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Attitude Commands Avoiding Bright Objects and Maintaining Communication with Ground Station

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The objective of the paper is to develop attitude commands for slewing a vehicle such that the angle of its boresight with the centroid of a bright object is not less than a minimum angle and its antennae do not lose communication with the ground. These commands involve three angles: the required pitch/yaw slew angle, the bright object's exclusion angle normal to the slew angle, and a roll angle for maintaining communication. The location of the bright object's centroid is formulated in terms of an angle normal to the ideal slew plane. If the ideal, minimum-angle slew path enters the forbidden perimeter around the bright object, two alternative exclusion angles are determined so as to pass the object tangentially from either side. Between the two angles, that exclusion angle is selected, which steers the ground station trace, in the communication beam, toward beam axis and not away from it. Communication links of the antennae are maintained by rolling the vehicle before, during, or after slewing. The three-axis attitude and rate commands are illustrated for a stressing scenario in which two bright objects are close by and hence pose special circumstances for the algorithm to tackle.

I. Introduction

SPACECRAFT, whether Earth-pointing, inertially stabilized, or interplanetary, and exoatmospheric interceptors are sometimes required to slew from one direction in space to another in such a way that, en route, the sensitive payloads do not see bright objects such as the sun, moon, and Earth, and that antennae do not lose communication with the ground. This paper is concerned with devising attitude commands for these purposes. The subject of the attitude maneuvers avoiding certain directions in space has been considered in the past. Following robotics science,[1] McInnes[2–4] utilized a composite function consisting of a harmonic potential and constraint potentials, the former having the global minimum at the desired final attitude and the latter generating vortex velocity fields centered at forbidden directions. Perhaps novel and ingenious, this procedure nonetheless seems irrelevant for the present application because the examples in Refs. 1–4 reveal that a telescope, while being slewed, moves toward, instead of away from, the avoidance cone and when near the cone, the telescope slides aimlessly around it unless incidentally pulled over by the global potential function. Thus, though the telescope boresight does avoid the forbidden directions, it meanders substantially away from its nominal path. Sorenson,[5] on the other hand, uses an approach based on spacecraft orbit geometry, relative motion of the sun around the Earth, and varying Earth disc diameter for an elliptic orbit. He formulates pointing constraints that minimize the heat input from the sun to a cryogenically cooled telescope by applying differential geometry to determine possible attitude paths. Singh et al.[6] developed a constraint monitor algorithm to protect sensors of Cassini spacecraft from viewing the sun. Frakes et al.[7] devised a velocity avoidance algorithm to protect the heavy ion large telescope instrument boresight from hazardous debris in the neighborhood of the spacecraft orbit. The algorithm maintains a minimum of a 90-deg ram angle of the boresight with the spacecraft velocity vector. It is the vectorial kinematics approach of Refs. 5–7 that is called upon in this paper.

Whereas the exclusion/communication algorithm developed in the paper generates time-varying attitude and angular rate commands, one may instead use, for simplicity, step commands. For example, Fig. 1a illustrates a minimum-angle slew path AB of a sensor starting from its initial orientation A to its final orientation B. En route, the sensor crosses the sun. To avoid this crossing, the sensor is step-commanded first to turn to the point C or to the opposite point D on the disc (the selection contingent upon the communication requirements). After arriving there, the sensor is step-commanded to the final orientation B. This approach is simple in that the attitude controller receives two sequential step commands, and therefore the associated flight software is compact. However, the disadvantage of this approach is that if the path ADB or ACB taken by the sensor enters the disc, depending on the location (α^*, ε^*) of the disc's centroid relative to the initial and final orientation of the sensor, this incursion will be neither detected nor averted by the flight controller. To redress this, the step commands may be devised more judiciously as shown in Fig. 1b (the disc's centroid in Fig. 1b lies, for simplicity, on the ideal slew path AB, $\varepsilon^* = 0$). Now, the forbidden area around the bright disc is enlarged so that, ignoring transients, the sensor will traverse the path ADB where AD and DB are tangential to the earlier forbidden area. The sensor is thus step-commanded to the orientation D, and, after arriving there and stopping, it is step-commanded next to its final orientation B. The intermediate orientation D can be determined analytically or numerically. Depending on the flight controller and actuators (wheels, thrusters), the actual path of the sensor in these two illustrations might differ significantly from the expected path ADB. For one thing, because of the step commands, the controller must stop and restart the sensor at D, which is wasteful. More important, because the slew angle α and the exclusion angle ε are about arbitrary axes in the pitch/yaw plane of the vehicle, they cause a coupled multi-axis motion. As a result, the actual path of the sensor may not be as well-behaved as what it will be if the flight controller receives reference α and ε command profiles from A to B and three-axis body rate commands involving $\dot{\alpha}$ and $\dot{\varepsilon}$. For this reason, the paper develops such reference commands.

The contents of the paper are briefly summarized now. Section II formulates various aspects of attitude motion for a bright object avoidance. The parameters of a minimum-angle slew, namely, slew angle, slew axis, and its orientation relative to both the initial vehicle frame and the final boresight direction, are determined first. The coordinates α^*, ε^* of the centroid of a bright object relative to the ideal slew plane are determined next. Then follows the determination of the two opposite exclusion angles (Fig. 1a) about an axis in the pitch/yaw plane, each enabling the telescope to pass the forbidden disc around a bright object tangentially at $\alpha = \alpha^*$. While the slew angle α is varied as a time/fuel-optimal profile, the exclusion angle ε varies as a versine function of α, reaching the desired avoidance angle at the slew angle $\alpha = \alpha^*$. Should this $\varepsilon(\alpha)$ profile intersect the disc for a certain range of α, this versine segment is replaced by the corresponding arc of the forbidden circle around the bright

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