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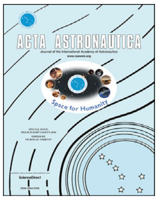

Embedded model control GNC for the Next Generation Gravity Mission

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ABSTRACT

A Next Generation Gravity Mission (NGGM) concept for measuring the Earth's variable gravity field has been recently proposed by ESA. The mission objective consists in measuring the temporal variations of the Earth gravity field over a long-time span, with very high spatial and temporal resolutions.

This paper focuses on the guidance, navigation and control (GNC) design for the science phase of the NGGM mission. NGGM will consist of a two-satellite long-distance formation like GRACE, where each satellite will be controlled to be drag-free like GOCE. Satellite-to-satellite distance variations, encoding gravity anomalies, will be measured by laser interferometry. The formation satellites, distant up to 200 km, will fly in a quasi-polar orbit at an Earth altitude between 300 and 450 km.

Orbit and formation control counteract bias and drift of the residual drag-free accelerations, in order to reach orbit/formation long-term stability. Drag-free control allows the formation to fly counteracting the atmospheric drag, ideally subject only to gravity.

Orbit and formation control, designed through the innovative Integrated Formation Control (IFC), have been integrated into a unique control system, aiming at stabilizing the formation triangle consisting of satellites and Earth Center of Masses.

In addition, both spacecraft must align their control axis to the satellite-to-satellite line (SSL) with micro-radian accuracy. This is made possible by specific optical sensors and the inter-satellite laser interferometer, capable of materializing the SSL. Such sensors allow each satellite to pursue an autonomous alignment after a suitable acquisition procedure. Pointing control is severely constrained by the angular drag-free control, which must ideally zero the angular acceleration vector, in the science frequency band.

The control unit has been designed according to the Embedded Model Control methodology and is organized in a hierarchical way, where the drag-free control plays the role of a wide-band inner loop, and orbit/formation and attitude/pointing controls are the narrow band outer loops. The relevant state equations were converted to discrete time providing the embedded model, a fundamental part of the control unit. The state predictor, control law and reference generator were built on and interfaced to the embedded model.

Simulated results, via a high-fidelity simulator, prove the concept validity and show that the control performances are in agreement with the defined mission requirements. Indeed, the presented control strategy is shown to be capable of keeping the attitude and formation variables stable within the required boundaries, all over the 10-year mission, through a low-thrust authority in the order of a few milli-Newton.

1. Introduction

Post ESA's GOCE (Gravity field and steady state Ocean Circulation Explorer [1]) and GRACE (Gravity Recovery and Climate Experiment [2]) space Earth gravimetry missions will rely on a formation of free falling ‘proof masses’ and on the measurement of their distance variations, encoding the gravity anomalies. As a matter of fact, one of the main objectives will be to increase at a greater extent the performance level of gravity missions. Such an ambitious objective can be achieved by adding a closed-loop formation control in addition to long-distance distributed

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Acronyms/Abbreviations: EMC, Embedded Model Control; NGGM, Next Generation Gravity Mission; FLOF, Formation Local Orbital Frame; SSL, Satellite-to-satellite line; MBW, Measurement bandwidth; IFC, Integrated orbit and Formation Control; AOCS, Attitude and orbit control system.

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space systems, as in GRACE, in the order of 100 km distance, but at a lower altitude (300–400 km). However, at those altitude ranges, the effects of the Earth atmosphere over the satellites are very severe. Hence, such kind of missions require that each satellite is controlled to be drag-free (up to a certain measurement bandwidth) and completed by an accurate distance measurement system.

Following these main principles, the Next Generation Gravity Mission (NGGM), under study at the European Space Agency (ESA), will consist in a two-satellite long-distance formation, placed in a low near-polar orbit. Each satellite will be autonomously controlled to be drag-free. Concerning the measurement principle, laser interferometry will ensure the satellite-to-satellite tracking and the inter-satellite distance variation measurements.

Consequently, a first set of mission requirements comes from the scientific data elaboration. In this framework, the main requirement concerns the non-gravitational CoM accelerations, as they must be ideally brought to zero. A second set of requirements concerns the orbit and formation control. In this case, the orbit and formation control is designed to counteract the effects of the drag-free control residual, which can make the satellite formation diverging. Finally, the attitude and pointing control system is intended to keep aligned the satellite optical axis and eventually ensure an orbital roll motion for tracking the Sun beam.

The NGGM mission technology is defined as a consequence of the established requirements [3]. Indeed, the drag-free control requires one or more GOCE-class ultrasensitive accelerometers capable of providing linear and angular accelerations. In addition, the formation control requires both a global navigation satellite system (GNSS), in order to materialize the relative satellite position, velocity, and the formation frame, and an inter-satellite link (ISL). As a design choice, all the control functions are actuated by an electric propulsion assembly, able to provide a few milli-Newton thrust level. Finally, satellite-to-satellite mutual alignment variations are measured via an inter-satellite laser interferometer and specific optical sensors.

