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Small satellite attitude determination during plasma brake deorbiting experiment

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ABSTRACT

This paper presents a study on attitude estimation during the Plasma Brake Experiment (PBE) onboard a small satellite. The PBE demands that the satellite be spun at a very high angular velocity, up to $200\frac{\text{deg}}{\text{s}}$, to deploy the tether using centrifugal force. The spin controller, based on purely magnetic actuation, and the PBE demands accurate attitude estimation for the successful execution of the experiment. The biases are important to be estimated onboard small satellites due to the closely integrated systems and relatively higher interference experienced by the sensors. However, bias estimation is even more important for PBE due to the presence of a high voltage unit, onboard the satellite, that is used to charge the tether and can be the source of interference. The attitude and the biases, when estimated simultaneously, results in an augmented state vector that poses a challenge to the proper tuning of process noise. The adaptation of process noise covariance has, therefore, been studied and analysed for the challenging PBE. It has been observed that adapting the process noise covariance improves the estimation accuracy during the spin-up phase. Therefore, it is very important to use adaptive process noise covariance estimation.

1. Introduction

Space debris is one of the major concerns and challenges for future space missions. There is an increasing amount of man-made debris in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). These bodies pose a collision risk to the operational spacecrafts in the orbit. LEO is the most highly congested region in near-Earth space, containing approximately 75% of all the catalogued objects [1]. In LEO, the region ranging from 600 km to 1000 km needs special attention, because of its need for Earth Observation (EO) missions. This region is also used by educational satellite missions, scale of the order of pico- and nano-satellites, that are launched at a relatively higher frequency than the conventional EO missions. Hence, it is required to take necessary measures that will help to reduce the amount of debris in the future.

An effective step, to control the future debris buildup, would be the possibility to deorbit and re-enter the satellites into the atmosphere once the active mission has ended. If performed using active propulsion, this would require a sufficient amount of fuel at the end of mission life. Due to such a requirement, this solution would increase cost and complications. There is an increasing interest in alternate propulsion and deorbiting methods [2–5]. The invention of the Electric-sail (E-sail) [6] has provided new means for propellantless propulsion, and efforts are also underway to utilize the concept for deorbiting the satellites [5,7]. Such a novel invention can be utilised to deorbit small satellites at the end of their useful mission lifetime.

Aalto-1, weighing 4 kg and measuring 10 cm × 10 cm × 34 cm, is a 3U CubeSat developed at Aalto University in collaboration with several Finnish institutes [8,9] and currently it is in the final testing phase. Aalto-1 will accommodate onboard an electrostatic tether-based satellite deorbiting experiment. The Plasma Brake Experiment (PBE) has challenging attitude requirements. To fulfill the experiment's attitude requirements, a solution has been studied and is presented in this paper. The main focus of this paper is on the attitude determination algorithm. PBE has been flown onboard the Estonian Cubesat, EstCube-1, for the first time. An attitude determination and control system was developed for EstCube-1 with a standard Unscented Kalman Filter (UKF) and magnetic spin controller [10]. However, the E-sail phenomenon is still to be validated. EstCube-1 discovered a strong Residual Magnetic Moment (RMM) in-flight [11] causing the satellite's spin axis to deviate from the desired axis.

The RMM is a major challenge for small satellites where several systems are integrated in a compact volume envelope [12,13]. It is a major cause of variations in magnetometer biases and errors.

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Hence, it is very important, first, to make the satellite magnetically clean and, second, to make sure that the subsystems' operation produces a minimum possible residual magnetic field and, third, to estimate the magnetometer biases online. Online estimation of sensor biases, together with the attitude, in a single estimator poses difficulties in tuning the filter. Also, if the priori information in covariance matrices does not adequately represent the real statistical noise levels then the estimation is not optimal and might produce unreliable results. It sometimes might even lead to filter divergence [14]. A solution to this problem is to vary the process noise covariance, online. Adaptive filters have been investigated in several studies, previously. The adaptive Unscented Kalman Filter (UKF) algorithms, for satellite attitude estimation, have previously been studied [15–17]. However, the authors have not found a documented study on the estimation performance over longer time durations as a part of a Kalman filter and for an application with the requirements as of PBE. The fast spin motion and attitude control demand an accurate and robust estimation technique. The algorithm used in this paper is based on the one presented in [14,17,18]. This paper presents the devised solution, for the PBE, as an Adaptive UKF (AUKF) and analyzes its performance in conjunction with spin control for high angular velocity motion. A concise preliminary study has been performed earlier [19]. However, a detailed analysis with a reduced order AUKF has been presented here with a comparative analysis of UKF and AUKF based on Monte Carlo simulations. The paper is divided into five sections. Section 2 introduces the PBE. Section 3 describes the details of the adaptive estimation technique. The simulation results, its analysis and a detailed discussion are presented in Section 4. Finally, the discussions and conclusions are given in Sections 5 and 6, respectively.

