Attitude Determination and Control of Future Small Satellites

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ABSTRACT

As well as other subsystems, Attitude Determination and Control System (ADCS) development is a challenging process for small satellites because of design limitations, such as size, weight and the power consumption. Besides, if they are thought in a concept with military missions, then the requirement for a high attitude pointing accuracy is something certain. Works on the effective attitude determination and control methods for small satellites can be accepted as a part of this struggle. In this paper, problems that are met during ADCS development phase for future small satellites are stated and possible solutions are suggested.

1.0 INTRODUCTION

Since their first appearance, small satellites have begun to play a more and more important role in space researches and today, they have a certain share in astronautic applications, especially about new technology demonstration. Because of many advantages such as low investment and operational costs, enabling COTS (commercial of the shell) technology in space, short system development periods etc. they have been highly preferred to their larger competitors. More than 400 micro satellites launched in the last 20 years is a good proof for that [1].

Mini Satellite	100-500 kg
Micro Satellite	10-100 kg
Nano Satellite	1-10 kg
Pico Satellite	0.1-1 kg

Table 1: Small satellite classification.

Although they have been investigated in depth, there are still many steps to be taken in the development phase of these types of satellites and an important field to be examined is their attitude determination and control systems (ADCS). In the 30 years prospective plan of them [2], France Ministry of Defence presents "*reduced access costs for capabilities, with identical performance and with no increase in lead times risks*" as one of the future capability improvements for space missions and that exactly points out the small satellites. Besides they enumerate other future targets as improved observational capabilities, improved telecommunication capabilities, access to new capabilities and increased availability of space systems. In report details of all these topics emphasize the importance of an accurate attitude determination and control system for small satellites.

In general scope, main aim of the attitude determination is to find the orientation of the satellite relative to an inertial reference or to some specific object of interest (the Earth for many applications). In order to realize that, there must be one or more available reference vectors, i.e. unit vectors in the known directions with respect to the satellite. Commonly used reference vectors are the Earth's magnetic field and unit vectors in the direction of the Sun, a known star or the centre of the Earth. Given reference vectors and these vectors' orientations in the frame of the reference of the satellite can be obtained by using the measurements of the attitude sensors. Below Table 2 and Table 3 show the attitude determination and control methods and associated devices respectively [3].

Control	Gravity gradient and magnetic	Momentum biased	3-axis reaction wheel
Sensors	Sun and magnetic	Sun and magnetic	Sun, star and magnetic
Cost	Low	Medium	High
Complexity	Low	Medium	High
Lifetime	High	Medium	High
Mass	Low	Medium	High
Volume	Low	Medium	High
Accuracy	Pitch, roll 1°, yaw 5°	Pitch, roll, yaw $\leq 5°$	Pitch, roll, yaw 1°
Drift rates	≈0.05°/s	≈0.005°/s	≈0.001°/s

Table 2: Attitude determination and control methods.

Stabilization and Control Type	Actuator	Attitude Sensor
Spinner	Reaction jets Magnetorquers Nutation damper	Sun, Earth sensors Magnetometers
Magnetic Stabilized	Magnetorquers	Sun, Earth sensors
3-axis	Magnetorquers Reaction wheel Gas jets	Sun, Earth, Star sensors Gyros Accelerometers
Momentum Biased	Magnetorquers Biased momentum wheel Gas jets	Sun, Earth sensors Gyros
Dual Spinners	Gas jets Nutation damper	Sun, Earth, Star sensors

Table 3: ADCS methods and associated devices.

When the ADCS is taken into consideration in point of view of small satellite implementations, design process becomes more sophisticated than the implementations on a satellite of several tons since such satellites have many design limits. Maybe most apparent ones of these constrains are the mass, size and the power budget of satellite. Therefore the problem is to design an accurate ADCS despite the limitations.

2.0 PROBLEM DESCRIPTION AND SUGGESTIONS

As it is aforementioned, because of design limitations ADCS development is a challenging process for small satellites. Besides, if they are thought in a concept with military missions then the requirement for a high accuracy is something certain. Works on the effective attitude estimation methods for small satellites can be accepted as a part of this struggle.

In a similar manner with most engineering problems there might be several methods to increase the accuracy of attitude determination and control for small satellites under general circumstances but they must be examined carefully and their applicability should be discussed.

One solution method for the handled problem is to increase the accuracy of attitude sensors and actuator onboard of the pico satellite individually. However an increase in the accuracy should not be a reason for larger size, mass and power budget demands. In other words, accurate sensors and actuators must be miniaturized and so they can be easily implemented on small satellites.

Miniaturization reduces the size and cost of the hardware and hence the cost of the spacecraft as a whole as well as, potentially, the launch costs. This process has been adapted from the core of the present semiconductor industry, which uses material deposition, photolithography and etching to name a few. These developments are most prevalent in the area of sensors, such as solid-state accelerometers, solid-state Earth horizon scanners, star sensors and single chip magnetometers [3]. Researches on MEMS (Micro ElectroMechanical Systems) based ADCS can be accepted as a part of this concept [4].

