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Attitude Estimation of Nano-satellite according to Navigation Sensors using of Combination Method

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The purpose of this paper is attitude estimation of nano-satellite which requires navigation sensors data for reducing the cost function and movement effect of nano-satellite. The data of navigation sensors and methods are used to achieve the required attitude estimation. The navigation attitude sensors are gyroscope, magnetometer and sun sensor. Furthermore, the extended Kalman filter is used to combine the measured data of gyroscope, magnetometer and sun sensor. This paper presents the methods for accurate estimation of the attitude of nano-satellite missions according to the developed quaternion estimation and nonlinear analysis along with the extended Kalman filter. This work demonstrates the application of nano-satellite with navigation sensors. The methods are used, to achieve high accurate and fast starting attitude estimation. The methods are simulated by MATLAB software. The obtained results were analyzed and compared with other sets of data.

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1. INTRODUCTION

In recent years, a number of universities have been working on space engineering projects, throughscientific projects. First nano-satellite developed at several universities including Iran, Japan and Europe. Nano -satellite is an outstanding satellite technology in astronautics field because of its light weight, short development cycle, low development cost, high functional density and flexible emission characteristics. Satellite attitude estimation sensor is a core part in the nano-satellite, which directly affects the performance of the satellite and satellite payloads. On one hand, the attitude estimation sensor can provide information feedback for the attitude control system to control the attitude of the satellite. At present, attitude estimation sensors which have been applied in launched satellites are star sensor, sun sensor, magnetometer, gyroscope, and so on, but all of these sensors hardly meet the requirements of nano-satellite's attitude estimation. The measurement accuracy of gyroscope that is used to measure angular velocity is higher in short period, and

could output continuous attitude information. But, there are error accumulations because of gyroscope drift in long time. Angular-measurement sensors such as star sensor, sun sensor and magnetometer do not havethe problem of error accumulation, but they cannot output attitude information and the data update frequency is slow.

Therefore, to improve the attitude determination accuracy of nano-satellite, an integrated attitude estimation sensor combining angle sensors with angular velocity sensors was built. In this way, the angle sensors the angular velocity sensors can make up the advantages and disadvantages of each other. The sensor includes gyroscope, sun sensor and magnetometer. Furthermore, the extended Kalman filter was used to fuse measurement data from gyroscope, magnetometer and sun sensor. A model has been simulated for attitude estimation using a combined method.

2. MEASUREMENT MODEL OF SENSOR

In order to establish an integrated attitude estimation model, the principle mathematical model required is

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measurement of the gyroscope, sun sensor and magnetometer. Also, the extended Kalman filter is used to fuse measurement data from gyroscope, magnetometer and sun sensor. Sensors are used to measure the vector components in the BODY frame, attached to the satellite and is moving and rotating with it and NED frame. The North East Down frame has its z-axis pointing downwards, perpendicular to the tangent plane of the Earth's reference ellipsoid frames. An attitude estimation system requires at least two vectors in order to estimate the attitude. Three types of sensors are used in the attitude estimation and control system for the nano-satellite.

2. 1. Gyroscope   Gyroscopes measure the angular velocity. Theoretically, a gyroscope can track the orientation of the satellite by integrating the change in velocity. In order to provide a good estimation, the initial orientation must be correct and the measurement errors should be small. All gyroscopes have some measurement error, called bias. Biases are usually constant or slowly varying. Because of the bias, the orientation cannot be tracked by only using gyros. With time, the attitude estimation will drift. The drift rate varies according to the choice of sensor, but will typically be less than 1deg/s [1]. An advantage is that many gyroscopes are small and can provide quite good measurement data. The gyroscope exporting mathematical model established in this paper is

$$\hat{\omega}_{ib}^{b} = \omega_{ib}^{b} + b + v \tag{1}$$

where ω_{ib}^{b} is the real angular velocity of satellite relative to inertial space, b gyroscope drift and v its white noise.
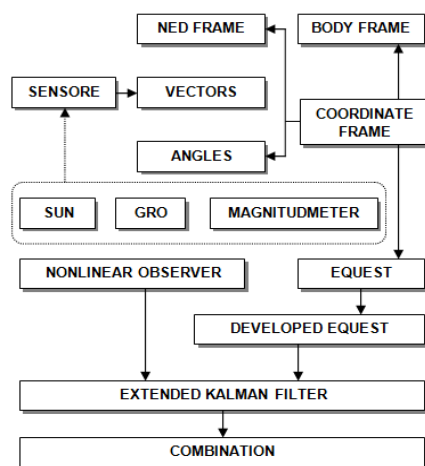