The approach adopted in the AOCS design for the NGGM mission is based on the Embedded Model Control (EMC) design methodology [4,5], which calls for a hierarchical and multi-rate control unit around the real-time internal model of the satellite controllable dynamics. This internal (or embedded) model describes the controllable dynamics and the disturbance dynamics. The disturbance dynamics model is in charge of estimating a wide range of unknown model errors as drag-free residuals, parametric uncertainties, cross couplings, and neglected non-linearities.

This paper focuses on the AOCS design principles for the science phase of the NGGM mission. One of the most relevant contributions of this paper is the definition of all the NGGM AOCS architecture control functions within the unified framework of the EMC design methodology. Specifically, for the orbit and formation control, this is enhanced via the definition of an innovative integrated orbit and formation control (IFC) architecture [6]. Such formulation is based on the definition of a peculiar formation reference frame (the formation local orbital frame, FLOF) and the formation triangle virtual structure. A further relevant contribution consists in testing through high-fidelity simulations the effectiveness of the proposed control architecture.

This paper starts with some concepts about the NGGM mission requirements and the architecture of the control design. After this brief outline, the paper describes the main principles of the EMC design and the drag-free concept. Further, the formation triangle dynamics model is made explicit, introducing the FLOF frame. The discrete-time (DT) final equations of the drag-free and the formation internal models are provided. As a consequence, leveraging the EMC design, the state predictor and the control law are built on and interfaced to the internal model. In addition, some sketches about the attitude and pointing control and its interface with the angular drag-free control functions are provided. Finally, some preliminary simulated results verify the control performances and the requirements compliance.

2. NGGM mission requirements and EMC control architecture

In this section some of the main characteristics of the NGGM mission will be addressed as well as the corresponding control requirements. Further, a general overview of the adopted design methodology (EMC) will be provided, together with the AOCS chief design principles.

2.1. Mission characteristics and requirements

Concerning the satellite formation geometry, two suitable formation types have been proposed as good candidates for the NGGM science mission mode: (i) inline, and (ii) pendulum. The inline formation is characterized by two satellites following the same orbital path, with different true anomalies. On the other hand, in the pendulum configuration, the two satellites are placed on two slightly separated but intersecting orbits, having different right ascension of the ascending node. Further, the nominal altitude range spans between 325 and 425 km on quasi-polar inclined orbits, and the orbit period varies among 5.46 and 5.59 ks. Finally, the nominal inter-satellite distance is in the range of 100–200 km. Such a set of orbital features will allow NGGM to provide an all-latitude coverage, short repeat cycles and a precise gravity signal with a long mission lifetime (up to 11 years, i.e. a full solar cycle).

The NGGM mission concept leverages a two-satellite formation, ideally drag-free and flying as test masses in the Earth gravity field. Such a pair of distant drag-free satellites acts as a sort of gradiometer, with a very long baseline (≈200 km). As a matter of fact, such configuration will make NGGM the first free-falling formation mission. Given the distance variation between the two satellites CoM, which is the mission fundamental observable, a gradiometer-like configuration of this kind has been conceived in order to retrieve only the small fraction, within the total distance variation, due to the gravity acceleration (i.e. the Earth gravity field anomalies effect).

Consequently, from the orbit and formation control perspective, such a drag-free formation implies that no stringent requirements apply to the formation control. Indeed, in principle the two satellites, while acting as proof-masses, must be left free to move under the action of the Earth gravity field. However, since the accelerometer errors (e.g. bias, drift) make an ideal drag-free control not possible, a loose orbit and formation control is needed [3].

Table 1 lists the main requirements driving the control design in the science mode of the NGGM mission. Note that the formation requirements have been split into distance, radial and lateral variations with respect to a nominal circular orbit; expressed as a percentage of the nominal inter-satellite distance. From the sensor perspective, the requirements match the four accelerometers configuration is adopted, coherently with the latest system studies (see also the tests configuration in Appendix A).

All the requirements above in Table 1 refer to the Scientific Mode (SCM), in which the measurements needed to obtain the scientific product are performed.

This control mode provides fully drag-free environment, formation flying control, optical link between satellites, and orbit control (by ground or autonomous). The science control mode is the last of a series of control modes, starting from the satellites separation from the launcher, and through a mode transition logic based on some monitoring variables. However, the science mode is the fundamental structure on which several control functions of the higher modes are based.

2.2. The embedded model control

The EMC rationale encompasses three model classes to describe the uncertainty affecting the models [4]. The term plant refers to the real system to be controlled (the NGGM spacecraft formation), whereas the digital control unit refers to the NGGM AOCS in charge of orbit, formation and attitude control. The word model corresponds to different classes: (i) the fine model is the more refined, (ii) the design model is a