrated compact and cheaper sensor system that has possibility to provide overall attitude, overall position and velocity for LEO spacecrafts and satellites. The navigation information is provided by the CANS with many measurement vectors. The star direction can be obtained by star channel; the earth direction can be obtained by earth channel. Then, the starlight angle and the apparent radius are calculated, which are fed into the proposed High-Precision Filter (HPF). The current orbit can be estimated, the details are shown in Fig.1. Certainly the 3-axis attitude can be determined by the Earth center vector and the optical axis vector in the inertial space. Commonly the CANS works in 4 operation modes:

1. Star sensor /the Earth sensor/KF for autonomous navigation based on starlight angle in daylight.
2. Star sensor/the 3-axis gyros/KF for 3-axis attitude determining in nightlight and the HPF for autonomous navigation.
3. Star sensor/ the 3-axis gyros/the Earth sensor/KF/HPF for both 3-axis attitudes and 3-axis positions with information redundancy.
4. The 3-axis accelerometers/ Star sensor/ the 3-axis gyros/the Earth sensor for orbit maneuver.

As is well known the optical wavelength range of current Earth sensor is infrared. Although ERADS uses ultraviolet spectral zone but its application is not be spread. According to the CANS scheme the 8 facets on the octahedron mirror cone and the fold mirror reflect the Earth verge on to the co-imaging lens and then on to the APS detector. The Earth verge image is split to 8 segments on the annulus FOV of the detector. On one of the segments there are many verge points extracted by the method of CRL (Cutting Radial Line). The CRL is a method of extracting the Earth verge by calculating image gray value gradient along the Cutting Radial Line. The rationale of CRL is shown in Fig.2. The extracted points will be transformed to a union reference frame and then used to find the earth center vector by the least square algorithm. For the Earth center determining we can choose the verge image arc that has the maximum radiation gradient by the CRL.

As a way to orbit modifying and holding there is a needless to continuous output of the orbit data as time orbit adjusting is required. Besides the number of the ground station is limited for many countries. Thus CANS's data in daylight is enough to obtain high precision of positions. Commonly the CANS is able to provide overall observation vectors of the starlight angle for orbit daylight autonomous navigation. In the situation of nightlight lacking for the Earth center vector CANS also has the capability to obtain the 3-axis positions and attitudes with HPF that uses star sensor/gyro measurement data and the orbit dynamic equations. But in nightlight the accuracy of positions by HPF is worse than that in daylight.

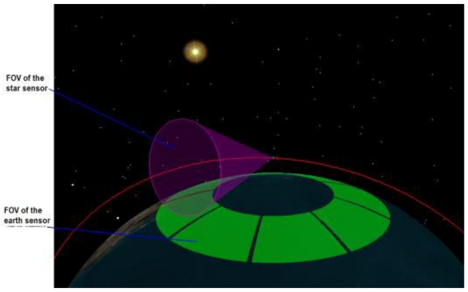


Fig.1 Navigation Principle

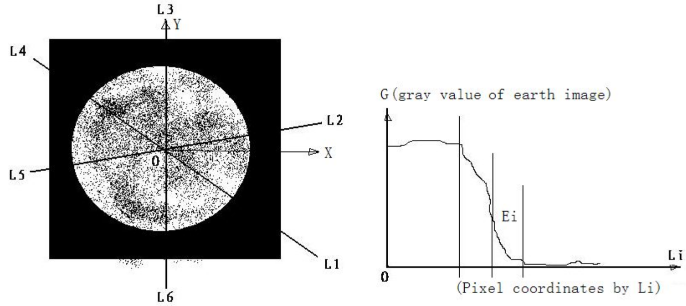
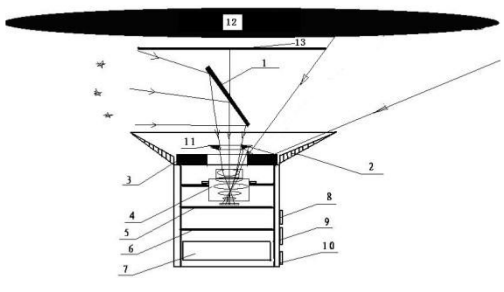


Fig.2 Rationale of the CRL method

Now that the Earth sensor in visible spectra is possible and realizable, it is the time to research the configuration of the CANS, the integrated multiple sensor system. Fig.3 shows us a CANS's structure configuration. Comparing with ERADS the different points are in that the star channel uses the center FOV of the co-imaging lens and the first surface of the lens is its entrance aperture. Furthermore, the materials of all lens is common optical glass, the image is flat and with less distortion. Above-mentioned character of the CANS makes the navigation system lighter, cheaper and easier to manufacture than the ERADS.

