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Real-Time Nonlinear Model Predictive Control Based on Set-Membership Approximation

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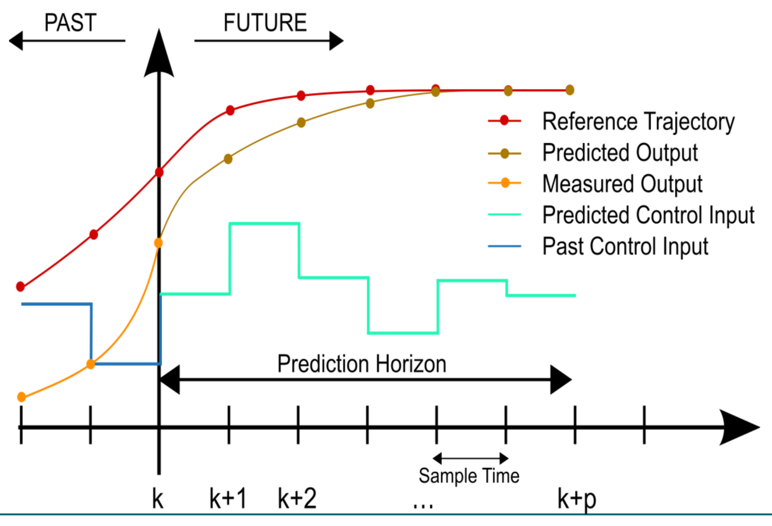
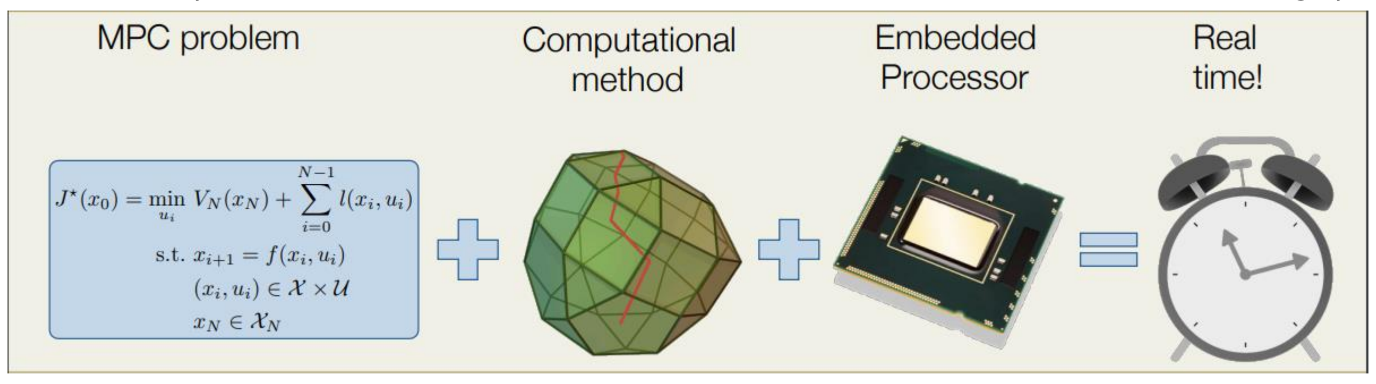
Research context and motivation

- **Autonomous vehicle guidance and control** are nowadays fundamental topics in the automotive field.
- A huge research effort is being spent worldwide by automotive companies and academic institutions with the goal of developing vehicles featuring a **high level of autonomy**, ranging from **advanced driving-assisted systems** to **fully automated vehicles**.
- **Modern control theory** offers a number of techniques and design paradigms that can be exploited for these applications.
- In particular, **Model Predictive Control (MPC)** has the potential to become a key technology in this context, thanks to its capability to: i) deal with linear and **nonlinear** systems, ii) efficiently manage **physical constraints**, iii) allow **multi-objective** performance optimization, iv) jointly perform **trajectory planning and control**.