Furthermore, in order to increase the accuracy of attitude determination and control system, different reference sensors and redundant data processing methods (statistical methods) can be used. By that way coarse inexpensive sensors suitable for small satellites can be integrated, using an effective sensor fusion algorithm like Kalman filter, in order to have higher accuracy. For instance as well as sun sensor and magnetometer a third one like horizon sensor can be utilized onboard. Simulation results have shown that accuracy increases significantly when a third attitude reference source is taken into consideration. On the other hand, despite the increased ADCS accuracy, several sensors/actuators mean a higher size mass and power budget in general. That problem may be surpassed by designing multifunctional devices, which achieve job of more than one sensor/actuator at the same time. Namely, some of sensors and actuators will be combined in a single unit with a reduced size and mass compared to their separated version.

A good example for multifunctional ADCS sensors is the inertial stellar compass [5, 6] which integrates MEMS gyroscopes and active pixel sensor imaging devices as a single unit. This system realizes attitude determination with an accuracy of 0.1° (1σ) and it only weights mostly 3kg with a power requirement lesser than 4.5 W.

Another approach for attitude determination is algorithmic methods. Kalman filter like stochastic techniques usually requires initial estimation values which are determined with an accurate deterministic method. TRIAD, QUEST and Wahba algorithms are well known examples for such deterministic methods. Although, these methods may not be used for the whole mission phase since they might demand high computation burden, with their accurate initial attitude calculations they can increase the accuracy of Kalman filter in an important degree. On the other hand, these methods have a drawback. When two reference sources are used one might meet with an ambiguity like the one caused by parallel vectors. Hence, a third reference is also needed for such problems so as to give reliable initial values to the Kalman filter.

At that point it is certain that at least three coarse sensors (if possible multifunctional, miniaturized one sensor) and a deterministic method to initialize the attitude estimation procedure are needed. Besides sensors must be fused with an effective filtering technique like Kalman filter. In other words for small satellites, on-board running filter algorithm must be accurate enough to remove the lower precision effects of smaller and lighter sensors.

Linear Kalman filter algorithm cannot be used for satellite attitude estimation problem because of the inherent nonlinear dynamics and kinematics of the satellite. Extended Kalman Filter (EKF) is proposed in order to overcome this problem and it is used instead of linear Kalman filter for estimating the attitude of the satellite as a commonly known method [7].

As well as being used for many missions, EKF has some disadvantages, especially for highly nonlinear systems. Generally this is caused by the mandatory linearization phase of EKF procedure and so Jacobians derived with that purpose. For most of the applications, generation of Jacobians is hard, time consuming and prone to human errors [8, 9]. Nonetheless, linearization brings about an unstable filter performance when the time step intervals for update are not sufficiently small and that results with the filter divergence [10]. Per contra, small time step intervals increase the computational burden because of the larger number of Jacobian calculations. As a result of these facts, EKF may be efficient only if the system is almost linear on the timescale of update intervals [9].

A relatively new Kalman filtering technique, which does not have the shortcomings of EKF for nonlinear systems, is Unscented Kalman Filter (UKF). UKF generalizes Kalman filter for both linear and nonlinear systems and in case of nonlinear dynamics, UKF may afford considerably more accurate estimation results than the known observer design methodologies such as Extended Kalman Filter. The basic of UKF is the fact that; the approximation of a nonlinear distribution is easier than the approximation of a nonlinear function or transformation [11]. UKF introduces sigma points to catch higher order statistic of the system and by securing higher order information of the system, it satisfies both better estimation accuracy and convergence characteristic [8].

As a spacecraft attitude estimation algorithm, UKF has many implementation examples in literature, especially for the last few years. In [12, 13] it is used as a state estimator, while both the states and the parameters of the satellite are estimated by UKF in [8, 14]. Besides, in [15] control of the multibody satellites is achieved by the use of UKF.

Below simulation results for attitude estimation of a pico satellite with two different filtering algorithms, EKF and UKF, are given.

Parameter	Absolute Estimation Error Values for EKF	Absolute Estimation Error Values for UKF
$\varphi\ (deg)$	9.0644	0.0278
$\theta\ (deg)$	2.7221	0.2191
$\psi\ (deg)$	8.9144	2.8457
$\omega_x\ (deg/s)$	0.6473	0.0003
$\omega_y\ (deg/s)$	0.8236	0.0018
$\omega_z\ (deg/s)$	1.3286	0.0018

Table 4: Comparison of EKF and UKF estimation performances.

As it is clear, UKF gives superior estimation results than EKF. Results prove the legitimacy of the trend about UKF usage. That means UKF should be chosen as the filtering algorithm for multi-sensor fusion in attitude estimation of pico satellites, especially if the problem is regarded in a progressive approach. Only disadvantage of UKF algorithm is the possibility of an increase in the computational burden which may be greater than EKF's one in some cases. However, continuing fast development process of the microprocessors in point of view of their capacity shows that such problems will not be so important in the near future.

3.0 CONCLUSIONS

In consequence small satellites have a big potential in point of view of applications in the military field. However because of the design restrictions like the limited size, mass and the power consumption, development procedure of their attitude determination and control system is a challenging one. So as to increase the ADCS accuracy some techniques are suggested in this study and these can be summarized as follow:

- More than two sensors must be utilized onboard for an accurate attitude determination.
- ADCS sensors and actuators should be minimized. MEMS technology should be taken into consideration as a part of this process.
- A vast area of research is the multifunctional sensors/actuators at the moment. By that way different type of sensors/actuators may be integrated and so a decrement in size, mass and power consumption can be secured.
- Attitude estimation must be initialized by a deterministic method like TRIAD, QUEST or Wahba algorithm.
- As a filter algorithm to fuse the sensor measurements more advantageous UKF should be preferred instead of EKF.

4.0 REFERENCES

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