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Inverse dynamics particle swarm optimization applied to constrained minimum-time maneuvers using reaction wheels

Dario Spiller [a,*], Robert G. Melton [b], Fabio Curti [c]

[a] Sapienza University of Rome, Dept. of Mech. and Aerospace Eng. (DIMA), Via Eudossiana 18, 00184 Rome, Italy
[b] Pennsylvania State University, Department of Aerospace Engineering, University Park, PA, 16802-1401, USA
[c] Sapienza University of Rome, School of Aerospace Engineering – ARCAlab, Via Salaria 851, 00138 Rome, Italy

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ABSTRACT

The paper deals with the problem of time-optimal spacecraft reorientation maneuvers by means of reaction wheels, with boundary and path constraints. When searching for solutions to optimal attitude-control problems, spacecraft can be easily modeled as controlled by external torques. However, when using actuators such as reaction wheels, conservation of the total angular momentum must be taken into account and the wheel dynamics must be included. A rest-to-rest slew maneuver is considered where an optical sensor cannot be exposed to sources of bright light such as the Earth, the Sun and the Moon. The motion must be constrained to prevent the sensor axis from entering into established keep-out cones. The minimum-time solution is proposed using the Inverse Dynamics Particle Swarm Optimization technique. The attitude and the kinematics of the satellite evolve, leading to the successive attainment of the wheel control input via fixed-step numerical integration. Numerical results are evaluated over different scenarios. It is established that the computation of minimum time maneuvers with the proposed technique leads to near optimal solutions, which fully satisfy all the boundary and path constraints. The ability to converge in a variety of different scenarios always requiring the same computational effort characterizes the proposed technique as a feasible future on-board path-planner.

1. Introduction

This paper examines a new numerical solution based on IPSO [1] to determine the approximate solutions for a constrained, time-optimal satellite reorientation problem accomplished with reaction wheels. Reaction wheels are commonly used for satellite attitude control and they can be mathematically modeled as internal torques in Euler's equation of rigid-body motion. IPSO is an inverse-dynamics approach based on PSO [2]. The Inverse Dynamics approach has been recently investigated to determine the spacecraft attitude profile, since it leads to the guidance solution in a straightforward manner, [3,4]. In [5] IPSO has been applied to a satellite formation problem considering the coupling between the attitude and orbital dynamics.

Unconstrained, minimum-time rest-to-rest maneuvers through large angles (so-called slew maneuvers) were first taken into account by Bilimoria and Wie [6]. Considering a rigid spacecraft with spherically symmetric mass distribution and with equal control-torque authority for all three axes, they showed that the intuitively obvious rotation about the eigenaxis is not the time-optimal solution. Bai and Junkins [7] reconsidered this problem proving that if the total control vector is constrained to have a maximum magnitude (i.e., with the orthogonal control components not necessarily independent), then the time-optimal solution is the eigenaxis maneuver.

The problem of reorientation maneuvers with path constraints was initially studied by McInnes [8]. Several constraints might be imposed during a slew maneuver. For example, the axis normal to the solar panels may be required to lie always within some specified minimum angular distance from the sun-line. For scientific missions, observational instruments might require to be kept beyond a specified minimum angular distance from high-intensity light sources (e.g. Sun and Moon) to prevent damage [9]. Finally, pointing boundaries for antennas might be needed to maintain the communication [10].

So far, several works considering slew maneuvers with reaction wheels may be found in the literature, starting from papers dating back to the 1990's [11,12] and continuing to recent years [13, 14]. The introduction of the wheel dynamics requires taking into

* Corresponding author.
E-mail addresses: dario.spiller@uniroma1.it (D. Spiller), rgmelton@psu.edu (R.G. Melton), fabio.curti@uniroma1.it (F. Curti).

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Acronyms

BRS	Body Reference System	MRP	Modified Rodriguez Parameters
CM	Center of Mass	POCS	Pseudospectral Optimal Control Software
DOF	Degree of Freedom	PSO	Particle Swarm Optimization
FSS	Feasible Search Space	IPSO	Inverse-dynamics PSO
lhs	left hand side	rhs	right hand side

account the conservation of the total inertial angular momentum and the saturation of the wheel velocity and acceleration.

