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Spiral coning manoeuvre for in-orbit low thrust characterisation in CubeSats

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ABSTRACT

The ability to accurately measure the level of thrust during in-orbit operations is fundamental to the characterisation of emerging propulsion systems for nanosatellites. Many new CubeSat missions use propulsion systems with thrust levels in the order of few micro-Newtons. Whilst laboratory sensing resources are able to resolve such low thrust values, in complementary in-orbit characterisation are limited and in the main not compatible with the standard CubeSat mission. Additionally, typical in-orbit assessment of micro-thrust is generally carried out through body angular speed changes, the effectiveness of which is drastically reduced when external perturbations and sensor noise approach or exceed the thruster action on the CubeSat. This investigation sets out to improve in-orbit micro-thrust characterisation via changes in body angular velocity periodicity due to off-centred thrust action in nearly axisymmetric CubeSats. Unlike traditional methods that rely on determining angular acceleration this method employs a frequency analysis of the transversal component of the angular velocity signal with the aim of reducing measurement error. Numerical simulations support the feasibility and adequacy of the proposed low-thrust gauging method, particularly for weak and noisy sensor signals. The robustness of the method allows for interchangeable analysed signal and enables the use of simple commercial-off-the-shelf rate sensors in fine micro-thrust characterisation.

1. Introduction

A major breakthrough in the CubeSat standard development and applicability is the inclusion of functional propulsion systems that enable autonomous and controllable satellite dynamics. Adequate thrust characterisation is fundamental in the development, improvement, and optimisation of propulsion technologies, however it is far from being a trivial task. In general, there exists a wide variety of space propulsion technologies developed to meet specific application requirements [16]. The selection of the propulsion system technology is often dictated by the delivered thrust level and working performance under the objective mission and environmental conditions. Thus, a method to correlate thrust level and input parameters, to identify performance dependency on external factors with sufficient precision, is required for optimal employment of any kind of propulsion system. Thrust characterisation is an arduous task that commonly involves the identification of the thrust vector, beam or jet divergence, plume structure, transient and steady-state responses, vibration modes, thermal ranges, electrostatic charging, ambient effects, and supply dependencies amongst other factors. The role of relevant parameters involved in the thruster performance can be estimated by using direct thrust measurements or by assessing features associated to the thrust. However, whenever possible, direct thrust measurement is universally preferred [17,21]. Various characterisation methods have been devised in line with the thrust level of the systems. Whilst some aspects of high levels of thrust are easily measured, low thrust features are often barely noticeable even for high accuracy state-of-the-art measuring apparatuses. Thrust characterisation under laboratory conditions is commonly carried out using static test rigs, pendulum balances, torsion balances, and time-of-flight mass spectrometry. Additionally propulsion system characterisation tests for in-space operation are generally performed in vacuum environment adding complexity to the tests design, qualification, and implementation.

Reduced dynamic noise generation and fine throttle control capability in the range of mN to μN [5,38] are frequently considered to be of paramount importance in satellite propulsion system requirements. These considerations clearly reduce the margin of possible laboratory test conditions to a few constringent scenarios. In some cases, higher vacuum level requirements as well as propellant reactivity concerns add to the complexity of the char-

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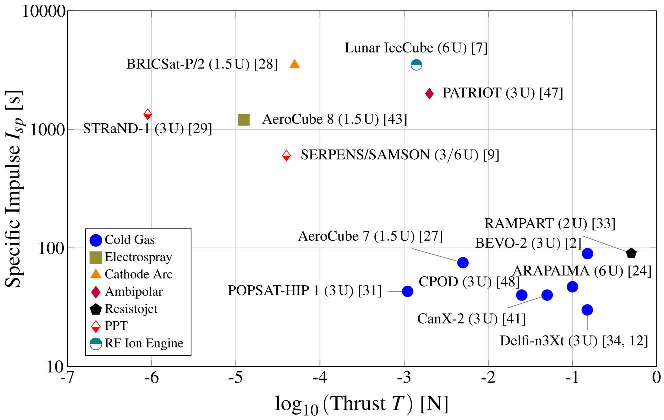

Fig. 1. Log–log plot of reported propulsion systems in CubeSats for various size factors (inside the parentheses) thus far. The value of I_{sp} is proportional to the efficiency of propellant mass consumption in the production of thrust for a given propulsion system. This investigation focuses on T values around μN encompassing current high I_{sp} engines and the throttle range of other thruster technologies.

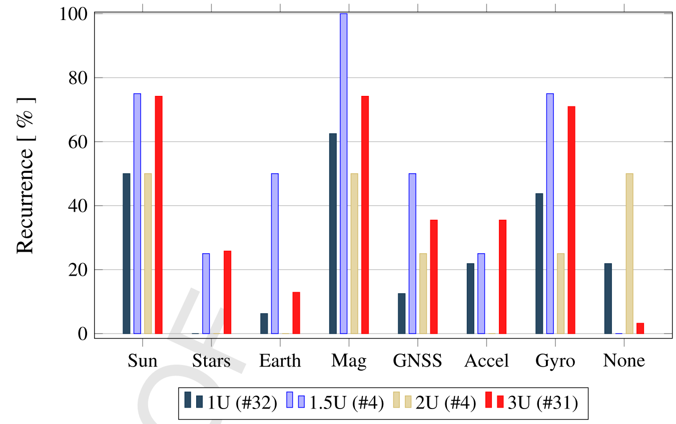

Fig. 2. Resources for attitude determination in CubeSats. Data from a random sample of CubeSats missions. The surveyed number of each size factor is reported in parentheses.

