FLIGHT RESULTS FOR A REVOLUTIONARY APPROACH TO MAXIMIZING SPACECRAFT IMAGING CAPABILITY

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1. Introduction

Karpenko et al.[1] presented the first flight results of shortest-time maneuvering, a paradigm that can reduce slew time and increase the availability of observation satellites performing imaging operations. Besides improving the agility of the spacecraft, the flight experiment illustrated how optimal maneuver design can be used to extend the capabilities of existing spacecraft systems. This paper presents the results of a subsequent series of flight tests that were designed to permit the evaluation of the technology readiness level of the shortest-time maneuvering concept in various operational settings. Among these flight experiments are maneuvers such as minimum-time slewing, attitude hold for point data collection, and attitude scan for tracking. These maneuvers are all relevant to the operation of an Earth observing satellite. These shortest-time maneuvers (STMs) are designed by constructing an appropriate optimal control problem that incorporates a detailed model of the spacecraft dynamics, which is solved using the Legendre pseudospectral method. The optimization model will be elaborated on in the final version of this paper and includes constraints on the spacecraft performance including the nonlinear reaction wheel torque-momentum envelope as well as other practical operational considerations. The flight results demonstrate that STMs can be designed for different operational scenarios and reliably executed on orbit. Thus, the techniques can be applied for maximizing the performance of new imaging satellites as well as those that are already on orbit.

2. Problem Formulation

The dynamics of an imaging satellite actuated by a set of four reaction wheels are given by the following equations[2]:

$$
\begin{aligned}
\dot{\mathbf{q}} &= -\tfrac{1}{2}\omega \times \mathbf{q} + \tfrac{1}{2}q_4\omega \\
\dot{q}_4 &= -\tfrac{1}{2}\omega^T \mathbf{q} \\
\dot{\omega} &= \mathbf{I}^{-1}\left[-\omega \times \left(\mathbf{I}\omega + I_W \textstyle\sum_{i=1}^{4} \mathbf{a}_i\Omega_i\right) - \textstyle\sum_{i=1}^{4} \mathbf{a}_i u_i\right] \\
\dot{\Omega} &= I_W^{-1}\mathbf{u}
\end{aligned}
\tag{1}
$$

In (1), $\mathbf{I}$ and I_W denote the spacecraft inertia matrix and inertia of each reaction wheel rotor, respectively. Vectors $\mathbf{a}_i$ are the unit vectors relating the reaction wheel spin axes to the spacecraft

[1]M. Karpenko, S. Bhatt, N. Bedrossian, A. Fleming, and I. M. Ross, "First Flight Results on Time-Optimal Spacecraft Slews," *Journal of Guidance, Control and Dynamics*, Vol. 35, No. 2, 2012, pp. 367–376.

[2]M. J. Sidi, *Spacecraft Dynamics and Control*. New York: Cambridge University Press, 1997.

body-fixed frame and $\mathbf{u} = [u_1, u_2, u_3, u_4]^T$ is the control torque input vector. The state vector is, $\mathbf{x} = [\mathbf{q}, \omega, \Omega]^T$, where $\mathbf{q}$ and ω are the spacecraft quaternions and body rates. The reaction wheel speeds are given by Ω.

The optimal control problem is to find the state-control function pair, $t \to (\mathbf{x}, \mathbf{u})$, that drives the spacecraft from the initial state, $\mathbf{x}(t_0)$, to the final state, $\mathbf{x}(t_f)$, while minimizing the cost function:

$$J[\mathbf{x}(\cdot), \mathbf{u}(\cdot), t_f] = t_f - t_0 \tag{2}$$

In addition to nonlinear reaction wheel power limits, the optimal control problem is also subject to a number of other practical constraints on the spacecraft states and controls.

3. Flight Test Results

In a typical operational scenario, an imaging spacecraft is required to slew to various collection regions in order to obtain data at a point or by scanning the Earth's surface. A five-pointed star pattern was designed to exercise the spacecraft along a variety of different axes within the envelope of normal operation in order to demonstrate optimal pointing maneuvers. The operationally relevant star maneuver was executed on board the TRACE[3] spacecraft. Flight test results obtained from the experiment are shown in Fig. 1. The motion of the instrument boresight on the plane is observed to follow non eigenaxis paths as the spacecraft rotates, in minimum time, between each of the desired collection regions. By following these non eigenaxis trajectories, it was possible to reduce the slew time by more than 10%. The results of a subsequent orthogonal stress scan experiment, also performed on TRACE, are shown in Fig. 2. In this test, it is required to minimize the maneuver time between scanning operations. Referring to Fig. 2, it is observed that the optimal transition between two back-to-back scanning operations (the slew between points 2 and 3) is also far from intuitive. We intend to more fully elaborate on these results and their role in improving the performance of Earth observing satellites in the final version of this paper.

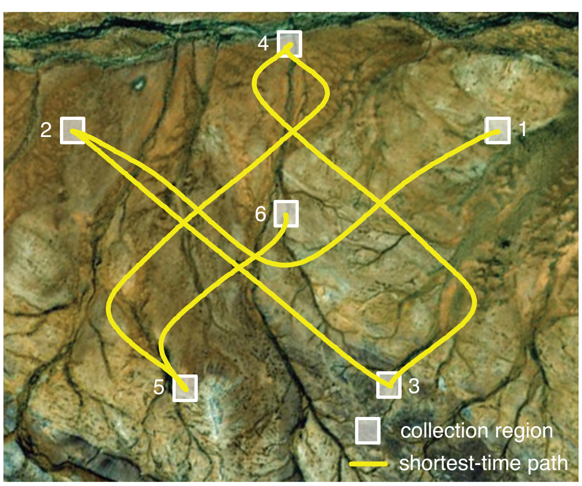

Figure 1. Operationally relevant star maneuver (flight test results).

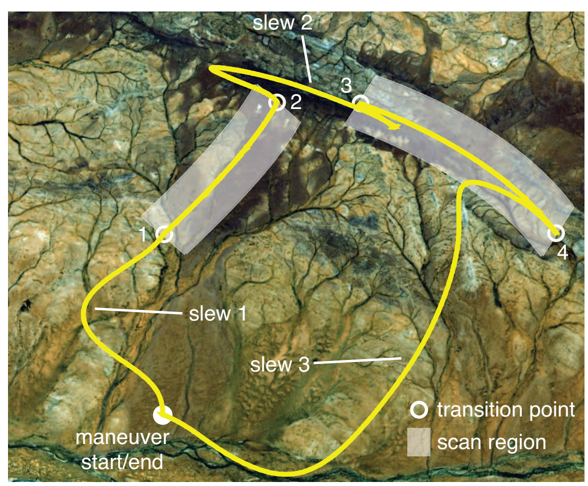

Figure 2. Orthogonal stress scan maneuver (flight test results).

[3]"TRACE Home Page," `http://sunland.gsfc.nasa.gov/smex/trace/`.