Addressed research questions/problems

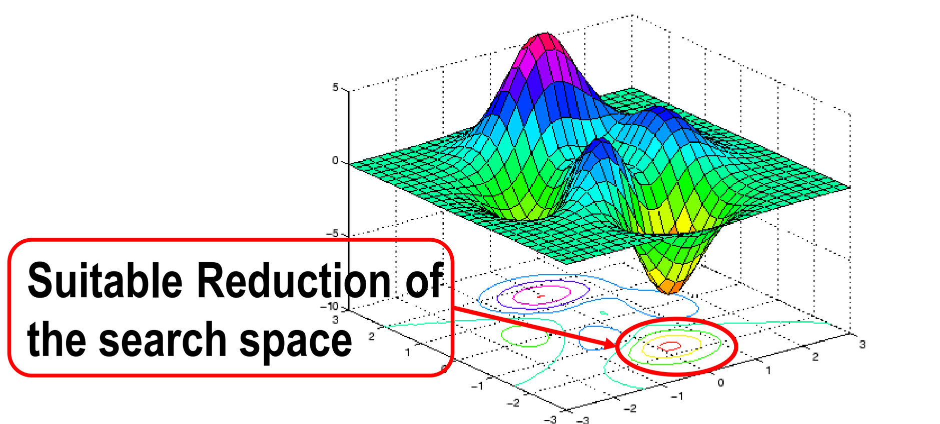
- **Nonlinear Model Predictive Control (NMPC)** is a very powerful control method but is quite demanding from a **computational point of view.** This makes its implementation in **real-time electronic boards** (with bounded computation time, CPU performance, and storage) hard.

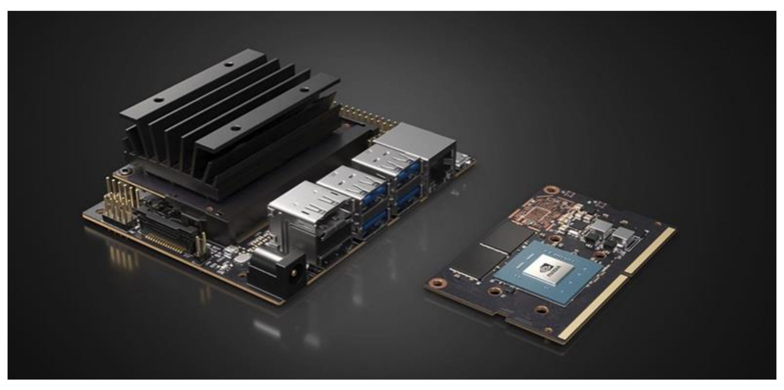


- In this regard, in my research activity, I address the problem of **numerical efficiency** of NMPC, in order to profit from its benefits also in systems with **fast dynamics** and **low computational complexity.**
- The aim is to obtain the same performance, from **accuracy** point of view, as the classical NMPC but with a **reduced number** of **cost function evaluations**. Indeed, in numerical optimization, the **computational efficiency** is directly linked to the **number of iterations** and **cost function evaluations** that the algorithm has to perform before finding a **'good' optimal solution**.
- This 'good' optimal solution is the global one only in the case of convex optimization. For nonlinear problems, instead, **many local minima** may be present. This leads the algorithm to explore a **wide area** of the **search space** and consequently **evaluate many times** the cost function, determining a slow convergence behavior to the sub-optimal solution.

Novel contributions

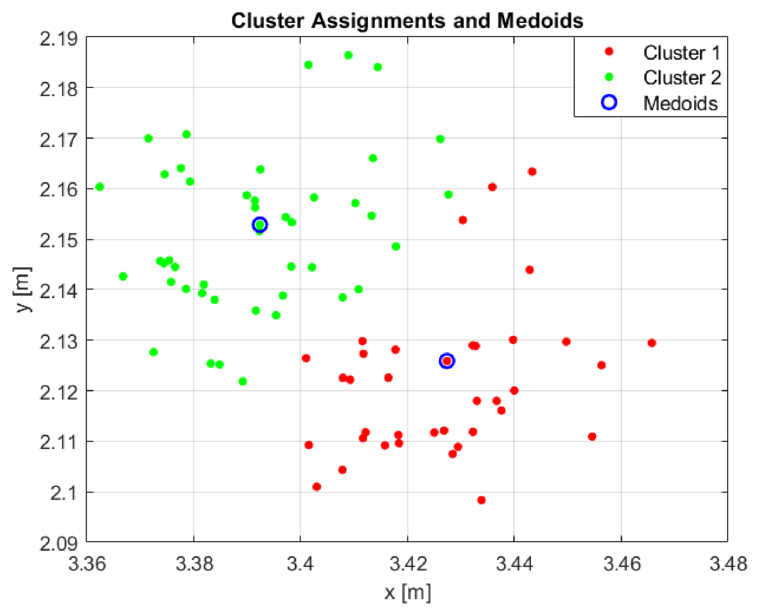
- **Extensive collected data**, together with **Set-Membership Approximation** and **Clustering**, are used to **speed-up** the optimization process by exploiting the **similarity** of previous problems to guide properly the algorithm.
- This allows to obtain a **suitable and adaptive restriction** of the area, in which the algorithm can search the minimum, determining consequently a **reduction** of the **computational time**.
- **Hardware-in-the-loop (HIL)** tests have been carried out to validate the algorithm and prove its ability to be executed in real-time.

