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Orbit and Formation Control for the Next Generation Gravity Mission [*]

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Abstract: This paper focuses on the orbit and formation control for the Next Generation Gravity Mission (NGGM), under study at the European Space Agency. In our past study, an innovative integrated orbit/formation model (IFC) has been designed, introducing a novel set of Hill-type equations. The aim of this study is the refinement and the enhancement of the IFC architecture. The proposed solution is based on a modified state predictor plus an extended hierarchical and multi-rate structure of the control law, with respect to the preliminary design. Care was taken in the control design to reduce as much as possible the demanded extra-thrust effort. This improved control strategy has been shown to be far less sensitive to the initial formation perturbations as well as capable of keeping the formation variables stable within the required band, all over the 10-year mission, through a low-thrust authority in the order of few milli-newtons.

Keywords: Spacecraft Formation Flying, Orbit Control, Formation Control, Low-Earth Formation, Gravimetry

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1. INTRODUCTION

Post ESA's GOCE (Gravity Field and Steady-State Ocean Circulation Explorer), space Earth gravimetry missions will rely on a formation of satellites, flying in loose formation in a low Earth orbit, acting as proof masses immersed in the Earth gravity field and on the measurement of their distance fluctuations, encoding the gravity anomalies. Indeed, the performance level of gravity missions can be substantially increased by adding a formation control to long-distance distributed space systems as in GRACE (Gravity Recovery And Climate Experiment), in the order of 100 km distance, but at a lower altitude (300 to 400 km). Such a mission configuration requires that each satellite is drag-free and completed by an accurate distance measurement system. As a result, the Next Generation Gravity Mission (NGGM), under study at the European Space Agency, will consist in a two-satellite long-distance formation, placed in a low near-polar orbit. Each satellite will be controlled to be drag-free, while laser interferometry will ensure the satellite-to-satellite tracking.

This paper focuses on the orbit and formation control for the NGGM mission, whose aim is the orbit and formation long-term stability (> 10 years). One of the most relevant contribution of this paper is the refinement and the enhancement of the integrated orbit and formation control (IFC) architecture described by Canuto et al. (2014a), so to overcome possible drift and stability issues due to a large envelope of the formation initial perturbations. As in Canuto et al. (2014a), the orbit and formation dynamics is formulated as a special kind of Clohessy-Wiltshire (CW) equations [Wiltshire and Clohessy (1960)]. Such formulation is based on the definition of a peculiar formation reference frame (the formation local orbital frame, FLOF) and the formation triangle.

There are many possible ways to define the dynamics of a satellite formation and to control it. Three main approaches may be found in literature [Ren and Beard (2004)]: leader-follower, behavioural, and virtual structure. The stability and the accurate formation dynamics free response has also been largely investigated. For small formations, the effects of the non-linear terms are negligible, but the effects of the gravitational perturbations and the reference orbit eccentricity are often significant [Alfriend et al. (2000), Schaub and Alfriend (2000)]. Hence, attention has been paid to include in the model generic gravity potential terms as in Guibout and Scheeres (2012) or to extend relative orbit motion to eccentric orbits as in Yamanaka and Ankersen (2002). There have also been analyses to develop formations that are insensitive to differential J2 disturbances, based on non-linear dynamic models [Schaub and Alfriend (2000)]. At this proposal, Schaub and Alfriend (2000) suggest that by specifying the relative orbit geometry in mean elements the true relative spacecraft motion does not deviate from the prescribed relative orbit geometry. However this method has been

