PhD Open Days

Spacecraft thruster management function

PHD IN ELECTRICAL AND COMPUTER ENGINEERING

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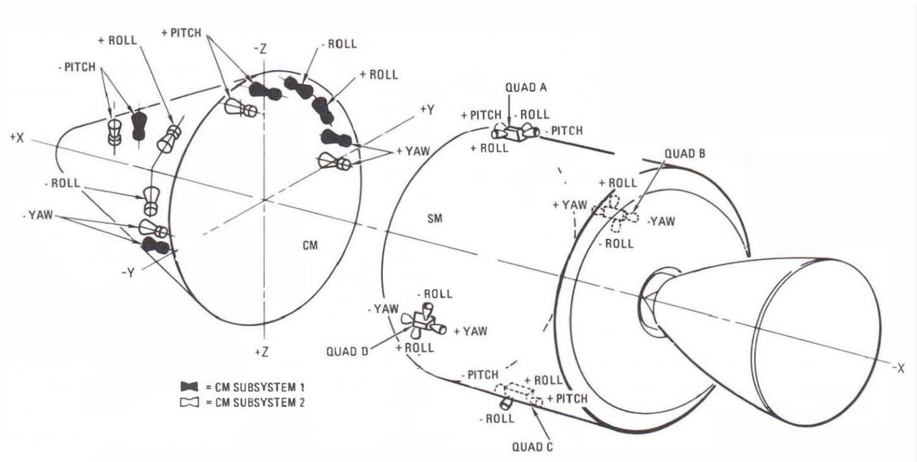
Introduction

The onboard control function of a spacecraft outputs force and torque commands in order to perform its objectives, *e.g.* tracking a trajectory, pointing in the desired direction, etc. These commands must then be translated to appropriate actuator commands. The problem then is, **how to best turn on/off each of the reaction control thrusters**, such that the sum of all of their individual forces and torques yield the force and torque commanded by the controller?



Reaction control system of the Apollo spacecraft. Source: NASA.

Problem formulation

Given force (F) and torque (T) commands from the controller, we want to generate appropriate thruster opening durations (t) to the n reaction control thrusters. This can be formulated as a **linear program** (LP)

$$
\begin{aligned}
P_1(F,T):\quad & \min_{t\in\mathbb{R}^n} \sum_{i=1}^{n} t_i \\
\text{s.t.}\quad & F = M_{dir} t \\
& T = M_T t \\
& 0 \le t \le t_{max},
\end{aligned}
$$

where M_{dir} is the thruster direction matrix, M_T is the torque capacity matrix, and t_{max} is the maximum opening duration.

One physical limitation of the thrusters is the minimum time (t_{min}) it takes to open and close the thruster valves, which results in the **minimum impulse bit** (MIB). The main contribution of this work is to consider this non-ideality, modifying the last constraint, resulting in a **non-convex** optimization problem

$$
\begin{aligned}
P_2(F,T):\quad & \min_{t\in\mathbb{R}^n} \sum_{i=1}^{n} t_i \\
\text{s.t.}\quad & F = M_{dir} t \\
& T = M_T t \\
& t_i \in \{0, [t_{min}, t_{max}]\}, \qquad i = 1, \dots, n.
\end{aligned}
$$

Methodology

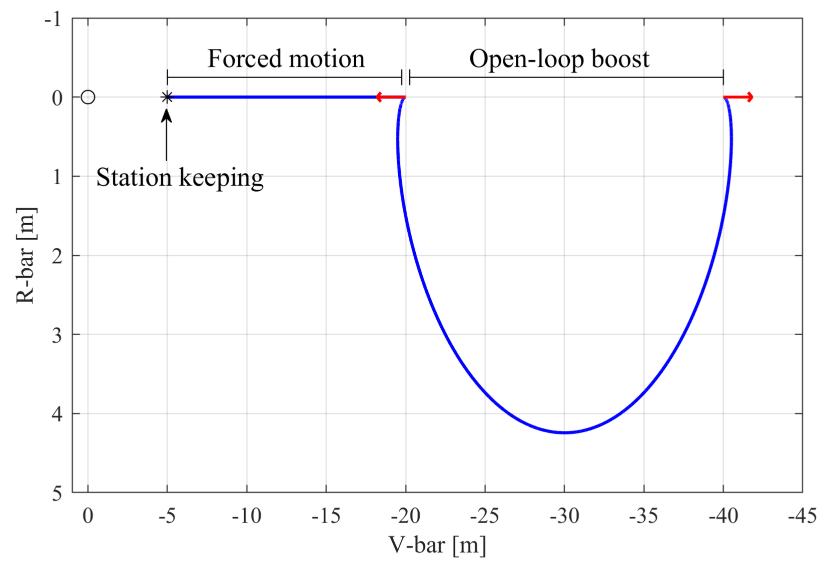
Problems P_1 and P_2 can be solved onboard with linear programming and mixed-integer linear programming numerical solvers, respectively. However, **online optimization has many downsides** for this real-time embedded application, such as high computational demand and lack of a deterministic computational worst-case.

Methods for solving P_1 **offline** as a function of F and T can be found in the literature, which result in an **analytical solution** that is a piecewise affine function of those parameters.