Figure 1. The block diagram of the method

2. 2. Magnetometer   Magnetic field is a vector field, which is the public resource of the earth. The

Magnetic field strength vector of any point in geo space is different from that of another, and corresponds to the latitude and longitude of the point. Therefore, we can determine the attitude of a satellite by precisely determining the position of every point in geo space. Then, we inquire magnetic table to get the Magnetic field vector in the terrestrial coordinate system, which can be used to conduct the solution of filtering together with the magnetic field vector detected by the magnetometer in the satellite coordinate system. According to the Transformation matrixes among geographic coordinate system, earth fixed coordinate system, geocentric inertial system, geocentric orbit system and satellite coordinate system, the Magnetic field under the coordinate system of the satellite is:

$$B_{b} = T_{o}^{b} T_{i}^{o} T_{e}^{i} T_{t}^{e} B_{t} \tag{2}$$

where T is the transformation matrixes among the coordinate systems, and the attitude angle of the system of three-axis stabilized satellite relative to the satellite orbit coordinate system is included in the transformation matrix T_{o}^{b}. When the measurement axis of magnetometer is fixed along the principal axis of inertia of satellite, the output of magnetometer is the vector $\hat{B}_{b}$ of earth's magnetic field in the satellite coordinate system:

$$\hat{B}_{b} = B_{b} + v \tag{3}$$

where B_{b} is the true value of magnetic field in the satellite coordinate system, while v is the measurement error of magnetometer.

2. 3. Sun Sensor   Sun sensors are popular, accurate and reliable, but require clear fields of view. The main idea is to measure the direction to the Sun. Small and cheap sun sensors can be bought and placed on each side of the satellite in order to detect the Sun angle. For nano-satellite, the solar cells might be used. Solar cells are not really sensors, but can be used to detect the direction to the Sun by monitoring the output current. The output from a solar cell depends on the angle between the solar panel and the sun rays. The sun sensors mounted on the satellite will be sensitive to every light source in space. Because of light reflected from the Earth, it is important to use an Earth albedo compensation when computing a sun vector, or else a large angular deviation might occur [2]. A sun sensor reference model is needed for the attitude determination [3]. The typical field of view for a sun sensor is $\pm 30°$, with an accuracy of approximately 0.01°[4]. Sun sensor is a kind of optical attitude sensor, which is used to get the orientation information of a spacecraft relative to the sun by determining the position of sun vector in the satellite coordinate system through sensing the position of sun vector. When the satellite is in a certain position, the vector of the sun in the satellite orbit coordinate

system is S_o and the output vector of the sun by the sun sensor is S_b, therefore:

$$S_b = T_o^b S_o + v \qquad (4)$$

where v is the Measurement error of a sun sensor.

3. MODEL OF ATTITUDE MEASUREMENT

After the detection of the initial attitude, a satellite starts scientific detections during its in-orbit stage. When the attitude of a nano-sattelite has been determined by the combination of Gyroscope, Sun sensor, and Magnetometer, State variables are the quaternion of the nano-satellite attitude and gyro drift, namely:

$$S = [q_0 \quad q_1 q_2 \quad q_3 b_x \quad b_y \quad b_z]_o^T \qquad (5)$$

Suppose ω_{ob} is the angular rate of satellite coordinate system relative to orbit coordinate system, ω_{gyro} the angular rate outputted by gyro drift, ω_{io} the angular rate of satellite orbit coordinate system relative to Inertial coordinate system, b gyro drift, and ξ gyro noise, then we have $\omega_{ob} = \omega_{gyro} - \omega_{io} - b - \xi$. According to the equations about Satellite attitude kinematics and gyro drift features [1],

$$\dot{q} = \frac{1}{2} q \otimes \omega_{ob}$$

$$\dot{b} = 0 \qquad (6)$$

Hence, the system state equation is:

$$\begin{bmatrix} \dot{q} \\ \dot{b} \end{bmatrix} = f(q, b) \qquad (7)$$

When measuring with sun sensor and magnetometer, we can get quaternion q which is the observed quantity by means of q-method. The measurement equation is:

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} X + v \qquad (8)$$

where v is the measurement error caused by the sensor. The nonlinear state equation and measurement equations of EKF are:

$$\dot{X} = F(X) + W$$

$$Z = h(X) + V \qquad (9)$$

where X and Z are state and measurement vectors, while W and V are white noise of system and measuring error, respectively.