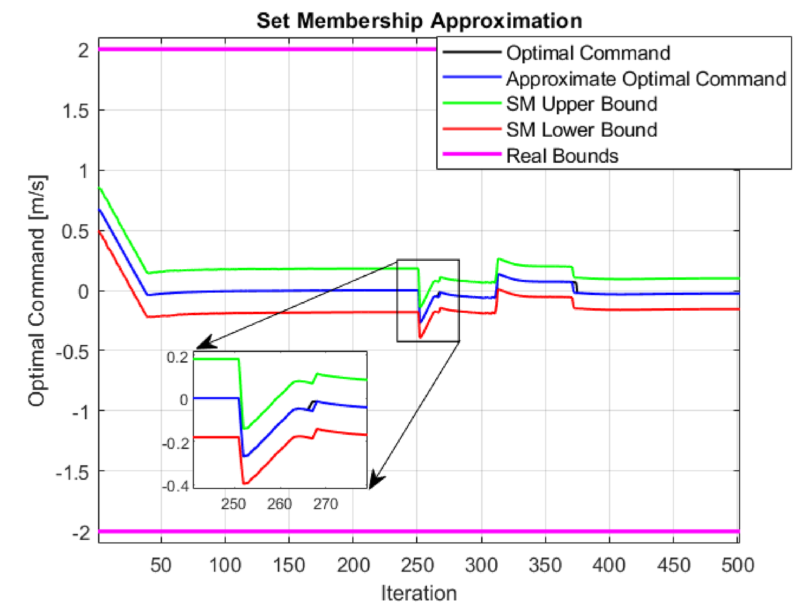




Adopted methodologies

- Starting from a specific scenario, in this case the **Parallel Parking**, a **Monte Carlo Campaign** has been carried out considering the **standard NMPC**. The resulting **States of the Vehicle** with the corresponding **Optimal Commands** and **Cost Functions** have been collected in a database.
- This database is appropriately reduced, through a **Clustering** operation (**k-medoids algorithm** is used) to find the data that best characterized the system, from **300000** to **2000 values**.
- These values are used to identify an **approximate model** which, depending on the state of the vehicle, generates the corresponding **optimal commands and cost function,** using the **Set-Membership (SM) Approach**.
- Exploiting the benefits of this method, the **estimate** of the variable of interest and the **bounds**, which **always contain** the true value of this variable, are obtained. This is fundamental for the **suitable reduction of the search area**.

