HIGH-FIDELITY MODELING AND CONTROL SYSTEM SYNTHESIS FOR THE MGRS DRAG-FREE SATELLITE

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Abstract: *The detection of gravitational waves remains to this day one of the fundamental open problems in physical science. Ground-based low-frequency interferometric detectors suffer from various disturbance interference effects such as seismic noise and environmental vibration. This motivates space-based interferometry missions such as the proposed LISA mission. A prerequisite to detecting gravitational waves using a space-based interferometer is the isolation of all components from non-gravitational forces. Such a task can be accomplished with a drag-free satellite which is composed of an internal proof mass shielded by an external satellite that compensates all dominant disturbance forces encountered in the space environment such as aerodynamic drag and solar radiation pressure. This paper addresses the development of a high-fidelity modeling environment for the Modular Gravitational Reference Sensor (MGRS) satellite. The MGRS mission aims to demonstrate three-axis drag-free operations with residual non-gravitational acceleration of a proof mass under* $10^{-12} ms^{-2}/\sqrt{Hz}$ *in the frequency range 0.01 to 1Hz. Our modeling framework allows us to compute an envelope for the expected satellite disturbance profiles, derive sizing constraints for a suitable micro-propulsion system, and formulate a preliminary drag-free translational and attitude control system.*

Specifically, since their inception in [1], drag-free satellites have served as promising platforms for facilitating precise experimental physics in areas such as geodesy, remote sensing and relativistic science. To date, there have been a limited number of successful drag-free missions, namely Gravity Probe B and GOCE. The ability to achieve an extremely low disturbance environment for the proof mass is strongly reliant on the performance abilities of a high precision micro-propulsion system. The need for such small thrusts stems from: 1) a low disturbance environment in space, and 2) miniscule required corrections to the external satellite (on the order of μm*) to maintain a desired distance with respect to the proof mass. Gravity Probe B had the advantage of having access to a large amount of Helium gas for an on-board experiment. Consequently, the drag-free control system was able to use this gas as propellant within a proportional control scheme. GOCE, on account of its large 1-ton mass and a low orbit altitude of 235km, experienced in-track forces large enough to be easily compensated by a 20mN Kaufman-type ion thruster. The lateral force and torque compensation however posed some difficulty due to lack of maturity in electric propulsion technology at such low thrust levels. MGRS is a 100kg microsatellite and consists of a 0.125*m^3 *rectangular cuboid body with two 0.25*m^2 *solar panels. Due to the satellite's small size, the external disturbance forces are quite small. Indeed, the radial axis of the satellite is expected to experience external non-conservative forces up to just* $\pm 3.5 \mu N$ *at a fairly low altitude of 300km. The lack of space to accomodate large quantities of propellant and the extremely small disturbances in the radial axis are among the primary challenges that must be addressed for the mission to be feasible. Our proposed solution for MGRS solves these challenges and in doing so, establishes the ability to achieve the best drag-free performance to date on a tightly constrained platform with feasible, existing technology.*

In addition to countering the external non-conservative disturbances, the drag-free control system must also minimize the effect of coupled disturbances between the external satellite and proof mass due to satellite gravity gradient and electromagnetic forces, as well as induced disturbances such as thruster noise. In order to synthesize an appropriate control scheme, it is essential to obtain a detailed model of all forces and torques on the satellite and proof mass. Consequently, we first detail the development of a simulation environment that provides insights into the range of expected disturbances for two candidate sun-synchronous orbits at altitudes of 300km and 650km. Using these results, we propose a suitable micro-propulsion system that is selected out of a trade-study involving several options such as ion-engines, cold-gas and electrospray thrusters. Finally, we formalize the proposed drag-free performance objective and propulsion constraints within a translational and attitude control system framework that attempts to center the proof mass at an unknown minimum disturbance point within the satellite. In addition, this control system must guarantee performance in the presence of uncertainties in system dynamics, unmodeled disturbances, and stringent power consumption constraints. A preliminary controller is designed using H_∞ techniques and its performance is assessed under nominal conditions. We conclude with a discussion on expected future work that will explicitly account for model uncertainties and utilize online disturbance estimation techniques within a robust, adaptive control framework.

Keywords: *Drag-free satellite, satellite simulation, drag-free control, H_∞ control.*

1. References

[1] Lange, B. “The Drag-Free Satellite.” AIAA Journal, Vol. 2, No. 9, pp. 1590–1606, Sep. 1964. ISSN 0001-1452. doi:10.2514/3.55086.