QuantSat-PT: An Attitude Determination and Control System architecture for QKD

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Abstract
This article presents the QuantSaT-PT project, an effort to create the first Portuguese nanosatellite for space to ground quantum communication. Focused on the Attitude Determination and Control System, it describes the different elements that allow for the attainment of diverse accuracy levels required for separate mission stages. Given the harsh pointing precision necessary for establishing a quantum downlink, the implementation of this module presents a major challenge in the Cubesat field. Furthermore, the introduced architecture aims to reduce system cost by replacing the state-of-the-art star tracker with ground beacon detection.

Keywords
ADCS, Beacon, CubeSat, Downlink, QKD

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Nomenclature

$\mathbf{q}$	*quaternion*
$\mathbf{e}$	*rotation axis*
ϑ	*rotation angle*
$\boldsymbol{\omega}$	*angular rate vector*
$\boldsymbol{\beta}$	*bias*
A	*attitude matrix*
η	*noise variable*
ϕ, θ, ξ	*euler angles*

Acronyms/Abbreviations

ADCS *Attitude Determination and Control System*

ESA *European Space Agency*

FOV *Field-of-View*

GS *Ground station*

LOS *Line-of-sight*

MEKF *Multiplicative Extended Kalman Filter*

QKD *Quantum Key Distribution*

TRL *Technology Readiness Level*

1. Introduction

In the information age, it is crucial to create and maintain secure communications. One way of improving our current security standards is to use Quantum Key Distribution (QKD) methods, which allows two parties to exchange encryption keys with absolute confidence that any eavesdropping by a third party will be detected [1]. Given that this property of QKD stems from fundamental quantum mechanics laws, it is theoretically impossible to intercept the encryption keys without this interference being detected and will remain so even considering future technological developments.

QKD is based on photonic communication links. Ground-based links typically rely on optical fibers, which have non-negligible losses, thus limiting transmission distances to a few hundreds of km [2]. As such, satellite-based QKD is a promising approach to establishing a global quantum network. The development of a reliable and efficient space-to-ground link is an important first step, which has been demonstrated by the Micius satellite [3]. Implementing this technology in a CubeSat is a further step in the deployment of QKD technology, allowing for the low-cost deployment of large constellations.

Given the limited quantum link budget, extremely narrow optical beams must be used. This places strict requirements on the attitude determination and control system to guarantee pointing accuracy in the range of tens of microradians [4]. Furthermore, due to the fact that space-based QKD can only be performed while the spacecraft is in eclipse, significant temperature variations can be expected and present a challenge for the internal alignment of optical components. These constraints are addressed using a three-level pointing system which allows for internal angular corrections using Fast Steering Mirrors and for spacecraft-to-ground locking using a laser beacon.

1.1. QuantSat-PT

The Portuguese Quantum Communications Cube-Satellite Project (QuantSat-PT) is the first step of a larger and longer-term vision of developing quantum communication satellites and ground stations in Portugal, making the country autonomous in such sovereignty technologies, and integrating Portugal in the future European Quantum Communication Infrastructure.

This project is funded by the Instituto de Telecomunicações. The aim is to begin the development of a 3U CubeSat for a quantum downlink. Namely, the goals of project QuantSat-PT are:

- To develop a quantum payload for space-earth quantum key distribution in 2U.
- To test the quantum payload on earth over a distance of several kilometres.
- To develop the preliminary design of the space segment.

To attain these goals, the project QuantSat-PT brings together a unique and multidisciplinary team. It explores the complementary expertise of IT researchers from:

- The Physics of Information and Quantum Technologies Group responsible for the development of the first free-space quantum key distribution system in Portugal.

- The Network Architecture and Protocols Group and the Antennas and Propagation Group, both involved in the ISTSat One, a Portuguese classical communications CubeSat to be sent to space in 2022 through the ESA program Fly Your Satellite.
- The Optical Networking Group, expert in classical and quantum optical communications.

1.2. Cubesat implementation

Since the CubeSat platform is now established as an attractive alternative for education and research organizations that aim to bring innovative technology to space, at a lower cost than larger platforms, it was selected as the basis for this mission. These nanosatellites have a standardized form factor, allowing for quick and accessible low-risk testing of novel technological concepts, as well as access to commercial launchers. Nevertheless, this implementation constrains the QuantSat-PT outline in terms of Size, Weight, and Power, in addition to the severe environmental conditions during launch and in-orbit that already posed a challenge regarding the miniaturization and ruggedization of the payload.

