POLITECNICO DI TORINO
Dipartimento di Automatica e Informatica

PhD in Computer and Control Engineering

XXIX cycle

Advisor

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Laser Metrology Spacecraft Formation for the Next Generation Gravity Mission

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1. Introduction

The Next Generation Gravity Mission (NGGM), under study by the European Space Agency, will consist of a two-satellites long-distance low-Earth formation. Satellite-to-satellite distance variations, encoding gravity anomalies (see Figure 2), will be measured by laser interferometry with an accuracy improvement of at least three orders of magnitude with respect to GRACE radiometric measurements. The formation spacecrafts must align their axis to the satellite-to-satellite line (SSL) with a micro-radian accuracy, while both satellites have to be made drag-free. An innovative formation control has been formulated, capable of controlling both altitude and distance; at the same time.

2. Goal

The final aim of this study will be the design, simulation, test and validation of an Attitude and Orbit Control System (AOCS) for the NGGM mission; compliant with the ESA requirements.

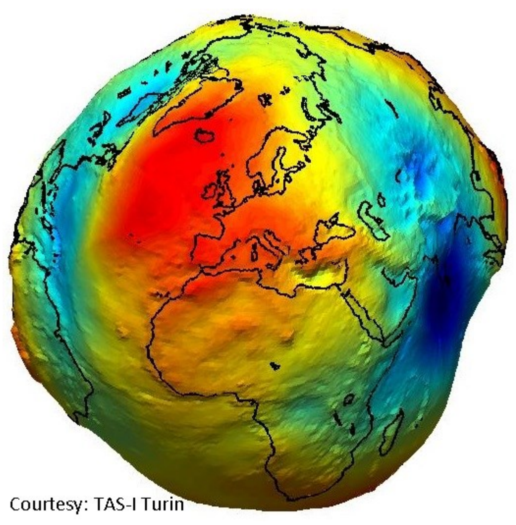

Figure 1: the Geoid

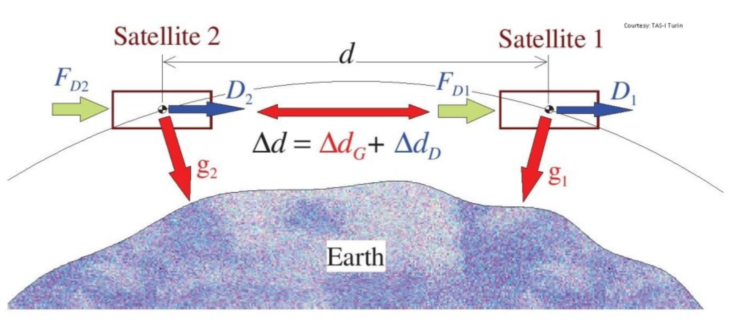

Figure 2: the measurement principle

3. Mission Requirements

The requirements come from the scientific data elaboration and, specifically, from the calibration of the GOCE-class accelerometers. The formation control must also guarantee the formation stability, i.e. that the perturbations of a nominal formation remain bounded during the whole mission life. Conversely, a pointing control will be responsible of the satellite-to-satellite alignment to the SSL.

Variable	Bound	Note
Drag-free control		
3D CoM acceleration	1 μm/s² - 0.01 μm/s²/√Hz	f > 1 mHz
3D angular acceleration	1 μrad/s² - 0.01 μrad/s²/√Hz	f > 1 mHz
Formation control		inter-satellite distance = 200 km
Formation distance variation	5% (inter-satellite distance)	
Formation radial variation	2% (inter-satellite distance)	
Mean orbit height variation	50 m	
Formation lateral variation	1% (inter-satellite distance)	
Attitude control		
SSL pointing (pitch, yaw)	1 μrad/s²/√Hz	f > 1 mHz

4. Mission Geometry

The formation distance variations must be measured along the satellite-to-satellite line which joins the satellites CoMs (Figure 3). The SSL can be materialized either via differential GPS, necessary for the formation control, or laser interferometry, employed by the attitude control. In the latter, the materialization can be obtained by aligning the axis of the launched beam to the SSL, better than the laser beam divergence (see Figure 3). Since any light direction of the laser beam passing through the companion satellite optical centre materializes the SSL, the relative alignment can be achieved by aligning each satellite to the SSL, independently [1].

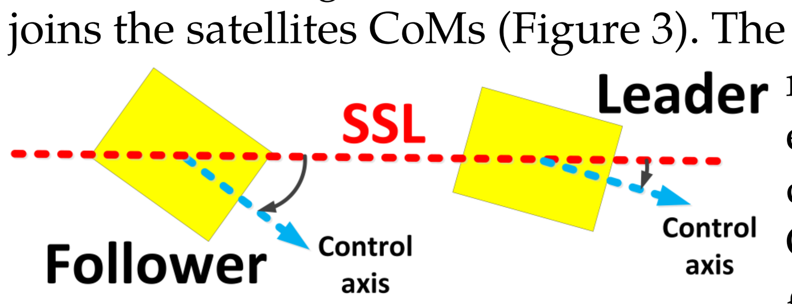

Figure 3: inter-satellite pointing

For the integrated formation and orbit dynamics and control [2], a combination of Cartesian and angular perturbations has been defined with the help of the formation triangle (see Figure 4). Through this geometrical formulation, attitude and orbit and formation controls turn out to be decoupled. They are combined in the thruster dispatching law, converting the 6D force/torque vector into eight thrusts. Hence, the only interconnection is solved by a pseudoinverse procedure, which accounts for thrust bounds (see thruster dispatching/optimization in Figure 5).