The star channel of the CANS involves the star fold mirror, the lens and the detector and occupiedΦ20° center FOV from the whole Φ46° FOV of the lens. Therefore the annulus FOV width of 13° remains for the Earth imaging from 450km to1200km of the orbit altitudes or for the fitting of attitude change in the orbit. The tilt angle of the star fold mirror is considered specially for the stray lights rejection from the Earth and for ensuring the two vectors attitude determination accuracy. The annulus FOV is broken to 8 sub-FOV that image the appearance partial surface of the Earth onto the detector. The every two adjacent sub-FOV images have an overlap which is in dependent of the number of the sub-FOV, the lens focal lens and the detector size. Fig.4 shows CANS's structure assembly drawing by the SolidWorks software. The CANS weight is calculated by the software with result, less than 2.0 kg. The volume of the CANS is smaller than 280mm by 120mm by 120mm. CANS images simulations of real design parameters are shown in Fig.5 in condition of 800km orbit altitude and 90° of sun elevation angle.



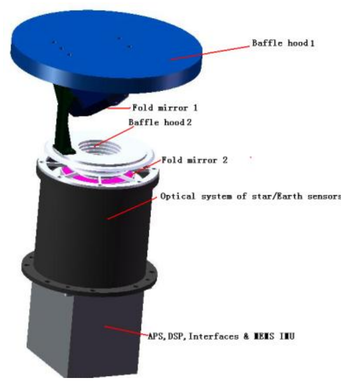


Fig.4. CANS prototype example in whole.

Fig.3 CANS's configuration

1— The star channel fold mirror; 2,13—Baffle hoods; 3—The Earth channel fold mirror; 4—Co-imaging lens; 5—APS CMOS imaging circuit board; 6—DSP circuit board; 7—Inertial measurement Unit based on MEMS; 8—Ground checking interface; 9—Camera Link for video test; 10—Power and Standard communication interface.11—Octahedron mirror cone; 12—The appearance of the Earth from CANS on LEO.

L.: CANS's simulation image as pitch and roll equal 0. R.: CANS's simulation image as pitch and roll equal 3°.
Fig.5. CANS's simulation images by its practical design (Orbit height is 800km, at 12:00 in local time).

III. SENSOR AND SYSTEM PARAMETERS

CANS's Parameters are in the following table 1. The sensor's parameters are in the table 2.

Table 1 CANS's Parameters

Parameters	Requirements	Conditions
Orbit high，(km)	800±350	Any orbit
Position accuracy	200m~240m （3σ）	The Earth is rradiated by Sun light
Velocities accuracy,(m/s)	0.5~2	By Kalman Filtering
Measurement references bias of MEMS IMU and optical unit	Not more than 0.005° (Max.)	After calibration
Output	3-axis attitude ; 3-axis orbit.	Updated rate 5Hz
Volume, mm3	280X120X 120	Without the baffles hood 1
Weight ,(kg)	Not more than 2.0	With the baffle hoods
Total power consumption,(w)	Not more than 8	
Interface	Dual RS422,Camera link	

Table 2 The sensors parameters

Parameters	Requirements	Conditions
Field of view, (°)	Φ20center cone Φ114° ~Φ140° annulus	_
Collecting aperture,(mm)	Φ22	_
IFOV	0.023°	_
Lens material	Common optical glasses	Flat image
Optical efficiency	0.65	Inc. fold mirrors
Star sensitivity	5 Mv	
Detector type	APS CMOS, LUPA 4000	2048X2048 with 0.012mm/ pixel
DSP type	SMJ320C6000	2000MIPS
Memory	32Mb	For 4Mb's image format
Star sensor accuracy,(°)	Random 0.005 (X/Y)（3σ） 0.04 (Z)（3σ） Bias 0.01 (X/Y)	Mean star number inΦ20center cone is not less than 10 stars
The Earth sensor accuracy,(°)	Random: 0.03 (X/Y)（3σ） Bias: 0.01 (X/Y)	By compensation of The Earth form and CRL
MEMS gyro null drift	0.0016° /s	±1σ
Weight ,(kg)	Not more than 2.5	Inc. baffles, plugs and sockets
Total power consumption,(w)	Not more than 8	
Interface	Dual RS422 Camera link	

IV. SYSTEM DESIGN

CANS's design include the designs of general scheme, optical system, electronical system, mechanical structure, algorithms and software. Space situations effects are considered in the designs.

