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XXXIV Cycle

NMPC for Autonomous Guidance & Control in Space Missions

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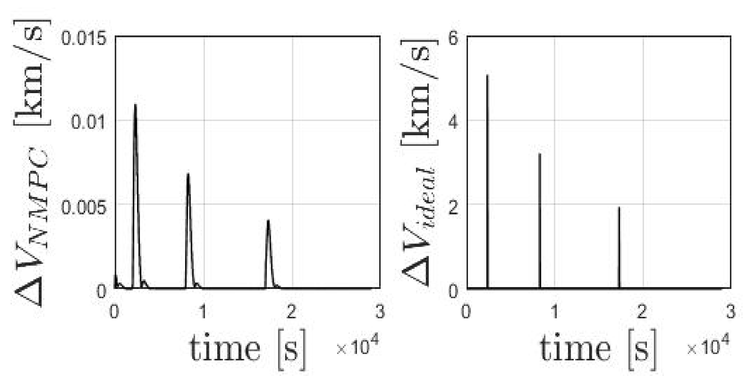
Research context and motivation

- Model Predictive Control (MPC) has a great potential to shape and revolutionize the future of aerospace control and guidance systems, thanks to its ability to systematically handle linear and nonlinear constraints, complex MIMO systems and to optimize a wide class of performance indexes.
- In this context, the search for an optimum in terms of guidance policy and closed-loop control action fits the 'green-oriented' trend in aerospace industry. Indeed, each 'Newton' of thrust action is paid with a huge amount of propellant. Hence, MPC appears to be a very promising approach for autonomous space missions, providing an unified optimal guidance and control policy.
- Model Predictive Control - either linear or nonlinear - is a suitable approach for several kinds of space applications: low-thrust missions, spacecraft rendezvous/dockings, station keeping, orbit phasing, deep space correction maneuvers, Earth observation and monitoring missions, etc.
- Nowadays, the literature about space MPC is focused on finding new classes of cost functions in order to design minimum-propellant controllers: in space applications, the propellant consumption represents the most important performance metric. Indeed, the quadratic cost function seems to be less suitable, since it drives to a suboptimal propellant consumption and a less sparse thrusting action. Thus, a new cost function may be defined as a sum of p-norms.

Addressed research questions/problems

- The main idea behind the NMPC based guidance and control is to skip the traditional mission planning carried out on ground by means of the classical astrodynamics open-loop methods (e.g. Lambert's problem solution), designing a spacecraft capable to autonomously plan the required maneuvers and merging the guidance and control tasks.
- In astrodynamics, the concept of impulsive and instantaneous thrust action is an unfeasible abstraction. In real applications, the ΔV budget cannot be concentrated in a single impulse. Furthermore, gravity and misalignment losses are introduced if no thrust direction and ΔV subdivision optimization are performed.



- The goal is to study the quasi-impulsive high-thrust policies, in order to design a satellite capable to autonomously plan different impulsive maneuvers during the mission.
- In order to design quasi-impulsive high-thrust policies, the command activity must be as sparser as possible.

Novel contributions

- The Guidance design is completely skipped. The NMPC approach allows to automatically manage the elapsed time and the ΔV subdivision and direction of the maneuver.
- The NMPC is often exploited for low-thrust applications and continuous maneuvers, whilst the aim of the research is to design and plan space missions expecting high-thrust impulsive maneuvers (e.g. Hohmann's transfer).
- The spacecraft must be able to maneuver in those points where changing the orbit shape requires a lower amount of propellant. As an example: for raising the orbit apoapsis, the engines must fire tangentially to the orbit when the satellite is at periapsis.
- The spacecraft nonlinear dynamics is studied by means of different orbital motion models:
  - Keplerian orbital elements dynamics.
  - Modified equinoctial orbital elements dynamics.
- A new formulation of cost function is studied while the classical quadratic form is abandoned in order to obtain a sparser control output, more suitable for impulsive maneuvers.

Other Activities

- Robust stability verification of aerospace nonlinear systems.
- Modelling of space GNC systems and sensors.

Submitted and published works

- Pagone, M. , Novara, C., Martella, P. and Nocerino, C., "*GNC Robustness Stability Verification for an Autonomous Lander*", submitted to Aerospace Science and Technology.

Adopted methodologies

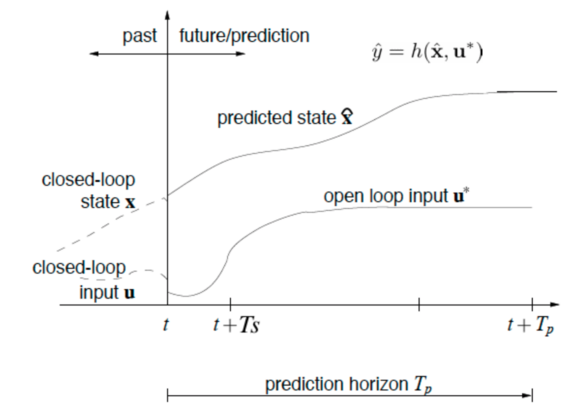
- Given the following nonlinear dynamic system, the purpose is to find a proper orbital motion dynamics capable of good performances in terms of tracking, propellant consumption and numerical integration.

