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FUEL OPTIMAL THRUST ALLOCATION ALGORITHM FOR SMALL-SAT 6-DOF SYSTEM UNDER ACTUATOR CONSTRAINTS AND NON-SPHERICAL TORQUE AUTHORITY SPACE

Abstract

For the Juventas mission a new 6-DOF cold-gas propulsion system has been designed. This system is to be used for orbit manoeuvres, momentum management, and in critical cases, to align the body-fixed solar panels to the sun.

This system has been optimized for the planned orbit manoeuvres, at the cost of torque authority. For the impulse components, the system provides an approximately spherical attainable set to enable the spacecraft to perform orbit corrections in any attitude. For the momentum components, the attainable set is significantly less spherical, and has a quasi-singularity that should be avoided. Initial simulations show cases where the momentum vector aligns itself with the quasi-singularity, and the spacecraft is not able to off-load the excess momentum within a reasonable time, and thus consumes fuel without any measurable effect of the total momentum. The issue with the attainable set is further compounded by an additional constraint; only 4 nozzles can be active at any given time.

To ensure a performant system, the thrust allocation problem is augmented to consider the attainable set, formulated as:

$$\begin{aligned} \min_{u} \quad & ||u||_{L_1} \\ \text{s.t.} \quad & \mathbf{G^{-1}Bu} = \mathbf{x} \\ & u \geq 0 \end{aligned} \tag{1}$$

Where $u \in \mathbb{R}^{8\times 1}$ is the opening duration of each thruster, $x \in \mathbb{R}^{6\times 1}$ is the desired impulse and momentum vector given as $x = [I_x, I_y, I_z, L_x, L_y, L_z]$ where $I_{x,y,z}$ is the requested impulse, and $L_{x,y,z}$ is the requested momentum. $\mathbf{B} \in \mathbb{R}^{6\times 8}$ maps from the thruster frame to the body frame, and $\mathbf{G} \in \mathbb{R}^{6\times 6}$ is a linear approximation of the attainable set, which is used to optimize the burn w.r.t to the attainable set. The L_1 norm is used to promote sparsity in the solution, however, as there is no constraint of the number of nozzles that can be used, it cannot be assumed that the solution uses a maximum of 4 nozzles. To satisfy this additional constraint, a sequence algorithm is introduced. This algorithm is designed to maintain the thrust direction, saturate the maximum burn time within a given time window t_w , and set

burn times lower than the minimum impulse bit t_{min} to 0.

$$\hat{u} = \begin{cases} \dfrac{u_i}{\max(u)} & \text{if} \quad u_i < t_w \\ \\ u_i & \text{if} \quad t_{min} < u_i \leq t_w \\ \\ 0 & \text{if} \quad u_i \leq t_{min} \end{cases} \tag{2}$$

With this, a burn that prioritizes the axes with good controllability is performed, leaving only a small residual momentum around the quasi-singularity

The thrust allocation scheme is tested and validated by model in the loop simulations under model uncertainties, and hardware in the loop simulations to validate the computational performance on the on-board computer.