A. Optical Design

The optical system includes two imaging channels. One of them is of the star sensor. Another is of the Earth sensor. The two imaging channels share a co-imaging detector and a co-imaging lens with large FOV and high imaging quality to image the stars and the Earth on the co-detector. The co-imaging lens layout is shown in Fig.6. The entrance aperture of the lens is located on the first surface of the lens. The lens is designed by CODE-V software of ORA. Its distortion is near 0. Its maximum lateral color is less than 30μm. Its FOV is Φ 46° . Its mean MTF shown in Fig.7 is not less than 0.3 at the Nyquist frequency. The design results in Fig.6 indicate that the lens design quality is very good at the frequency.

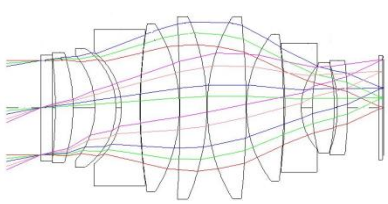


Fig.6. The layout of the co-imaging lens

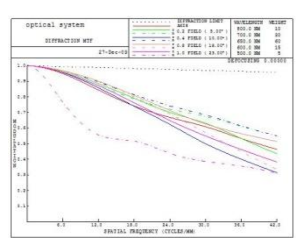
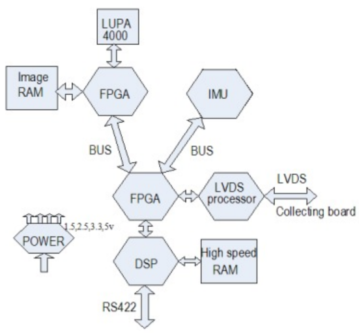


Fig.7. The MTF of the lens

B. Electronical System Design

As shown in the Fig.8 the CANS's electronical systems include power circuit, APS image collecting circuit, LVDS processor, the IMU circuit, the DSP circuit, FPGA circuit and interface circuit. The electronical system can satisfy a series of requirements of imaging, image memory, image transfer, image processing, back tracking and etc. The inside information flow and the circuits structure are shown in the Fig.9.



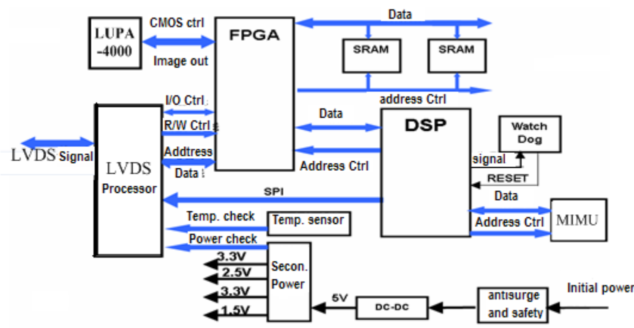


Fig.8. CANS electronical system principle diagram **Fig.9.** The inside information flow and structure

C. Software Modes

The software of the CANS consists of 8 modes. The modes diagram is shown in Fig.10. The initializing mode take in charge in program self checking, initial parameters setup, accepting command, setting exposure time and etc. When the reset command is coming or the power is cycling initializing mode should be operated.The star image channel works as a star sensor. The Earth channel works with the Earth verge and center extracting algorithms developed by our Lab. The autonomous navigation algorithms and simulation results will be explained in the following text.

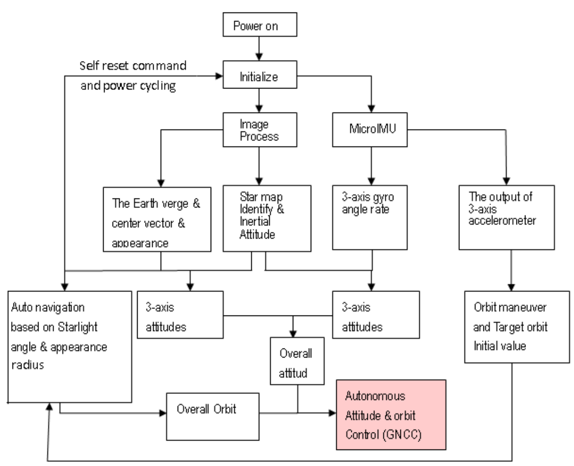


Fig.10. The CANS mode diagram

V. ATTITUDE DETERMINATION

Attitude Determination is a key technology for autonomous navigation satellite. In this article, we proposed the two attitude determination schemes.