$$\dot{x} = f(x,u)$$
$$\dot{y} = h(x,u)$$

- Different cost functions are searched for promoting the command sparsity, avoiding the undesirable continuous thrust. The optimal command activity u^* over a time interval $[t, t+T_P]$, where T_P is the prediction horizon, is:

$$u^*(t{:}t+T_P) = \arg\min_{u(\cdot)} J\left(u(t{:}t+T_p)\right)$$

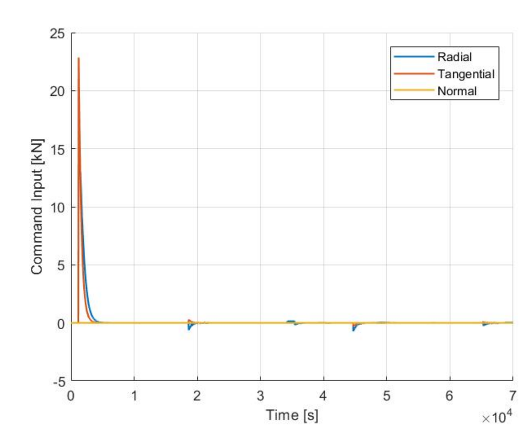
$$J\left(u(t{:}t+T_P)\right) = \int_t^{t+T_P} \left(\|\tilde{y}_P(\tau)\|_{Q,p} + \|u(\tau)\|_{R,p}\right)d\tau + \|\tilde{y}_P(t+T_P)\|_{P,p}$$

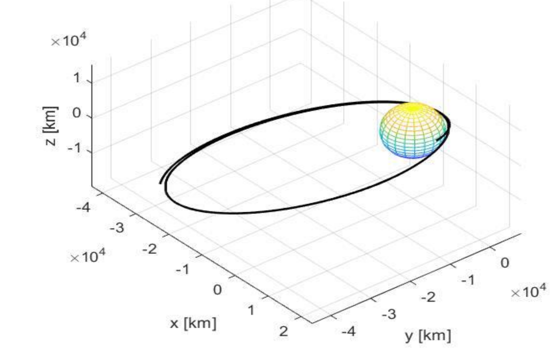


- The $\|x\|_{W,p}$ denotes the matrix weighted p-norm.
  In particular the 1-norm seems to guarantee the best performances in terms of propellant consumption, reference tracking and command sparsity.
- The NMPC algorithm is tested and its parameters are tuned by simulating simple maneuvers: inclinations changes, apoapsis raising, multiple swing-by, etc. A simple Earth's observation mission profile is used as testbench.

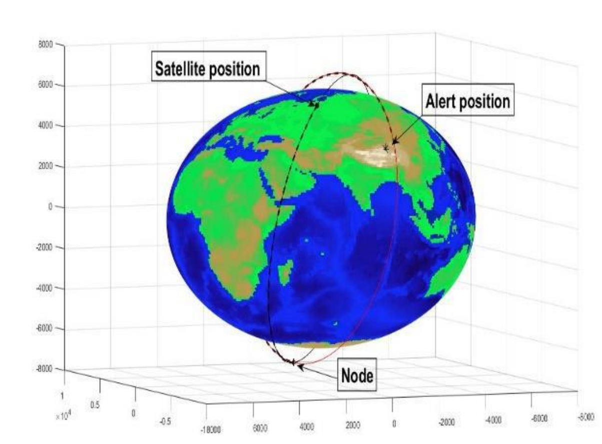
Simulation Results

- **Apoapsis raising**: the spacecraft autonomously maneuvers at the apses.





- **Earth observation missions:** the spacecraft performs the orbit plane change at the intersection of the current orbit with the target orbit.
- In both cases, the performances, in terms of ΔV, are similar to the ideal impulsive thrust scenario. Since the maneuvers are not instantaneous, the NMPC performances are slightly worse.



Future work

- Trade-off between different p-norms in cost function on the basis of the different mission profiles (e.g. in low-thrust mission seems to be more convenient the 2-norm while in high-thrust mission the 1-norm).
- Mathematical evaluation about convergence and tracking of the new cost functions used.
- The reliability of the controllers designed for Earth's observation mission will be verified by means of a Monte Carlo campaign.
- Design of complex space missions (e.g. Moon's sphere of influence injection, multi-target rendezvous, interplanetary missions, asteroids redirection missions).
- Integration of attitude control in the case of steering engines.

List of attended classes

- 01TEVRV – Deep learning (Didattica di eccel.) (04/06/2019, 6 CFU)
- 01LCPRV – Experimental Modeling: costruzione di modelli da dati sperimentali (04/02/2019, 6 CFU)
- 01RKXQW – Nonlinear control and aerospace applications (04/07/2019, 6 CFU)
- 01SQKNG – Ottimizzazione per Machine Learning (04/02/2019, 6 CFU)
- 01QSFURV – Programmazione scientifica avanzata in Matlab (27/06/2019, 4 CFU)
- 01RISRV – Public speaking (04/01/2019, 1 CFU)
- 01SWPRV – Time management (27/12/2018, 1 CFU)