3.1. Suppose EKF Formulas

$$\Phi = I + \frac{\partial F(X)}{\partial X} + \partial \left[\frac{\partial F(X)}{\partial X} F(X) \right] / \partial X \& H = \frac{\partial h(X)}{\partial X} \qquad (10)$$

$$P_k = (I - KH) P_{k/k-1} (I - KH)^T + KRK^T$$

$$K = P_{k/k-1} H^T (HP_{k/k-1} H^T + R) \qquad (11)$$

$$P_{k/k-1} = \Phi P_{k-1} \Phi^T + Q$$

$$X_k = X_{k/k-1} + k[Z_k - h(X_{k/k-1})]$$

$$X_{k/k-1} = F(X_k)T + \left[\frac{\partial F(X_k)}{\partial (X_k)} F(X_k) \right] \frac{T^2}{2} \qquad (12)$$

State variables X of the system can be calculated by the equations listed above given the initial conditions X_0 and P_0 and therefore we can get the attitude information of the nano-satellite.
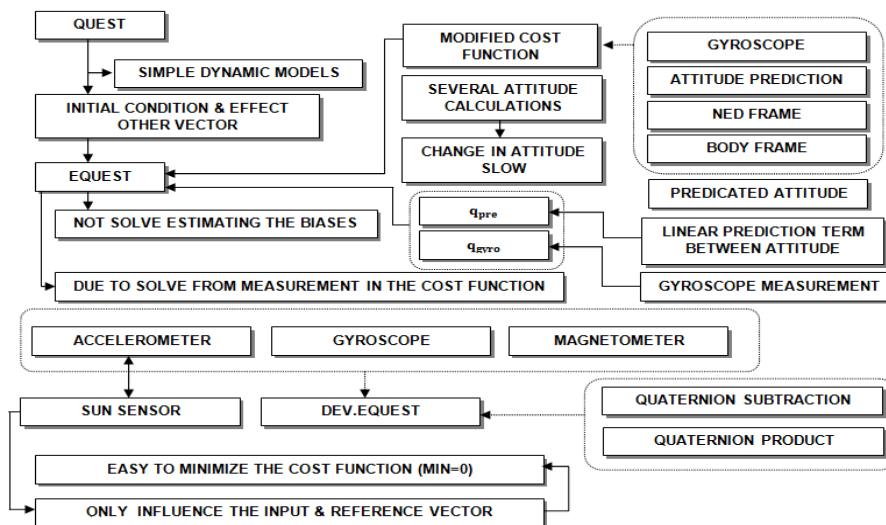

Figure 2. Block-diagram of steps

3. 2. Extended Quaternion Estimation   The estimation quaternion method can only used for very simple dynamic models, and cannot estimate anything apart from the attitude quaternion. The extended method is used to have prior information and consider the effects of other state vector measurements [1]. The extended quaternion estimation method has been used to improve the relevant in performance[5]. For extension of the estimation quaternion method, cost function must be modified. This function includes terms with gyroscope measurements and attitude prediction. Two new quaternions are included in the equation. A linear prediction term, q_{pre} is based on previous samples. The other extension denoted by q_{gyro} is the next quaternion estimated by tracking the gyroscope. The original cost function is extended to:

$$J(\boldsymbol{q}) = \frac{1}{2}\sum_{j=1}^{n}\left\{\frac{1}{\sigma_j^2}\left(\boldsymbol{b}_j - \boldsymbol{R}_b^i(q)\boldsymbol{r}_j\right)^T\left(\boldsymbol{b}_j - \boldsymbol{R}_b^i(q)\boldsymbol{r}_j\right)\right\} + \frac{1}{2}\left(\mathbf{q} - \widehat{\boldsymbol{q}}_{gyro}\right)^T\mathbf{D}\left(\mathbf{q} - \widehat{\boldsymbol{q}}_{gyro}\right) + \frac{1}{2}\left(\mathbf{q} - \widehat{\boldsymbol{q}}_{pre}\right)^T\mathbf{S}\left(\mathbf{q} - \widehat{\boldsymbol{q}}_{pre}\right) \tag{13}$$

Two new symmetric weight matrices, D and S are introduced. The added terms penalizes deviations both from the predicted attitude, and the rotation matrix estimated by the gyroscope measurements. It is possible to predict the orientation based on previous attitude calculations, as long as the change in attitude is slow. The change will be minimal for a short period of time. In this period, several attitude calculations are made, and a linear relation can be established between the change in attitude and time [5]. The extension of the estimation quaternion method does not solve the problem of estimating the biases, but this could be solved by other techniques before subtracting the results from the measurements in the cost function. This will, however, be computationally expensive. The method is developed and implemented for the use of an accelerometer, a gyroscope and a magnetometer. But, the accelerometer will eventually be replaced by a sun sensor measuring the direction towards the sun. This replacement will only influence the input of the method, and the reference vector. Both are easily manipulated used subtractions in the two added terms, which makes it easy to minimize the cost function because the minimum value will be zero. However, the subtraction of two quaternions does not result in a new attitude quaternion. To achieve this, the quaternion subtraction terms must be replaced with quaternion products. The new extended estimation quaternion method with quaternion products instead of quaternion subtractions will be referred to as the developed extended estimation quaternion method.