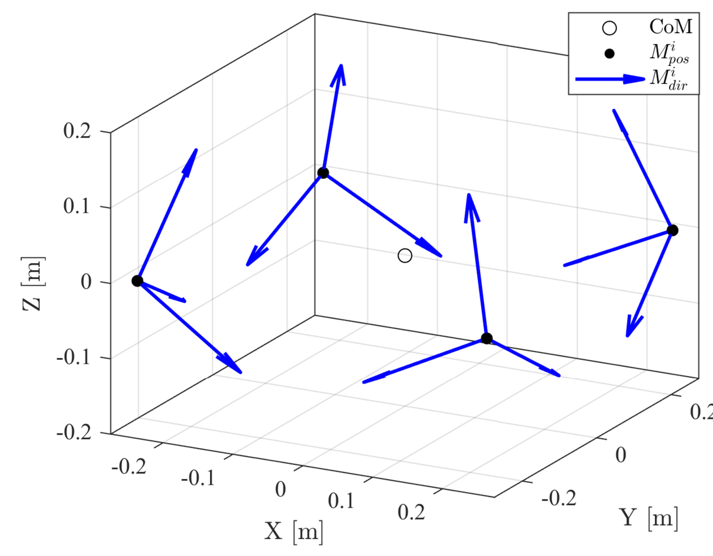
In this work, we have developed a different offline solution method, based on **multi-parametric linear programming**, which easily allows for the inclusion of the MIB constraint and therefore to solve P_2 as well.

Results

We consider a close-range orbital rendezvous scenario, with a 100 kg chaser spacecraft with 12x1N thrusters. Three manoeuvres are simulated: open-loop boost, forced motion, and station keeping.



Close-range rendezvous profile



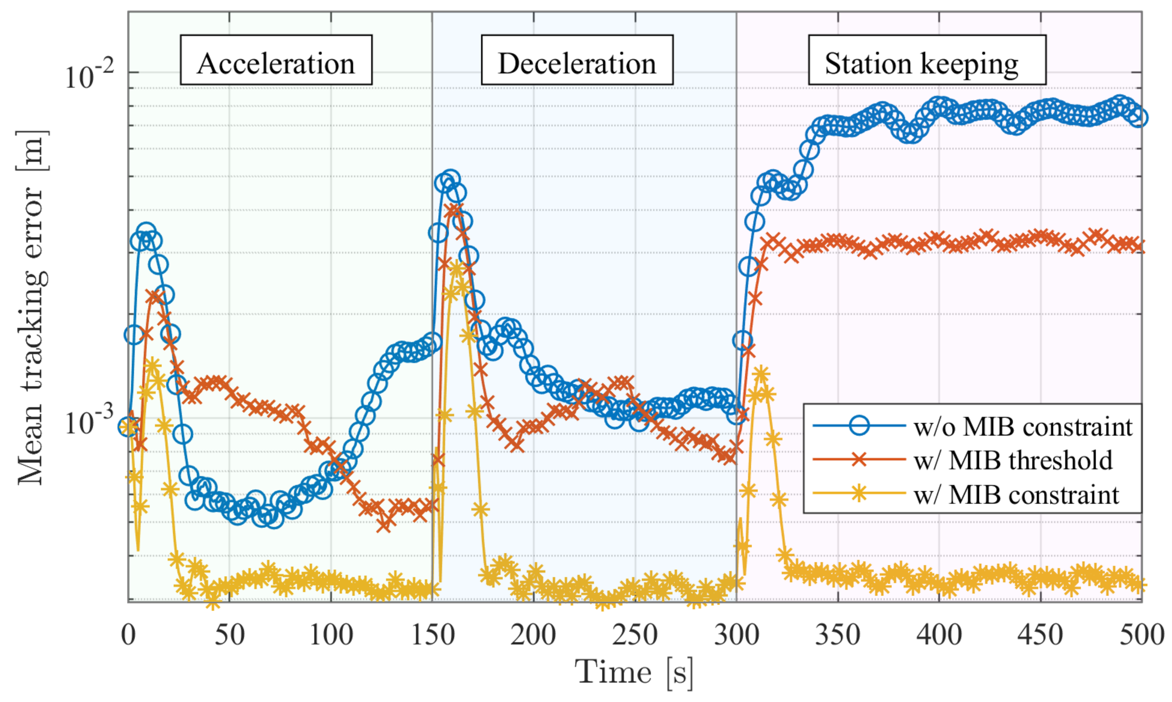
12 thruster configuration

We compare the performance of three thruster management functions: without the MIB constraint (P_1); P_1 with a commonly used technique known as MIB threshold; with the MIB constraint (P_2, our contribution). A Monte-Carlo campaign with 100 simulations is performed.

For the open-loop boost, the **inclusion of the MIB constraint improves the final position and velocity error** by at least two times on average, at the cost of increased fuel consumption:

TMF	Position error [m]		Velocity error [mm/s]		Propellant mass [g]	
	Mean	Max	Mean	Max	Mean	Max
1) w/o MIB constraint	5.304	6.605	0.9751	1.048	0.04631	0.09859
2) w/ MIB threshold	1.479	3.145	0.2155	0.3159	0.08833	0.1786
3) w/ MIB constraint	0.7763	2.546	0.1094	0.2844	0.2158	0.4199

For the forced motion and station keeping, the average **performance of the controller tracking error is strictly better with the MIB constraint**, at the cost of higher fuel propellant (one order of magnitude), and higher computational load (two orders of magnitude).



Controller tracking error for forced motion and station-keeping

Conclusions and future work

We propose a spacecraft thruster management function with implicit inclusion of the MIB constraint, which was shown to improve control performance for three types of close-range orbital rendezvous manoeuvres.

Future work will focus on improving the computational load of the onboard algorithm.

Acknowledgements
Part of this work was supported by national funds from FCT, Fundação para a Ciência e a Tecnologia (Portugal) to INESC-ID, under project UIDB/50021/2020. Afonso Botelho was recipient of PRT/BD/152809/2021 PhD fellowship by the Portuguese Space Agency - Portugal Space, and FCT.

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