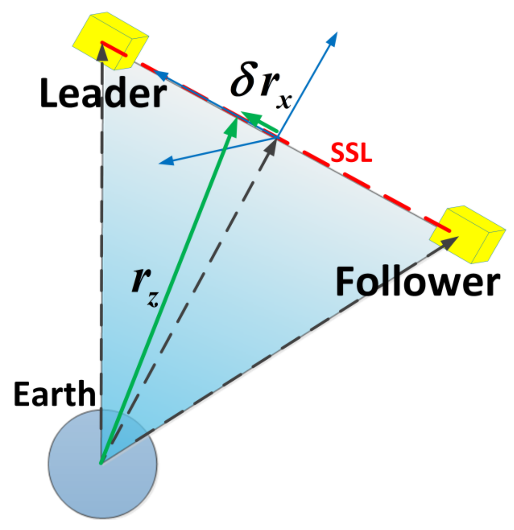

Figure 4: integrated formation triangle

5. Methodology and Control Design Principles

The NGGM control is designed around the Embedded Model Control theory.

The Embedded Model Control methodology implies the design of an internal model (Embedded Model, EM) coded into the control unit and running in parallel with the plant. The EM is divided into a dynamics controllable by the command and the dynamics of the disturbances acting on the controllable part. The controllable dynamics is a simplified representation of the input-output plant dynamics. By contrast, the stochastic disturbance dynamics model aims at modelling the unknown disturbances, non-linear effects and parametric uncertainties. As a result, the disturbances are estimated and canceled by means of the state predictor and the control law, respectively. Further, the disturbance dynamics is driven by a noise vector playing the role of a disturbance input, to be real-time retrieved from the model error (plant output less model output). By tuning the eigenvalues of the closed-loop system, the stability of the state predictor versus the neglected dynamics is achieved.

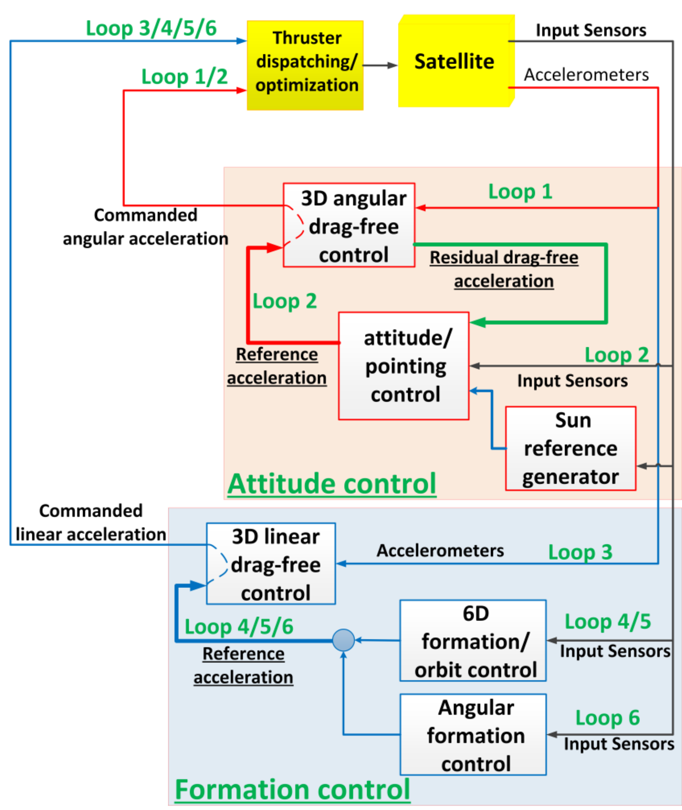

Figure 5: AOCS architecture higher-level block scheme

Some further basic principles rule the control design:

- Coordinate decoupling: each embedded model splits into three separate SISO models.
- Hierarchy: the AOCS is made up by several control loops. Hence, the control command is split into the drag-free command (inner loop), designed to ideally bring to zero the accelerations, plus the outer command (formation/pointing), providing the reference to the inner loop; as depicted in Figure 5.
- Frequency coordination: allowing the reference command to respect drag-free requirements, thus preventing interference among inner/outer loops. Such frequency coordination strategy consists mainly in cancelling the accelerometer drift/bias (i.e. the drag-free residuals) for f < 1 mHz while filtering the attitude sensor noise for f > 10 mHz; as sketched in Figure 6.
- Hybridization: the accelerometer measurements directly enter into the attitude embedded model as the input reference command (residual drag-free acceleration loop, in figure 5).