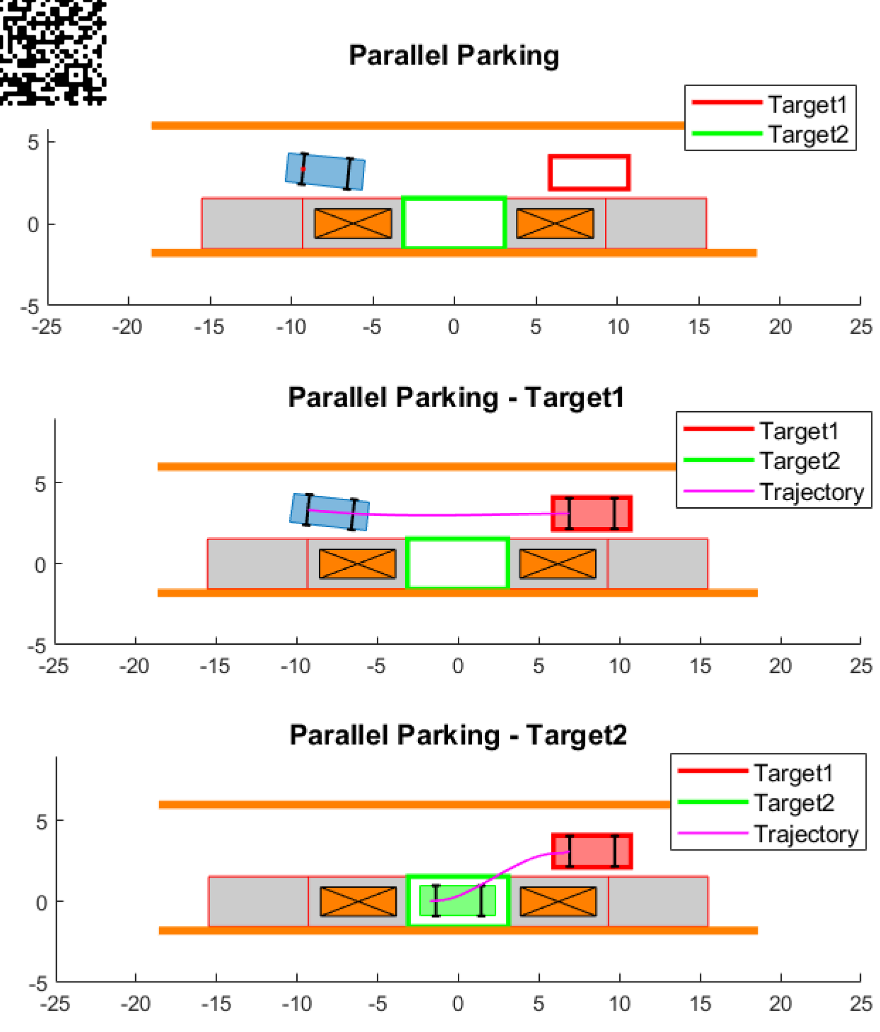


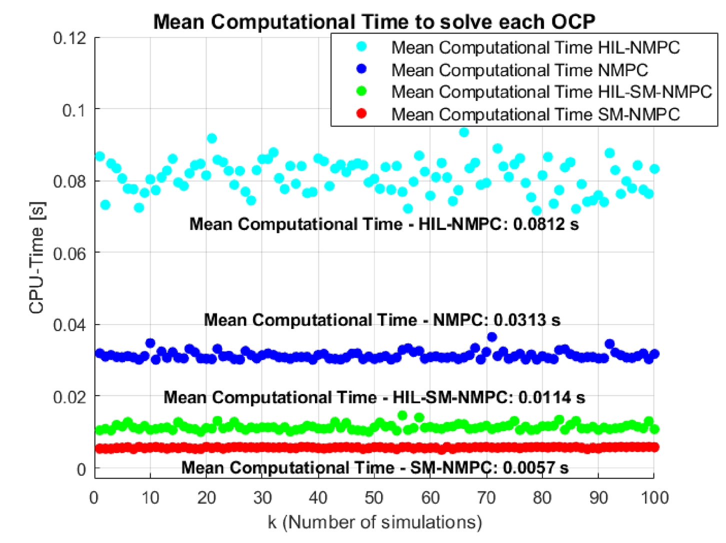


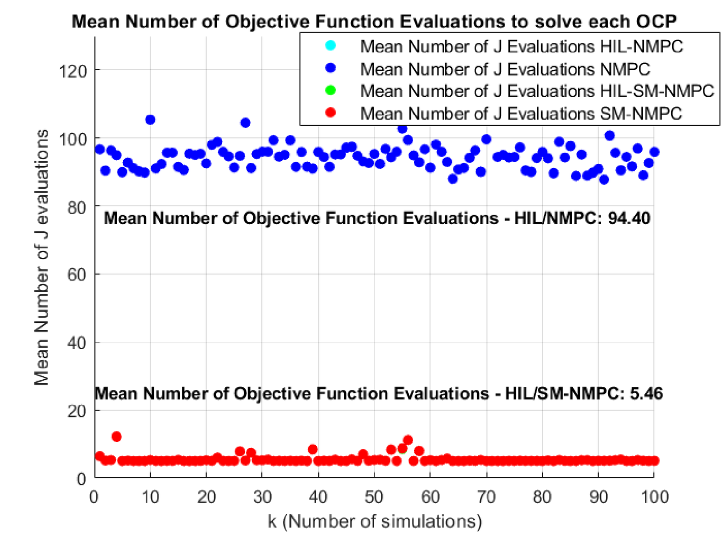
- Once the approximate model has been created, it is used in **different conditions** from those considered previously. The model must, indeed, be **general**, working also for situations not contained in the database from which it was created.
- From the current state of the vehicle, the SM model generates the **optimal command** and the corresponding **bounds**. The former is used to **warm start** the algorithm, while the latter to **optimally narrow down the search area**. This makes it possible to further **improve performance**, making the controller **more robust** and **reducing the computational time**.

Results

- The standard NMPC and the developed SM-NMPC have been simulated both on a **Dell Precision 5820** (Processor: **Intel(R) Xeon(R) W-2123 CPU @ 3.60GHz**) and on a **Jetson Nano board** (Processor: **Quad-core ARM A57 @ 1.43 GHz**).
- The **metrics**, used for comparing the performance of the two algorithms, are: i) **accuracy** in reaching the final target (scan the QR code), ii) **computational time**, iii) **number of functions** evaluated for finding the minimum. Note that **HIL** means the simulation on Jetson Nano board.







Future work

- **Theoretical study** of the **computational complexity** with respect to the **volume of the search area** and the **number of optimization variables**.
- **Parallelization** of the optimization algorithm.

Submitted and published works

- Boggio, M., Colangelo, L., Virdis, M., Pagone, M., and Novara, C., "*Earth Gravity In-Orbit Sensing: MPC Formation Control Based on a Novel Constellation Model*", Remote Sensing, vol. 14, no. 12, 2022, pp. 2815-2832