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found to be too weak in some particular orbit conditions by Schaub et al. (2000), which study methods to reestablish these J2 invariant relative orbits by feedback. Another way to address the description of proximity relative motion for formation or rendezvous mission is to develop the state transition matrix, even for eccentric orbits, both in dependence of time [Melton (2000)] or true anomaly [Inalhan et al. (2002), Yamanaka and Ankersen (2002)]. On the other hand, care must be taken in employing CW perturbation equations for control design in the case of a long-distance formation baseline, since significant non-linear gravity terms are neglected. For instance, Alfriend et al. (2000) used state-transition matrices to account the orbit eccentricity and the gravity perturbations. The approach adopted in this paper is based on the Embedded Model Control (EMC) design [Canuto et al. (2014c), Canuto et al. (2014b)], which calls for a hierarchical and multi-rate control unit around the real-time internal model of the satellite formation controllable dynamics. The embedded model control technique fully solves this sort of problems through a simple but effective disturbance estimation dynamics. Hence, the main advantages, inter alia, consist in both being free to adopt a simplified internal model and directly rejecting the perturbations from the LTI model, reducing the required thrust level and fuel consumption.

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 formation triangle dynamics model, introducing the FLOF frame. The discrete-time (DT) final equations of the formation internal model 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. Finally, some preliminary simulated results proving control performances are provided.

2. NGGM MISSION REQUIREMENTS AND CONTROL ARCHITECTURE

The NGGM mission fundamental observable is the distance variation between the two CoMs. However, within the total distance variation, only the small fraction due to the gravity acceleration (i.e. the Earth gravity field anomalies effect) is of interest. Consequently, 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 ($\approx 200\,\mathrm{km}$).

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, an ideal drag-free control is not possible, mainly due to the accelerometer errors (e.g. bias, drift). Hence, an orbit and formation control is needed.

The 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. Concerning the attitude and orbit control system (AOCS) design, the main design principles are:

Table 1. NGGM mission science control mode: main performance requirements for the AOCS.

Performance variable	Bound	Unit
Drag-free control		
CoM acceleration (PSD in MBW)	0.01	$\mu\mathrm{m/s^2}/\sqrt{\mathrm{Hz}}$
CoM acceleration	1	$\mu\mathrm{m/s^2}$
Orbit and formation control		
Formation distance variation	5	% (distance)
Formation lateral variation	1	% (distance)
Formation radial variation	2	% (distance)

Embedded Model Control AOCS is designed around a simplified, discrete-time model of the spacecraft and formation dynamics to be embedded in the control unit. This embedded model consists of the controllable dynamics and of the disturbance dynamics. The disturbance dynamics is in charge of estimating a wide range of unknown model errors as drag-free residuals, parametric uncertainties, cross couplings and neglected non-linearities.

Integrated orbit and formation control The orbit and formation control design is driven by an innovative approach to multi-satellite formation and orbit control. Such innovative approach is based on the integration of orbit and formation dynamics and control through the formation triangle concept and leads to new Hill-type equations (see Canuto et al. (2014a) and Section 3).

Multi-hierarchical control Control tasks are carried out via a multi-hierarchical control design, as described later in this section.

Frequency coordination The drag-free control and the formation control are actuated at different frequency bands. This is deemed necessary in order to prevent any possible interference among inner/outer loops control functions and to coordinate properly the several tasks of the control design.

The higher-level block-diagram of the AOCS architecture, in science phase, is sketched in Fig. 1. From the control architecture perspective, formation and drag-free control are designed in a hierarchical way. Indeed, the integrated orbit and formation control is an outer loop which provides the long-term reference accelerations to be tracked by drag-free control. As a result, in Fig. 1, loops 3, 4, and 5 pertain to the enhanced integrated orbit/formation control plus the linear drag-free. The loops 4 and 5, addressing the control of the formation position (loop 4) and the formation rate (loop 5), are actuated at different and appropriate frequency bands. Indeed, the low-frequency formation position control (loop 4) employs orbital-averaged measurements in order to filter out any component of gravitational nature and the command is actuated at the orbit frequency (close to 0.2 mHz). Further, a damping control function (loop 5) has been added in the present enhanced IFC configuration. Such damping control, concerning the formation linear rate variables, is actuated at an higher frequency and it has been proved to be necessary to ensure the orbit and formation BIBO stability. This sub-hierarchical structure within the orbit and formation control is the main novelty with respect to