6. Simulated Results

The first simulated results, from a complete high-fidelity numerical simulator, show a good compliance with the mission requirements, within the range of frequency of interest (1 mHz < f < 100 mHz). Specifically, both the formation triangle variables and the drag-free residuals are kept well below the requirements (e.g. in Figure 7, see the linear drag-free residuals PSD). In addition, during the control design, it has been possible to detect some criticalities in terms of frequency requirements. Such critical aspects are mainly due to the extremely severe mission objective scenario, compared to the current state-of-the-art sensors and actuators technology level.

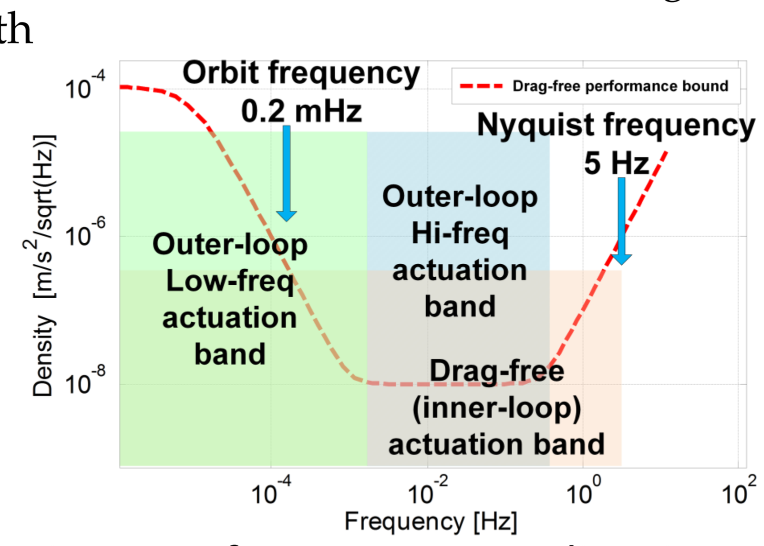

Figure 6: frequency coordination

7. Conclusions

A coordinated design of simulation and control models is crucial to cope with NGGM control challenges. The simulated results prove the design validity and the control performances compliance with the mission requirements. Finally, the proposed control strategy appears to be 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-Newton.

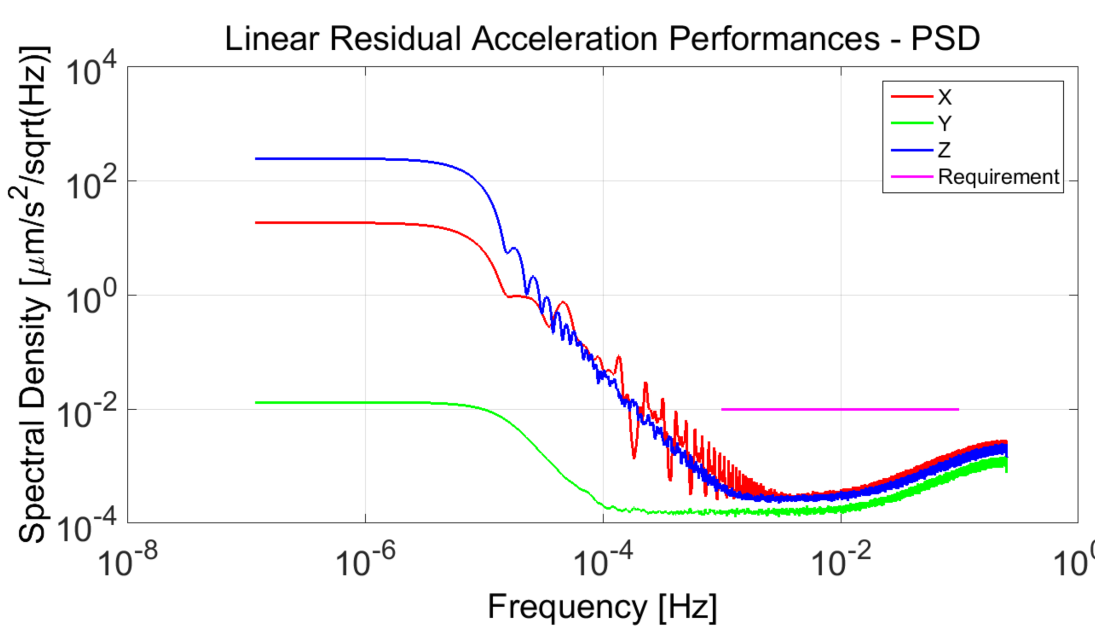

Figure 7: linear acceleration residuals PSD

References

1. E. Canuto, L. Colangelo, M. A. Lotufo, S. Dionisio, **Satellite-to-satellite attitude control of a long-distance spacecraft formation for the Next Generation Gravity Mission**, European Journal of Control, Vol 25, September 2015, ISSN 0947-3580.
2. L. Colangelo, E. Canuto, L. Massotti, C. Novara, M.A. Lotufo, **Orbit and Formation Control for the Next Generation Gravity Mission**, IFAC-PapersOnLine, Vol 49, 17, 2016, pp 284-289, ISSN 2405-8963.

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Further Information

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