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XXXIII Cycle

Control design for the LISA space mission

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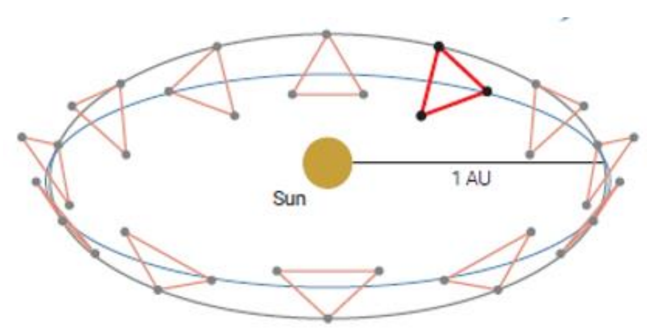
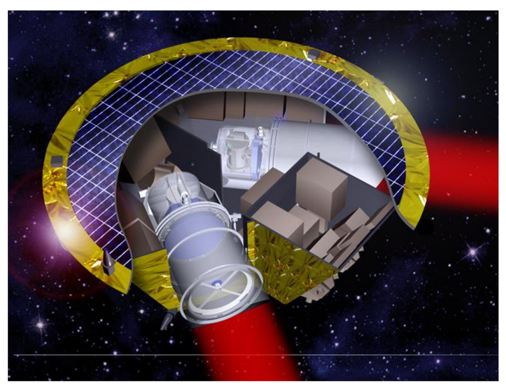
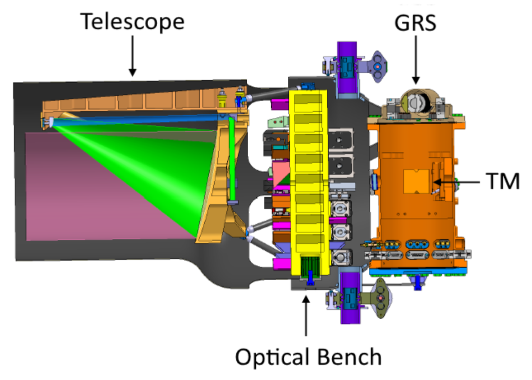
Research context and motivation

- LISA is a large class space mission of the European Space Agency, whose launch is planned for 2034. It consists of a triangular constellation of satellites potentially able to observe gravitational waves in the 10^{-5} to 10^{0} Hz bandwidth.
- The main idea behind a space-based gravitational wave observatory, is to consider two free falling test masses and to measure their relative distance by means of a laser interferometer. Each test mass is shielded by a spacecraft and kept in free fall thanks to a Drag Free and Attitude Control System (DFACS), which compensates for all the external disturbances.
- LISA is a very complex mission both in terms of orbital dynamics, spacecraft design and performance requirements. The three heliocentric orbits set up a Sun facing spinning triangle with a mean side length of 2.5 Mkm, located at 50 Mkm from the Earth. The complexity of a single spacecraft is such that there are 38 states to be controlled, subject to nanoscopic scale requirements.



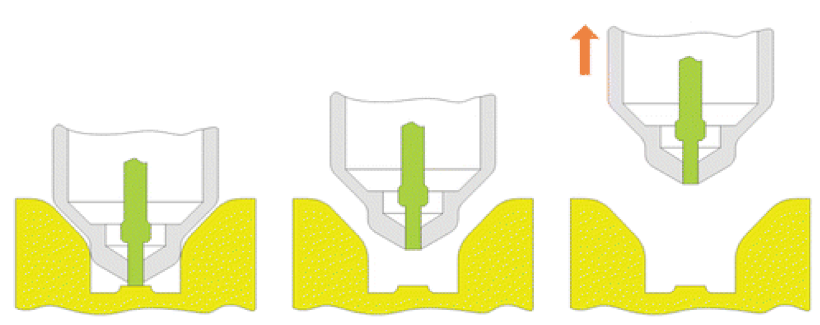


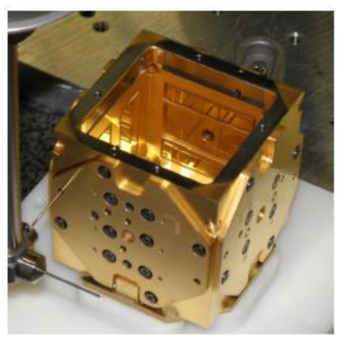


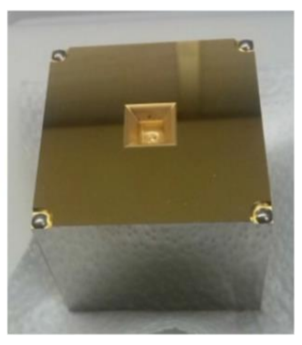
- Even if a preliminary spacecraft prototype has been already designed and is currently under the Phase-A system study, very little was done regarding the mathematical modelling, development and testing of the controllers. Politecnico di Torino was selected for these tasks and developed nonlinear, linearized and decoupled dynamic models back in 2018. Then, several controllers have been designed for the LISA mission phases in 2019, which are of primary importance for the mission success.