This article is focused on the Attitude Determination and Control System (ADCS) which is responsible for determining the orientation of a satellite and then controlling it so that it points to the desired direction [5]. It also includes other functions, such as providing initial damping for the satellite angular motion after deployment. It is composed of sensors, actuators and an onboard computer. ADCS design is subject to strict constraints when it comes to size and mass, often limiting the pointing and slew-rate requirements.

With these restrictions in mind, the proposed solution repurposes the Optical devices from the Quantum payload to increase attitude estimation accuracy without the use of additional sensors. The Ground Station (GS) beacon is used as the Earth reference on an attitude estimation filter, when available.

2. Mathematic Models

The different mathematic models used are presented in this section.

2.1. Quaternion Kinematics

The quaternion is used as the attitude representation since it is the lowest-dimensional parameterization that is free from singularities [5]. The quaternion is defined in Equation 1.

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_{1:3} \\ q_4 \end{bmatrix} = \mathbf{q}(\mathbf{e}, \vartheta) = \begin{bmatrix} \mathbf{e}\sin(\vartheta/2) \\ \cos(\vartheta/2) \end{bmatrix}$$

(1)

The quaternion has the following attitude matrix representation given in Equation 2.

$$A(\mathbf{q}) = \left(q_4^2 - \|\mathbf{q}_{1:3}\|^2\right) I_3 - 2q_4[\mathbf{q}_{1:3}\times] + 2\mathbf{q}_{1:3}\mathbf{q}_{1:3}^T \quad (2)$$

where [$\mathbf{q}_{13}$ x] is a skew-symmetric matrix for the quaternion vector components.

The quaternion kinematics are given in Equation 3.

$$\dot{\mathbf{q}} = \frac{1}{2}[\boldsymbol{\omega}\times]\mathbf{q} \quad (3)$$

where $[\boldsymbol{\omega}\times]$ is the skew-matrix for the angular rate.

2.2. Sensor Models

2.2.1. Gyroscope

The gyroscope measures the angular rate vector w and it is considered to be corrupted by a constant bias, as seen in Equation 4.

$$\widehat{\boldsymbol{\omega}} = \boldsymbol{\omega} + \boldsymbol{\beta} + \eta_g \quad (4)$$

where η_g denotes an independent zero-mean Gaussian white-noise process.

2.2.2. Beacon

For attitude determination purposes the beacon is modelled as a line-of-sight LOS sensor, instead of an optical device. Its output is subject to LOS to the GS and FOV restrictions. It is modelled as seen in Equation 5.

$$\hat{\mathbf{b}}_b = A_{\eta_s}\mathbf{b}_x \quad (5)$$

where A_{η_s} is a noise attitude matrix that corrupts the measurement with the structure and statistics as seen in Equation 6.

$$\begin{aligned} A_{\eta_s} &= A(\mathbf{e}_1, \phi_b)A(\mathbf{e}_2, \theta_b)A(\mathbf{e}_3, \xi_b) \\ E\{\phi_b\} &= E\{\theta_b\} = E\{\xi_b\} = 0 \\ E\{\phi_b\phi_b^T\} &= E\{\theta_b\theta_b^T\} = E\{\xi_b\xi_b^T\} = \eta_b \end{aligned}$$

(6)

where η_b the angle's covariance. This model is based on [6] converted from quaternions to rotation matrices

3. General Architecture

From the mission objectives, the attitude requirements are defined. In order to ensure Quantum communications, an attitude error in the range of tens of microradians must be obtained, whilst in eclipse.

Other CubeSats with optical communications missions have been designed to meet the attitude accuracy requirements through star-trackers [7]. In [8], a staged approach is proposed for the attitude determination, where the beacon, when received, is used to improve pointing accuracy in the fine stage.

A staged attitude determination system is proposed. The pointing, hence, estimation, requirements increase when more accurate sensors and actuators can be employed.

The first stage consists of using the common ADCS sensors to receive a signal from the beacon being transmitted by the GS. The attitude required for this stage is where the payload is pointed at the GS with an attitude error of 10°, equivelent to the FOV of the telescope that perceives the beacon.

The second stage uses the Earth's reference from the beacon to improve the attitude estimation, with the goal of obtaining a pointing error of 0.1°. This value is defined by the amplitude of actuation of the fast-steering mirrors (FSM).