(1) Gyro and star sensor are utilized to estimate inertia attitude, including direction-cosine matrix C_{bi} and quaternion q. The orbit information is estimated by high-precision filter algorithm to calculate the transformation matrix C_{io} between inertial coordinate system and orbit coordinate system. Then, the attitude angles, such as roll, pitch, yaw, can be estimated by C_{bi} and C_{io}.
(2) The star/earth sensors are combined to determine 3-axis attitude of a spacecraft by the two-vector method.

The first way can be used as the main working-mode at any time. The second way only can be used in daylight, thus it often is utilized as the redundancy working-mode. The orbit coordinate system attitude estimated error is shown in Fig.11, and the gyro drift estimated error is shown in Fig.12.

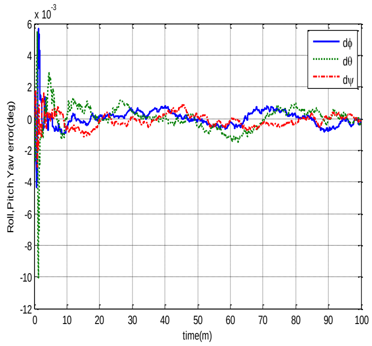


Fig.11. Attitude angle estimation errors

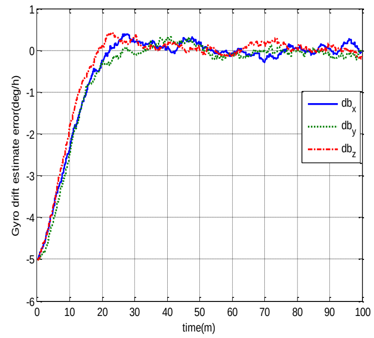


Fig.12. Gyro drift estimation errors

VI. AUTONOMOUS NAVIGATION ALGORITHM & SIMULATION

In the section, a high precision filter algorithm is proposed. The algorithm is not only robust to initial error, but also enhances the system reliability. The system frame is shown in Fig.13. The following simulation results will prove its effectivity of the algorithms. In following text we will discuss the filter model, the observation equation and the simulation results. In the case that only the gravity is considered, the state equation is,

$$\dot{\boldsymbol{r}} = \boldsymbol{v}$$

$$\dot{\boldsymbol{v}} = \boldsymbol{a}_e + \boldsymbol{w} \qquad (4.1)$$

where the vector r and v denote the inertial position and velocity of satellite, a_e is the earth gravity and w is model error, satisfying the following characteristic, $E(w_t)=0$, $E(w_t w_t^T)=Q_t$, The state transfer matrix can be calculated by Eq. (4.2),

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{D} * T \qquad (4.2)$$

where I is unit matrix, T is sampling period and D is Jacobian matrix.

A. Filter Algorithm

The selection of initial value is a key technology. Assumption initial values submit the Gauss distribution, then the initial estimation value $\hat{x}(0/0)$ possibly deviates far from true value, as is shown in Fig.14.From Fig.14, the red line denotes 3σ probability ellipse. These black dots denote the initial values that can match the true value; these blue dots denote the initial values that cannot match the true value.

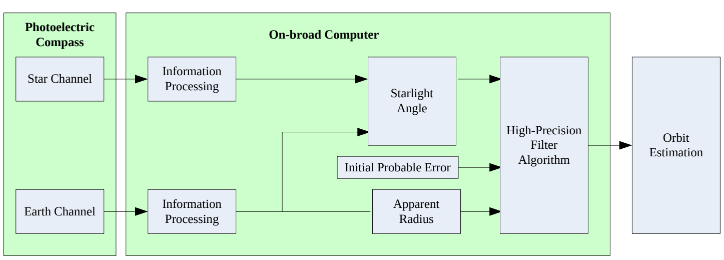


Fig.13. System Frame

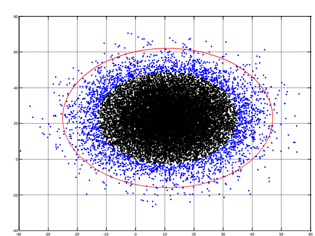


Fig.14. Initial value distribution

The high-precision filter algorithm provides these EKF with different initial values that are created by unscented transformation and are weighted equally. The outputs of every EKF are weighted by auto regression method to obtain the estimation of current state. The details are shown inFig.15.

