Innovative and high performance ADCS for mini and nano satellites

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Introduction

The miniaturized technologies for the space segment of satellite launch industries have grown rapidly in the last years. Several kind of small satellite have been built. Mini and nano satellites are two of these. Typically **mini satellites** have mass lesser than 10kg while nano satellites have mass lesser than 500kg. Thus, for these kind of satellites particular miniaturized devices have to be used. This implies a loss in accuracy and makes the devices outputs affected by **noise**.

The Attitude Determination Control System (**ADCS**) is composed by sensors, actuators, avionics, algorithms, software and all the theoretical methods and ground support equipment that are needed to determine and control the attitude of a vehicle, as well as to improve the accuracy of the miniaturized devices. The most important theoretical methods existing in the literature are based on the **Kalman Filter**. This filter is able to estimate the state of a satellite (attitude, position, velocity, etc) using the noise output of devices placed inside a satellite.

In general the standard Extended Kalman Filter (**EKF**), a non linear version of the Standard Kalman Filter, is not very accurate in the presence of **high non linearities**.

In the present work a **new algorithm**, called **UKFplus**, based on a combination of three techniques, has been introduced for application to satellites with "variable attitude" as well as "stable attitude".

Simulation results based on **real sample data** from Smart 1 nano satellite showed high performances of the new proposed approach concerning accuracy, lost convergence and high robustness together with **high computational efficiency**.

Satellite Attitude Model

In the present work, the satellite attitude model is based on the information from the star tracker and gyroscope. The quaternion is defined by $q = [q_0\ \rho]$ with $\rho = [q_1, q_2, q_3]^T = e \sin(\vartheta/2)$ and $q_0 = \cos(\vartheta/2\ )$, where e is the axis of rotation vector and ϑ is the angle of rotation. The star tracker output is used in the observed measurement equation, while the gyroscope output is propagated using the unobserved state of system:

$$\boldsymbol{x}(k+1) = -\frac{1}{2}\begin{bmatrix} 0 & \omega_x(k) & \omega_y(k) & \omega_z(k) \\ -\omega_x(k) & 0 & -\omega_z(k) & \omega_y(k) \\ -\omega_y(k) & \omega_z(k) & 0 & -\omega_x(k) \\ -\omega_z(k) & \omega_y(k) & \omega_x(k) & 0 \end{bmatrix}\begin{bmatrix} q_0(k) \\ q_1(k) \\ q_2(k) \\ q_3(k) \end{bmatrix} + \boldsymbol{v}(k)$$

$$\boldsymbol{y}(k) = [q_{st0}(k) \quad q_{st1}(k) \quad q_{st2}(k) \quad q_{st3}(k)\ ] + \boldsymbol{w}(k)$$

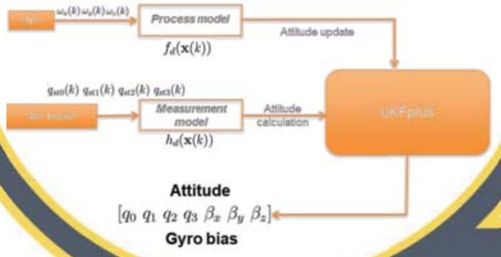
ω_x, ω_y and ω_z are the angular velocity taken by gyroscope.

Aim

To propose a **new UKF version** suitable for application to mini and nano satellites

To improve the computational performances

Increase numerical robustness



Sensor Equipment Overview

Star Tracker

S.T. accuracy: 30 arcsec 1σ
S.T. output: quaternions in ECI

Gyroscope

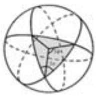
Gyro noise: 0.05°/s (1σ)
Gyro bias: 15°/h
Gyro output: angular velocity in ECI

Dataset

The real data sample has been extracted using a tool for auxiliary scientific calculation available in the web site *http://fd-tasc.info/roscmd/*. This web service makes available Flight Dynamics data to e external users of European Space Agency's Space Spacecraft Mission

Metodology

STEP 1: Set of sigma points



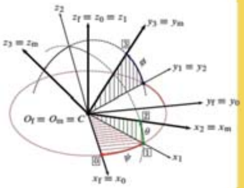
The computational cost is directly proportional to the number of sigma points that are used. It is therefore enough to minimize the number of sigma points. In the standard UKF approach 2n+1 sigma points are used for an n-dimensional space. In this new procedure only n + 2 sigma points are needed;

STEP 2: Update

To save computational cost and increase numerical robustness, we considered a different form of the state covariance matrix that can be directly taken and updated in the algorithm ;

STEP 3: Filter in attitude problems

A peculiar form of a Filter technique, generally used in navigation attitude problems, is usually implemented with the **EKF** algorithm. This procedure, able to exceed singularity problems due to attitude parametrization, has been adapted in the present work to the UKF method



STEP 4: Kalman gain update

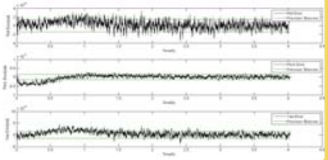
Typically when satellites orbit around the earth, there are long stable periods in absence of perturbations to the motion of satellites. In this case the satellite attitude is near to be "linear". Thus an automatic control to verify the state of the satellite is performed to reduce computational cost.

Standard vs New Approach

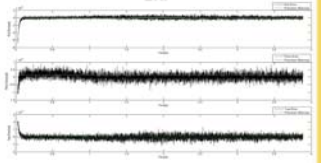
The **UKFplus** and the standard **EKF** have been compared with the same initial state and parameters of the model. The Figure shows the time series of the **attitude angle error** on the roll-axis, pitch-axis and yaw-axis, considering a 30 arcsec precision, obtained from the **UKFplus** and **EKF**, respectively. It is evident a better performance of **UKFplus** about precision compared to the **EKF**.

Precision	roll axis	pitch axis	yaw axis	speed
UKFplus				
< 30 arcsec	86,64 %	81,72 %	77,33 %	< 2 times EKF
< 20 arcsec	68,62 %	67,46 %	59,78 %	
< 10 arcsec	38,49 %	38,96 %	33,94 %	
EKF				
< 30 arcsec	41,66 %	50,02 %	42,16%	
< 20 arcsec	28,92 %	34,81 %	29,09 %	
< 10 arcsec	14,40 %	17,60 %	14,19 %	

UKFplus



EKF



Conclusions

Every year interest in mini\nano satellites grows up. A lot of peculiarities can explain this interest, such as the time and the **cost of production** (much cheaper than larger spacecraft).
However, the devices used on board can be very **inaccurate**. That implies a difficulty in reaching a high level of accuracy in pointing by the **EKF**. We showed that the proposed new filter technique **UKFplus** s overcomes the limited performance of standard **EKF** making the most of the UKF characteristics .

Further, the several mathematical and engineering innovative approaches applied to implement the **UKFplus make it usable both on board and on ground**. On board, it is able to provide attitude measurements in **real-time**. On ground, it can be used to **improve** the attitude and the orbit estimation.

References

[1] John L Crassidis and F Landis Markley. Unscented filtering for spacecraft attitude estimation. *Journal of guidance, control, and dynamics*, 26(4), pp. 536-542, 2003.

[2] Simon J Julier. The scaled unscented transformation. In *American Control Conference, 2002. Proceedings of the 2002*, vol. 6, pp. 4555 - 4559. IEEE, 2002.

[3] Guoliang Liu, Florentin Wörgötter, and Irene Markelic. The square-root unscented information filter for state estimation and sensor fusion. In SENSORNETS, pp.169 - 173, 2012.