3. 3. Nonlinear Observer   The observer, described as an explicit complementary filter with stationary reference vectors. It was proven that this observer has global stability if the reference vectors are stationary, or if the gyroscope measurements are unbiased. Global

exponential stability was proven even with the inclusion of time-varying reference vectors and gyro bias, provided an uncoupled vector estimation. Apart from the excellent stability properties, the nonlinear observer has the advantage that it is less sensitive to disturbances compared to developed extended estimation quaternion method. The observer equations are presented with q0 and as the scalar and vector parts of the quaternion.

$$:= [q_1 \quad q_2 \quad q_3]^T q_{vec} \tag{14}$$

S represents a skew symmetric matrix. For the nonlinear observer equations, the estimated parameters will be written with roof accents. The estimated rotation matrix:

$$\hat{R}_n^b(q) := I_{3\times3} + 2q_0 S(q_{vec}) + 2S(q_{vec})^2 \tag{15}$$

The observer equations are:

$$\dot{\hat{R}}_n^b(q) = \hat{R}_n^b(q)S\left(\omega_m - \hat{b}_g + \omega_{inj}\right)$$
$$\dot{\hat{b}}_g = \text{Proj}\left(\hat{b}_g, k_I\omega_{inj}\right) \tag{16}$$

where ω_m is the measured gyroscope data and b_g the estimated gyroscope bias. Theparameter k_I is an injection gain to be designed.

$$\omega_{inj} = -\text{vex}\left(\sum_{j=1}^{n}\frac{k_j}{2}b_j(\hat{b}_j)^T - \hat{b}_j^T(b_j)^T\right) \tag{17}$$

3. 4. Combination of Developed Extended Estimation Quaternion and Nonlinear Observer The developed extended estimation quaternion method has the advantage of being fast, and will find the optimal attitude quaternion in one time step. However, it is less robust towards disturbances than the nonlinear observer. This is the reason for the implementation of a combination of the two methods. The developed extended estimation quaternion method provides an initial condition for the nonlinear observer. This way, a fast response at the start-up phase, and robustness against disturbances can be achieved.
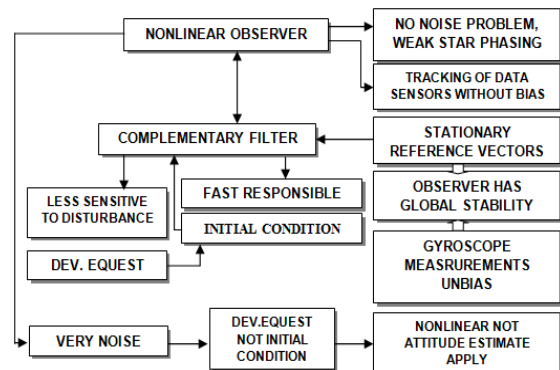

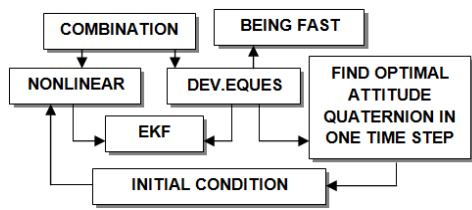**Figure 3 .** Block-diagram of nonlinear method

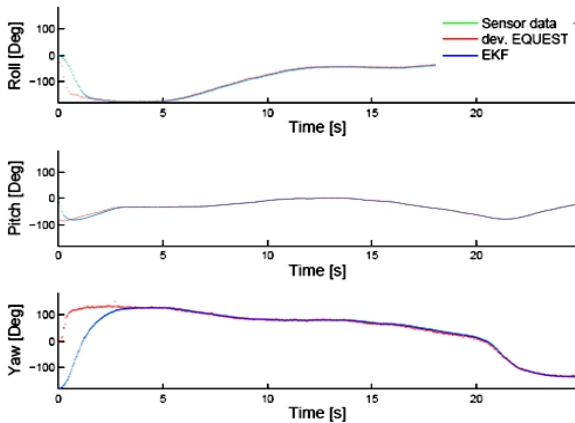**Figure 4.** Block-diagram of combination method