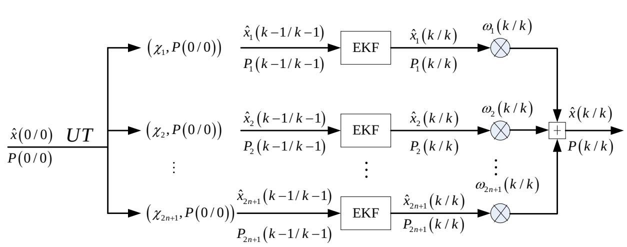


Fig.15. Filter Algorithm

In the article, the starlight angle and apparent radius are chosen as observation. Their equations are written as,

$$\alpha_S = \arccos(-\frac{\boldsymbol{u}_S \cdot \boldsymbol{r}}{|\boldsymbol{r}|}) \quad (4.3)$$

$$\theta = \arcsin(R_e / |\boldsymbol{r}|) \quad (4.4)$$

where u_s denotes the star direction and R_e is earth radius.
The observer equation is shown by Eq. (4.5),

$$\boldsymbol{z} = h(\boldsymbol{x}) + \boldsymbol{v} \quad (4.5)$$

where $h(x) = [\alpha_s \quad \theta]^T$, v is measure noise, that is incorrelate to process noise w and satisfies the following characteristic, $E(\boldsymbol{v}) = 0$, $E(\boldsymbol{v}\boldsymbol{v}^T) = \boldsymbol{R}$.

B. Simulation Results

Navigation coordinate system: the origin is the centre of the earth, the fundamental plane is the plane of the equator, the x-axis directs to the vernal equinox, the y-axis is perpendicular to the x-axis in the fundamental plane and the z-axis points out perpendicularly with respect to the fundamental plane at the origin following the right-hand rule. Simulation conditions are in the following. True model is provided by software STK, according to all kinds of perturbation. start time: 2007.7.1, 12:00:00; end time: 2007.7.1, 15:00:00 ;
Initial state: $a = 7138km, e = 0, i = 97^o, w = 0^o, \Omega = 0^o, f = 0^o$ To prove the effectivity of the proposed filter algorithm, both the high-precision information fusion algorithm and the EKF is used to estimate the orbit. The position and velocity errors are shown in Fig.16 and Fig.17 respectively.

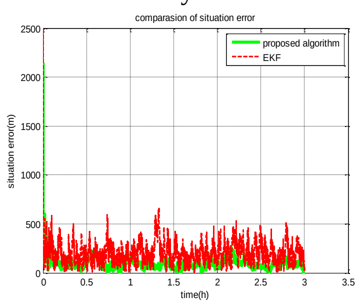


Fig.16. Situation error

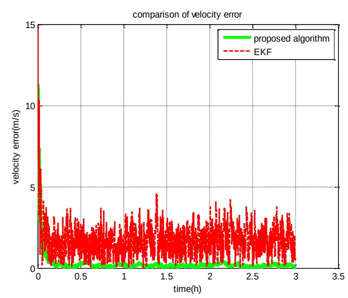


Fig.17. Velocity error

VII. CONCLUSION

A new type of a compact autonomous navigation system (CANS) is provided for determining of overall attitude and overall position/velocity. The principle example scheme of the CANS is designed and realizing. Analysis indicates that CANS in visible spectra for LEO is possible to realize. Reform from IR and ultraviolet spectra to visible make the CANS design very compact and easier. The CANS has a series of characters, such as integrative and compact structure, high accuracy, good engineering capability, which facilitate its application for micro-satellite. The simulation results of the CANS show that the position error in a orbit period can be less thean240m (3σ) and the velocity error can be less than 2.5m/s. Design results indicate that its volume is of 280mm by 120mm by 120mm. The prototype sample manufacturing is expected to be finished in 2010 year.

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