A fine optical pointing stage is necessary to obtain the pointing accuracy required for quantum communications. The optical pointing system within the payload is in charge of this part of the mission. The laser beacon coming from the ground enters through the telescope and passes through an assemble of mirrors and lenses, guiding it to a quad-cell. The error signal generated from the difference between the measured and desired position of the beacon on the quad-cell is employed to drive a Fast Steering Mirror to actuate on the beacon attitude, augmenting the pointing accuracy without the need to move the satellite structure. This fine pointing process is executed continuously throughout the mission, designed as a closed control loop that runs in parallel with the other stages managed by the ADCS. The process, architecture, and implementation of this section of the pipeline for the Quantum-Sat project are illustrated in [9].

4. Attitude determination System

Even though the attitude determination system implemented in the ADCS progresses through two stages, the same estimation filter is used.

The filter used is a Multiplicative Extended Kalman Filter (MEKF) is implemented, based on [5].

The multiplicative attribute of the filter is due to the error quaternion expression that follows the Equation 7.

$$\mathbf{q} = \delta\mathbf{q}(\delta\vartheta) \otimes \hat{\mathbf{q}} \quad (7)$$

The filter not only estimates the quaternion but also the gyroscope bias, such that the state is given in Equation 8.

$$\mathbf{x} = \begin{bmatrix} \mathbf{q} \\ \boldsymbol{\beta} \end{bmatrix} \quad (8)$$

Since the attitude kinematics are non-linear, an EKF structure must be used, where the quaternion is not estimated but a "local" state vector, composed of a three-component $\delta\vartheta$ rotation vector and an estimation error for the bias, given in Equation 9.

$$\Delta\mathbf{x} = \begin{bmatrix} \delta\vartheta \\ \Delta\boldsymbol{\beta} \end{bmatrix} \quad (9)$$

The structure of the MEKF and its equations are based on an EKF and are given in Appendix A and B, respectively, and are based on [5]. The discrete-time, non-batch version of the filter is used.

The measurement update uses attitude sensors to correct the state estimate. The measurement vector, sensitivity matrix, measurement covariance and Kalman gain vary in order to accommodate sensors availability. The reset step transports the local error state $\Delta\mathbf{x}$ to the global error state $\mathbf{x}$. The propagation step is based on the quaternion kinematic from Eq. 3 and for the gyroscope bias are given in Equation 10.

$$\dot{\boldsymbol{\beta}} = 0 \quad (10)$$

5. Results (and Discussion)

The simulation is a self-made Simulink/Matlab 2020a model. It includes orbital and attitude motion, environmental disturbances and sensor models. The gyroscope used in the MPU9250 whilst the beacon was simulated based on [8].

In order to isolate the impact of the beacon in the attitude estimation, two different simulations are performed.

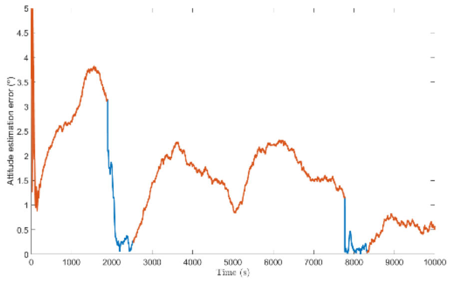

Figure 1 . Angular estimation error (°) with the beacon. Areas in blue represent the regions where the beacon is available.

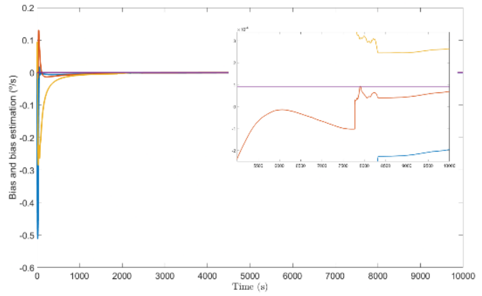

Figure 2 . Bias estimation error (°) with the beacon.

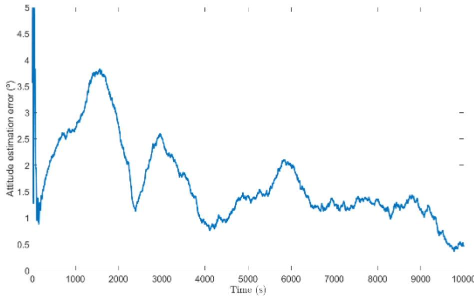

Figure 3 . Angular estimation error (°) without the beacon.