Addressed research questions/problems

- Each mission phase is characterized by specific issues to be carefully addressed.
- *Test Mass Release*: the aim of this mission phase is to capture electrostatically the gravitational reference body (a 2 kg cubic test mass) suddenly after the retraction of the locking clamps. Unfortunately, initial conditions are critical and the actuation authority is very low (max 1 μN) resulting in a difficult regulation of the states. If the test mass is not correctly captured or gets scratched by hitting the cage walls, the entire mission could be compromised since the laser interferometry would be affected.



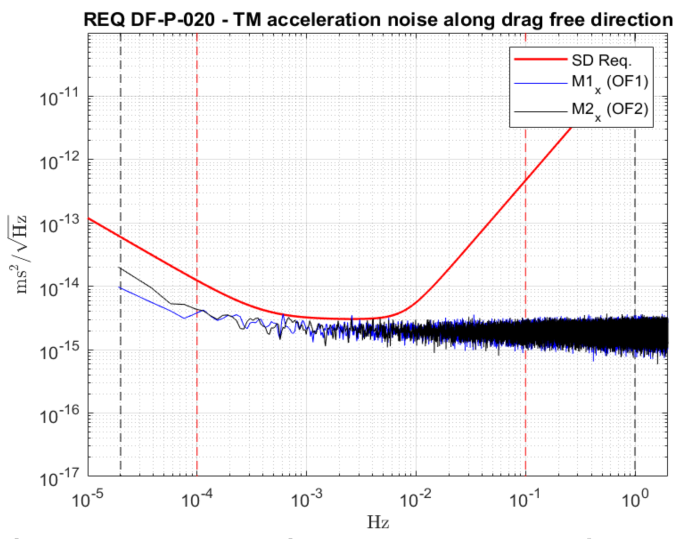


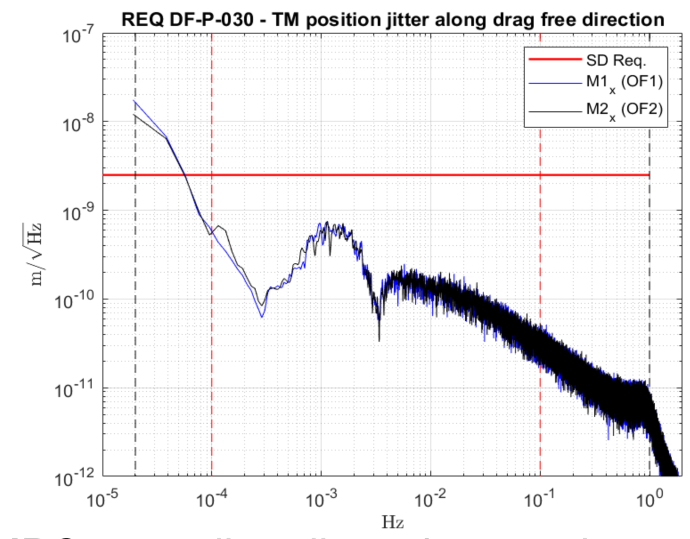


- *Drag Free Mode*: once the two test masses have been placed at their cage centres and the laser links have been acquired, the system enters drag free mode. Here, all the 19 degrees of freedom have to be controlled simultaneously and are subject to nanoscopic scale requirements in the frequency domain. If they are not fulfilled, gravitational waves cannot be observed.
- Another aspect of this study, was to identify potential flaws in the spacecraft design that could affect the control and eventually the mission feasibility.