Heuristic algorithms [15] have been studied extensively and the high interest generated from their results is proved by the research performed by NASA [16]. Such approaches are particularly interesting in order to design autonomous on-board slew-planning, as stated in [17]. They can also be used to find the best available initial guess for a pseudospectral optimizer thereby diminishing the total required computational time [18]. Among these methods, the PSO has been extensively used for the planning of optimal trajectories and attitude maneuvers as illustrated in [19,20].

From the previous works, the PSO has been used to determine the optimal control profile for spacecraft attitude maneuvers obtaining the kinematic history after numerical integration. In [1] it has been shown how such an approach fails in satisfying the boundary constraints (i.e. final position and final velocity). In this work, the problem described in [1] is modeled with more details introducing the internal torques of the wheels. The inverse dynamics approach is exploited and, accordingly, the object of IPSO evolution is the kinematics rather than the control. As a result, the final boundary constraints are exactly satisfied. However, the proper modeling of the wheels requires the integration of only a part of the equation of motion: in this paper this issue has been tackled involving a fixed-step integrator.

The paper is organized as follows. In Sec. 2 the statement of the optimization problem is reported. Sec. 3 describes the fundamental features of PSO and the implementation of IPSO for the problem under examination. Sec. 4 reports the numerical results. Sec. 5 concludes the paper.

2. Problem statement

The overall approach requires separate treatment of the dynamics and the kinematics. In this section the dynamics and kinematics models are detailed.

2.1. Dynamical model

In a satellite-fixed reference frame $\mathcal{S}$ placed at the CM, we define the satellite angular momentum as $\boldsymbol{H}^{\mathcal{S}} = I^{\mathcal{S}}\boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}}$, where $\boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}}$ is the angular velocity of the satellite with respect to the inertial frame $\mathcal{I}$ expressed in $\mathcal{S}$.

If reaction wheels are used to accomplish the maneuvers, we can define the total angular momentum $\boldsymbol{H}^t = \boldsymbol{H}^{\mathcal{S}} + \boldsymbol{H}^{\mathcal{W}}$, with $\boldsymbol{H}^{\mathcal{W}} = I^{\mathcal{W}}\boldsymbol{\omega}^{\mathcal{W}/\mathcal{I}}$ (the angular momentum of the wheels) where $\boldsymbol{\omega}^{\mathcal{W}/\mathcal{I}}$ is the angular velocity of the wheels with respect to $\mathcal{I}$ expressed in $\mathcal{S}$.

The free rigid-body motion of a satellite equipped with reaction wheels is described by Euler's equation [21]

$$\dot{\boldsymbol{H}}^t + \boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}} \times \boldsymbol{H}^t = \boldsymbol{0} \tag{1}$$

that can be split into the satellite and wheel contributions:

$$\dot{\boldsymbol{H}}^{\mathcal{S}} + \boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}} \times \boldsymbol{H}^{\mathcal{S}} = -\dot{\boldsymbol{H}}^{\mathcal{W}} - \boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}} \times \boldsymbol{H}^{\mathcal{W}}. \tag{2}$$

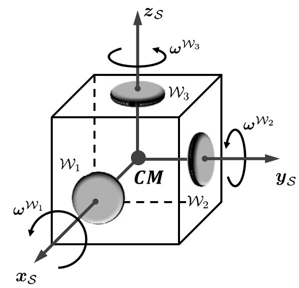

Fig. 1. Wheels position in $\mathcal{S} = \{\boldsymbol{x}_{\mathcal{S}}, \boldsymbol{y}_{\mathcal{S}}, \boldsymbol{z}_{\mathcal{S}}\}$.

The rhs of Eq. (2) properly defines the internal torques $\boldsymbol{T}_{int}$ of the system, i.e.

$$\dot{\boldsymbol{H}}^{\mathcal{W}} + \boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}} \times \boldsymbol{H}^{\mathcal{W}} = -\boldsymbol{T}_{int}\,. \tag{3}$$

The motion of the wheels influences the motion of the satellite by 1) changing the speed of the wheels through an electric motor (1st lhs term in Eq. (3)) and 2) changing the orientation of the wheels with respect to $\mathcal{I}$ (2nd lhs term in Eq. (3)). Note that the second term is a gyroscopic term due to the motion of the satellite.