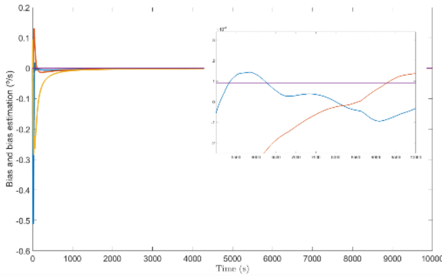

Figure 4 . Bias estimation error (°) without the beacon.

Figure 1 and Figure 2 show the estimation error and the bias estimate of the filter with the beacon whilst Figure 3 and 4 represent the estimation error and the bias estimate of the filter without the beacon.

When the GS is in LOS of the satellite, the estimation error is reduced, in some passes being able to reach the 0.1° estimation error.

When the beacon is not used, the estimation error is not low enough to meet the requirements.

Table 1 shows the mean of the estimate error of the attitude and bias. As it can be seen, the usage of the beacon drastically increases estimation accuracy in the downlink area.

The bias estimation doesn't suffer a drastic variation with the inclusion of the beacon.

Table 1. Estimation performance

Mean	With Beacon	Without beacon
Estimation error (°)	1.24	1.33
Estimation error (º) in FOV	0.3353	1.40
bias error (°/s)	0.0019	0.0018

6. Conclusions

An architecture for the ADCS, alongside with a filter was proposed in order to increase estimation performance. The GS beacon is repurposed as an attitude sensors.

Whilst within LOS, the beacon increases estimation performance since it provides an Earth reference.

Simulations show the effectiveness of the new sensor through the analysis of the estimation errors.

Acknowledgements

The authors thank the support from Fundação para a Ciência e Tecnologia (Portugal), namely through project UIDB/50008/2020, as well as from project QuantSat-PT.

Appendix

Appendix A - Multiplicative Extended Kalman Filter structure

Initialization: $\hat{\mathbf{x}}_0, P_0$
loop
  Propagation: $\hat{\mathbf{x}}_{k+1}^-, P_{k+1}^-$
  if observations ready: $\mathbf{y}_{k+1}$ **then**
    calculate kalman gain: K_k
    Calculate uncertainty: $\delta\hat{\mathbf{x}}_{k+1}$
    Update: $\hat{\mathbf{x}}_{k+1}^+, P_{k+1}^+$
    Reset: $\delta\hat{\mathbf{x}}_{k+1} = \mathbf{0}$
  end if
  return $\hat{\mathbf{x}}_k^+, P_k^+$
end loop

Figure A1. Pseudo-code for the MEKF

Appendix B - Multiplicative Extended Kalman Filter equations

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^T(\bar{\mathbf{x}}_k^-)[\mathbf{H}_k(\bar{\mathbf{x}}_k^-)\mathbf{P}_k^- \mathbf{H}_k^T(\hat{\mathbf{x}}_k^-) + \mathbf{R}_k]^{-1}$$

$$\Delta\hat{\mathbf{x}}_k^+ = \mathbf{K}_k[\mathbf{y}_k - \mathbf{h}_k(\hat{\mathbf{x}}_k^-)]$$

$$\mathbf{P}_k^+ = [\mathbf{I} - \mathbf{K}_k \mathbf{H}_k(\hat{\mathbf{x}}_k^-)]\mathbf{P}_k^-$$

$$\mathbf{h}_k(\hat{\mathbf{x}}_k^-) = \begin{bmatrix} A(\hat{\mathbf{q}}^-)\mathbf{r}_1 \\ A(\hat{\mathbf{q}}^-)\mathbf{r}_2 \\ \vdots \\ A(\hat{\mathbf{q}}^-)\mathbf{r}_N \end{bmatrix} t_k$$

$$\hat{\mathbf{q}}_k^+ = \frac{1}{\sqrt{1+| \delta\hat{\theta}_k^+/2 \|^2}} \begin{bmatrix} \delta\hat{\vartheta}_k^+/2 \\ 1 \end{bmatrix} \otimes \hat{\mathbf{q}}_k^-$$

$$\hat{\boldsymbol{\beta}}_k^+ = \hat{\boldsymbol{\beta}}_k^- + \Delta\hat{\boldsymbol{\beta}}_k^+$$

$$\hat{\omega}(t) = \omega_m(t) - \hat{\boldsymbol{\beta}}(t)$$

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