Figure 5. Attitude estimation using the developed EQUEST method and the EKF.
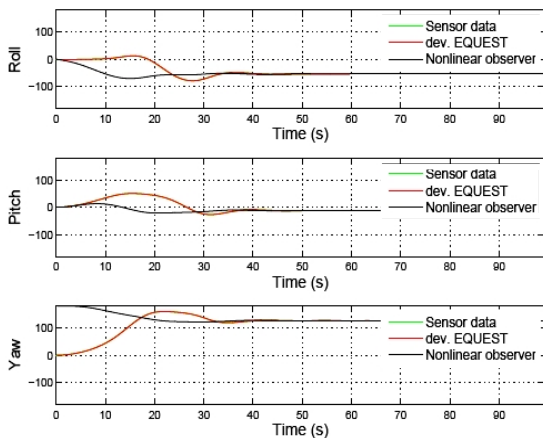

Figure 6. Attitude estimation for the developed extended estimation quaternion method and the nonlinear observer
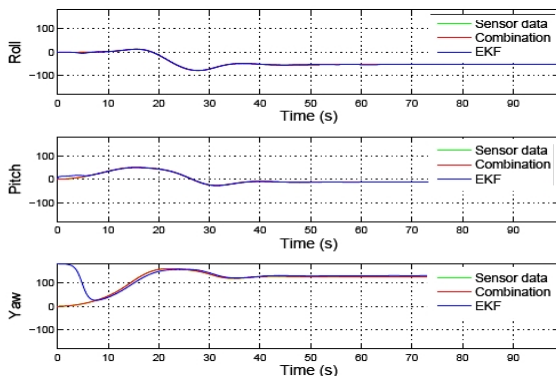

Figure7. Attitude determination for the combination method and the EKF

There is no difference in performance for the extended estimation quaternion method and the developed extended estimation quaternion method. The largest difference between the EKF and the extended estimation quaternion methods is in the start-up phase, where the performance of the extended estimation quaternion methods has a larger deviation from the sensor data than the EKF has. Developed extended estimation quaternion method finds the correct value faster than the nonlinear observer. The method computes the correct value in just one time-step, which will give a faster response in the start-up phase. Because developed extended estimation quaternion method is used for finding the initial value, the response for the combination method can be seen to be faster than nonlinear observer response. The response for the nonlinear observer is slower with the disturbances, but it converges towards the correct value and is smoother than the EKF.

4. CONCLUSION

According to the movement of nano-satellite and its stability in three directions, the attitude estimation should have high accuracy on the direction of sun mode of nano-satellite. Therefore, one can design integrated attitude estimation methods using data sensors while considering the orientation sun and different configuration of gyroscope, magnetometer and sun sensor. The combination of developed extended quaternion estimation method and nonlinear observer method presented high accurate results. The initial values were different in both methods. Also, one needs initial value for reference quaternions. The developed extended quaternion estimation method finds correct initial value for nonlinear observer method during the starting phase. Nonlinear observer follows the sensor data without any deviations. No deviation was observed for nonlinear observer. If the noise is excessive, the developed extended quaternion estimation method is unable to find the right initial value.

5. REFERENCES

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چکیده

هدف از این مقاله تخمین وضعیت ماهواره نانو است که نیاز به داده‌های حس گرهای ناوبری برای کاهش تابع هزینه و تاثیرات حرکت ماهواره نانو دارد. تمرکز این تحقیق روی استفاده از داده‌های حس گرهای ناوبری و روش‌هایی جهت دستیابی به ملزومات تخمین وضعیت می باشد. در این مقاله‌تخمین وضعیت را بر طبق جهت به سمت خورشید از ماهواره نانو می باشد حس گرهای وضعیت ناوبری مورد استفاده ژیروسکوپ، مغناطیس سنج و حس گرخورشید می‌باشد.علاوه بر این فیلتر کالمن اصلاح شده برای ترکیب داده‌های اندازه‌گیری شده از ژیروسکوپ، مغناطیس سنج و حس گرخورشید استفاده شده است.این مقاله روش‌ها و دقت تخمین وضعیت ماموریت‌های ماهواره نانو را مطابق با توسعه تخمین وضعیت کواترنین بهینه یافته و ناظر غیرخطی ارائه سپس با استفاده از فیلتر کالمن اصلاح شده با هم ترکیب نموده است. این مقاله کاربردهای سنسورهای ناوبری که از ملزومات دقت در روش‌ها برای دستیابی به دقت بالای تخمین وضعیت و براورد در لحظه شروع را ارائه می‌نماید.بخشی از این روش‌ها به وسیله نرم افزار متلب شبیه سازی شده و سپس نتایج با همدیگر مورد بررسی قرار گرفتند.