2. The Plasma brake experiment

The PBE hardware has been developed by Finnish Meteorological Institute (FMI) with the collaboration of University of Helsinki and University of Jyväskylä. It is based on the E-sail concept. The E-sail is a recent discovery regarding the propellantless propulsion of spacecraft [6]. The principle is based on Coulomb drag which is caused by the exchange of momentum between the ions or electrons and the positively charged or negatively charged conductive tether, respectively.

A positively charged tether, in a plasma stream, can collect momentum from the ions. The electrons tend to neutralize the positive charge. The experiment demands that the tether's positive potential must be maintained at a certain level. The collected electrons, therefore, must be removed from the tether. Electron guns have thus been included in the setup in order to remove the excessive electrons and maintain the required positive potential. This phenomenon has been depicted in Fig. 1. Similarly, momentum exchange also takes place between the charged tether and the plasma stream in the negatively charged tether mode. It is planned to test both the modes onboard Aalto-1. The primary mission aim of the PBE is to validate the E-sail concept and quantify the force acting on the electrostatically charged tether moving with respect to the ionospheric plasma. The secondary aim is then to deorbit the satellite depending on the success of the primary aim. The different phases of the experiment have been delineated in Fig. 2.

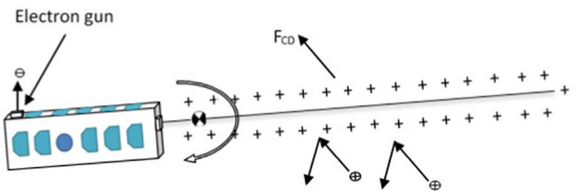

Fig. 1. The resultant Coulomb drag force, F_{CD}, generated in positively charged tether mode. Figure not drawn to scale.

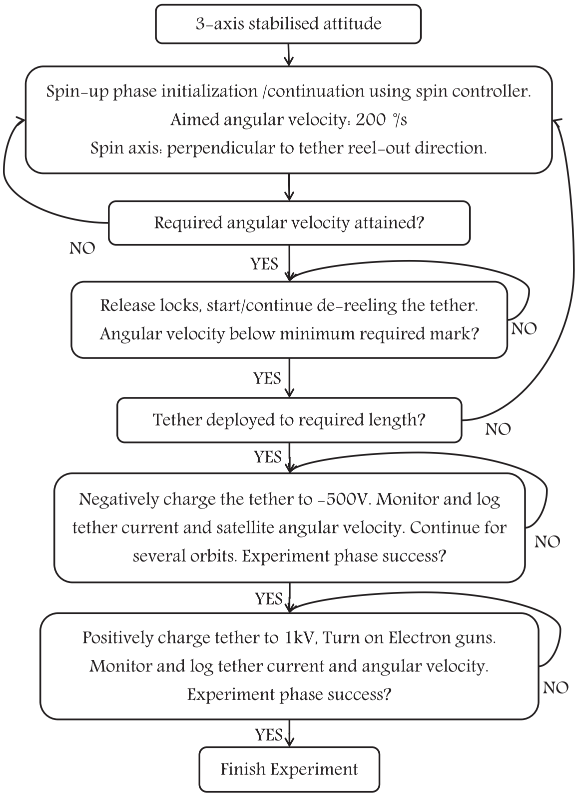

Fig. 2. PBE flow graph.

The PBE hardware comprises four components: a high-voltage power supply, a motor and reel mechanism, electron guns and a 100 m long conductive heytether [20]. The tether will be deployed using the centrifugal force produced as a result of the satellite spin motion. The charged tether, moving relative to the ionospheric plasma, experiences several forces acting on it. Two of the major force components result from the tether's interaction with plasma and the magnetic field. The conductive tether experiences the Lorentz force due to the interaction with the magnetic field around it. The net force depends upon the magnetic field and the current flowing in the tether. These forces are an important factor as they would cause the spin axis to deviate from the required orientation as the tether will be charged. Along with these forces, the moments of inertia of the satellite also change as the tether reels out thus changing the system model. This also increases the estimation and control complexity. Even a small mass attached to the end of a long tether can cause a noticeable change in the system's inertia and thus the attitude, as the tether is reeled out.

An important part of the experiment to be considered during the attitude determination system design is the high-voltage source unit that provides the voltage supply to charge the tether. It is a potential source of electromagnetic disturbance. This disturbance source, along with the residual magnetic field within the satellite, poses a challenge in correct magnetic field sensing and actuation. They adversely affect the sensors by adding a bias to the sensor measurements. This paper mainly focuses on the attitude estimation during the spin-up phase of the experiment due to its being the most critical of all the phases. The affects of adaptation of the process noise have been discussed in detail and a comparison has been made, for the specific case of the PBE onboard