When a BRS aligned with the principal inertia axes is chosen in $\mathcal{S}$ such as BRS$=\{\boldsymbol{x}_{\mathcal{S}}, \boldsymbol{y}_{\mathcal{S}}, \boldsymbol{z}_{\mathcal{S}}\}$, the inertia tensor $I^{\mathcal{S}}$ is diagonal and the satellite angular momentum $\boldsymbol{H}^{\mathcal{S}}$ is

$$\boldsymbol{H}^{\mathcal{S}} = [I_x^{\mathcal{S}}\omega_x^{\mathcal{S}/\mathcal{I}} \;\; I_y^{\mathcal{S}}\omega_y^{\mathcal{S}/\mathcal{I}} \;\; I_z^{\mathcal{S}}\omega_z^{\mathcal{S}/\mathcal{I}}]^T\,. \tag{4}$$

Without loss of generality, let us assume that three reaction wheels labeled as $\mathcal{W}_1$, $\mathcal{W}_2$ and $\mathcal{W}_3$ with the same polar moment of inertia $I^{\mathcal{W}}$ are exploited and that they are aligned with the reference system axes as reported in Fig. 1. Accordingly, denoting with $\omega^{\mathcal{W}_1/\mathcal{I}}$, $\omega^{\mathcal{W}_2/\mathcal{I}}$ and $\omega^{\mathcal{W}_3/\mathcal{I}}$ the norm of the angular velocities of the three wheels, we can define the total angular velocity of the wheels as

$$\boldsymbol{\omega}^{\mathcal{W}/\mathcal{I}} = \begin{bmatrix} \omega^{\mathcal{W}_1/\mathcal{I}} \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \omega^{\mathcal{W}_2/\mathcal{I}} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega^{\mathcal{W}_3/\mathcal{I}} \end{bmatrix} = \begin{bmatrix} \omega_x^{\mathcal{W}/\mathcal{I}} \\ \omega_y^{\mathcal{W}/\mathcal{I}} \\ \omega_z^{\mathcal{W}/\mathcal{I}} \end{bmatrix} \tag{5}$$

and $\boldsymbol{H}^{\mathcal{W}} = I^{\mathcal{W}}\boldsymbol{\omega}^{\mathcal{W}/\mathcal{I}} = I^{\mathcal{W}}\left(\boldsymbol{\omega}^{\mathcal{W}/\mathcal{S}} + \boldsymbol{\omega}^{\mathcal{S}/\mathcal{I}}\right)$ takes the following form:

$$\boldsymbol{H}^{\mathcal{W}} = \begin{bmatrix} I^{\mathcal{W}} & 0 & 0 \\ 0 & I^{\mathcal{W}} & 0 \\ 0 & 0 & I^{\mathcal{W}} \end{bmatrix} \begin{bmatrix} \omega_x^{\mathcal{W}/\mathcal{S}} + \omega_x^{\mathcal{S}/\mathcal{I}} \\ \omega_y^{\mathcal{W}/\mathcal{S}} + \omega_y^{\mathcal{S}/\mathcal{I}} \\ \omega_z^{\mathcal{W}/\mathcal{S}} + \omega_z^{\mathcal{S}/\mathcal{I}} \end{bmatrix}. \tag{6}$$

Simplifying the notation and using $\mathcal{W}$ and $\mathcal{S}$ to denote $\mathcal{W}/\mathcal{S}$ and $\mathcal{S}/\mathcal{I}$ and introducing Eq. (4) and Eq. (6) into Eq. (2) yields

$$\begin{aligned} &I^{\mathcal{S}}\dot{\boldsymbol{\omega}}^{\mathcal{S}} + \boldsymbol{\omega}^{\mathcal{S}} \times I^{\mathcal{S}}\boldsymbol{\omega}^{\mathcal{S}} \\ &\quad = -I^{\mathcal{W}}\dot{\boldsymbol{\omega}}^{\mathcal{W}} - I^{\mathcal{W}}\dot{\boldsymbol{\omega}}^{\mathcal{S}} - \boldsymbol{\omega}^{\mathcal{S}} \times I^{\mathcal{W}}\boldsymbol{\omega}^{\mathcal{W}} - \boldsymbol{\omega}^{\mathcal{S}} \times I^{\mathcal{W}}\boldsymbol{\omega}^{\mathcal{S}}\,. \end{aligned} \tag{7}$$

Rearranging Eq. (7) and defining $I^t = I^{\mathcal{S}} + I^{\mathcal{W}}$ we obtain