- Pagone, M. , Boggio, M., Novara, C., Pruskurnikov, A. and Calafiore, G.C., "*A penalty function approach to constrained Pontryagin-based Nonlinear Model Predictive Control*", IEEE Conference on Decision and Control, Cancún, Mexico, 2022
- Pagone, M. , Boggio, M., Novara, C., and Massotti, L., "*NMPC-based guidance and control for autonomous high-thrust non-coplanar LEO-GEO missions*", International Astronautical Congress, Paris, 2022
- Pagone, M. , Boggio, M., Novara, C., and Vidano, S., "*A Pontryagin-based NMPC approach for autonomous rendez-vous proximity operations*", IEEE Aerospace Conference, 2021
- Boggio, M. , Cotugno, P., Perez Montenegro, C., Pagone, M., Novara, C., and Massotti, L., "*NMPC-Based Orbit and Formation Control for an Earth-Gravity Monitoring Mission*", International Astronautical Congress, Dubai, 2021
- Pagone, M. , Boggio, M., Novara, C., Massotti, L., and Vidano, S.,"*NMPC-Based Guidance and Control for Earth Observation Missions*", International ESA Conference on Guidance, Navigation & Control, 2021
- Pagone, M. , Boggio, M., Novara, C., Massotti, L., and Vidano, S.,"*A Sparse Nonlinear Model Predictive Control for Autonomous Space Missions*", International Astronautical Congress, 2020

List of attended classes

- 02LCPRV – Experimental modeling: costruzione di modelli da dati sperimentali (6/8/2021, 7 CFU)
- 01RGBRV – Optimization methods for engineering problems (7/6/2022, 6 CFU)
- 02SFURV – Programmazione scientifica avanzata in matlab (25/5/2021, 6 CFU)
- 01QTEIU – Data mining concepts and algorithms (3/2/2022, 4 CFU)
- 01QFFRV – Tecniche innovative per l'ottimizzazione (26/2/2021, 4 CFU)
- 02LWHRV – Communication (8/6/2021, 1 CFU)
- 01SWPRV – Time management (16/12/2020, 1 CFU)
- 01UNVRV – Navigating the hiring process: CV, tests, interview (30/8/2022, 1 CFU)
- 01UNXRV – Thinking out of the box (20/1/2021, 1 CFU)

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