acterisation [5]. For propulsion systems in the order of μN, the characterisation can be particularly difficult because factors such as the weight of the thruster, stiffness of the feed and supply elements, ambient noise, thermal deformation, electrostatic and electromagnetic forces, and vacuum pump vibrations, are generally of higher magnitude than the thrust level itself overwhelming its action [5,17,42]. Another relevant aspect of these sort of laboratory tests is that in the absence of a dominant damping medium, primarily air, the start-up transient responses are long lasting. Despite all the above, current gauging technologies are able to resolve thrust values of few tens of nN for specific thruster characteristics [25]. However, important aspects of the ultimate operational environment (outer space) for satellite propulsion systems, have not been successfully reproduced in laboratory conditions. This makes supplementing laboratory data with in-orbit characterisation specially for low-thrust systems desirable [31].

CubeSats represent the current frontier of propulsion miniaturisation in space applications. Ongoing efforts are directed towards developing, testing, and characterising suitable systems for CubeSats. Current capabilities of nanosatellite propulsion systems range from tenths of N to few μN as illustrated in Fig. 1. Detailed information is reported in Table 2 in Appendix A.

Although propulsion system operational characteristics may be varied amongst technologies, general in-orbit thrust characterisation in CubeSats relies upon attitude changes and the resolution of onboard attitude determination resources. Acceptable attitude determination is of central importance for system characterisation through in-orbit attitude manoeuvres such as detumbling, target pointing (Sun, Nadir, etc.), and controlled spin [13,31,34]. Ongoing efforts of space industry and private research are directed towards the development and adaptation of suitable sensing technologies to the reduced space and power resources of CubeSats.

A survey of available attitude determination approaches in CubeSats from randomly selected historical nanosatellite missions is shown in Fig. 2. For the sake of homogeneity, the selected nanosatellites are approximated to standard CubeSat form factors (when necessary) and sensors with similar characteristics are grouped into eight representative classifications. Fine and coarse sensors measuring the Sun vector (2-axis) may include specialised or Commercial Off-The-Shelf (COTS) elements. Some missions like the surveyed Colony-1 and GeneSat-1, use solar panels power input for coarse solar vector estimations. The second group includes missions using the stars as reference frame (2-axis). This group encompasses high-end missions like the RAVAN, MinXSS, Aalto-1, STARE, AeroCube 7-OCSD, CADRE, and SENSE. The third group uses the Earth shape as reference (2-axis) mostly in the form of horizon sensors (in configurations of COTS IR pyroelectric sensors). This group include missions like the DICE, Drag-free CubeSat, GOMX-3, AeroCube-3, AeroCube-4, CUTE-1.7+APD-2, and AeroCube 7-OCSD. The Earth's magnetic field is amply used for 3-axis attitude determination in all nanosatellite size factors as shown in the fourth group in Fig. 2. In this case, magnetometers mostly in the form of COTS elements, provide local magnetic field measurements that are compared to onboard reference Earth magnetic field models, e.g. the International Geomagnetic Reference Field (IGRF) or the World Magnetic Model (WMM), to estimate spacecraft attitude. Although the space environment produces fluctuations in the Earth's magnetic field, which increase with altitude, available models capture most of its characteristics in low LEO enabling reliable coarse estimations. CubeSats have greatly benefited from the development, optimisation, and miniaturisation of Global Navigation Satellite System (GNSS) receivers from the electronics consumer market. COTS GNSS receivers assists enhanced attitude estimations by providing superior spatial identification to complement star map and Earth magnetic models. Although in some cases location continues to be estimated by onboard orbit propagations, the use of GNSS receivers is gradually implemented in all CubeSat form factors. In a similar way to GNSS technologies, MicroElectroMechanical Systems (MEMS) are in constant improvement to meet the electronics consumer market demand. The basic Inertial Measurement Unit (IMU) in standard CubeSats is composed of COTS MEMS accelerometers and gyroscopes providing a simple and low-cost solution for attitude variation identification. However, intrinsic fluctuations within the fundamental device operation gradually add measurement errors, namely bias or drift instability, which need correction. Eventual device calibration, i.e. zeroing, is normally enough to mitigate this fact. In spite of this, MEMS gyroscopes provide the current best short-term reference for 3-axis attitude determination in CubeSats. In practice each group shown in Fig. 2 may contribute to form an integral estimation of spacecraft attitude. Raw data from a variety of different sensors can be combined, e.g. using Kalman filtering, to furnish improved attitude estimations.

For CubeSat missions, it is therefore highly desirable to devise methods capable of drawing upon simple sensing resources to support effective thruster characterisation. The purpose of this investigation is to provide an alternative and effective method to resolve low thrust levels with COTS sensors for in-orbit low thrust characterisation in standard CubeSat configurations. Although this investigation encompasses 1.5U and 3U CubeSat form factors, the proposed methodology can be applied to other nearly symmetric geometries wherein appendages do not represent an important source of short term attitude changes as discussed below.

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