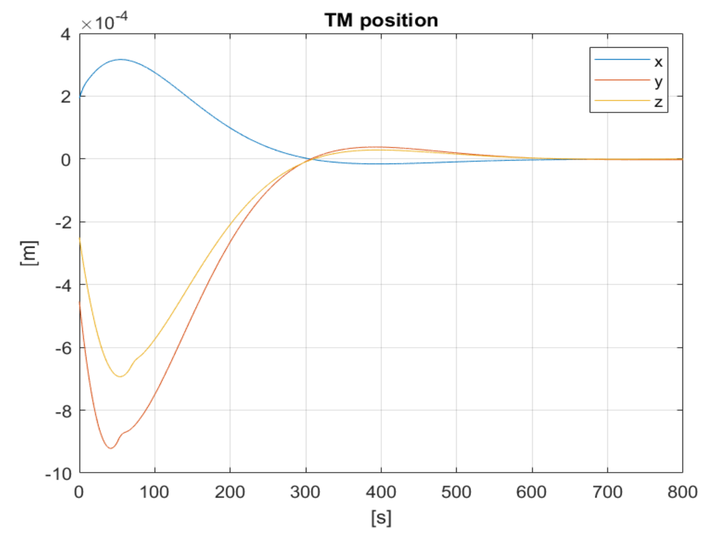
Novel contributions

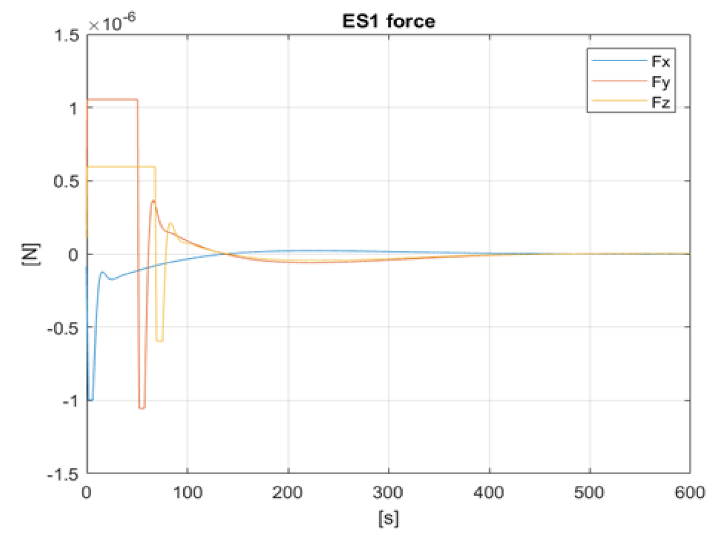
- The novelty of the present work resides in the design of modern controllers for a future large class space mission. For what concerns the drag free mode, a h-inf controller has been designed jointly with a novel constrained decoupling approach. Finally, a feasibility assessment of the performance requirements has been performed and some criticalities have been found, which will require a review of the spacecraft equipment.
- Among the several controllers, the H-infinity proved that the mission is feasible down to $5 \cdot 10^{-5}$ Hz. Below this frequency, the too high sensing noises do not allow to satisfy the performance requirements.





- For what concerns the test mass release, the MPC controller allowed to regulate all the 12 test mass states in presence of a very low actuation authority.





Adopted methodologies

- *H-infinity (H∞)*: it is a suitable technique for the drag free mode, since it allows us to obtain an optimal controller given requirements and noise shapes in the frequency domain. H-inf allows also to understand if the requirements can be theoretically satisfied. Indeed, if the loop functions between noises and outputs exceed the performance requirements, it means that the control problem is infeasible (in practice, the considered noises are too high). This control method fits better with a decoupled control architecture because every SISO controller can be synthesized by considering only the performance requirements and the noise shapes of a specific loop. One last advantage is that the design process is theorical, structured and not too much based on time-consuming tuning procedures, as it happens for the PID approach.
- *MPC:* it is suitable for the test mass release mode, since it is a MIMO control technique that finds the optimal/sub-optimal control inputs in presence of constraints on states and inputs. It allows also to reduce the command activity by means of a suitable cost function.

Future work

- Monte Carlo test campaign and mu analysis.
- Constrained decoupling (theoretical control-oriented research activity)

Other activities

- *Mathematical Models Review* at ESA, Noordwjik-Binnen, Netherlands.
- *2nd Workshop on Innovative Spacecraft Attitude and Orbit Design Techniques*, Milan.
- Workshop *Brainstorms on Space Technology*, Siena.

Submitted and published works

Works submitted this year:

- C. Possieri, S. Vidano and C. Novara, *"A finite-time local nonlinear observer in the original coordinates for nonlinear control systems"*, Transactions on Automatic Control. (3rd review ongoing)
- S. Vidano and C. Novara, *"The LISA DFACS: a nonlinear model for the spacecraft dynamics"*, Aerospace Science and Technology. (submitted)

List of attended classes

Classes attended this year:

Soft Skills:

• 01QORRV	–	Writing Scientific Papers in English	(06-06-2019, 3 CFU)
• 01RISRV	–	Public speaking	(05-01-2019, 1 CFU)
• 01SHMRV	–	Entrepreneurial finance	(12-01-2019, 1 CFU)
• 01SWPRV	–	Time management	(26-12-2018, 1 CFU)
• 01SYBRV	–	Research integrity	(17-01-2019, 1 CFU)
• 02LWHRV	–	Communication	(30-12-2018, 1 CFU)
• 08IXTRV	–	Project management	(10-01-2019, 1 CFU)

Hard Skills:

• 01TEVRV	–	Deep learning (didattica di eccellenza)	(04-06-2019, 6 CFU)
• External	–	Model Predictive Control (IMT Lucca)	(06-05-2019, 6 CFU)