Attitude Control of Solar Electric Spacecraft by Thruster Gimballing

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Theme

THE concept of two-axis mechanical gimballing of individual thrusters for attitude control of solar electric spacecraft has been evaluated and determined to be feasible with advantages over other control schemes. The primary advantage of the concept is its high redundancy character and implied reliability. For attitude control purposes, maximum two-axis symmetry should be observed in the thruster configuration to reduce coupling between axes. When an odd number k of thrusters operates, $k-1$ thrusters should be arranged in symmetric pairs and the unsymmetric thruster not be used for controlling the thrust axis. The thruster gimballing scheme, together with articulated solar array-mounted celestial sensors, can also be used for reorienting the thrust vector and simultaneously retaining solar array sun orientation.

Contents

Many concepts have been suggested for controlling the attitude of a solar electric spacecraft. Most emphasis has been placed on the thruster array translation-gimballing idea.[1] Three-axis gimballing of the entire thruster array has also been proposed. A third scheme incorporates electrostatic gimballing where no moving parts are required.[2] Translation of the thruster screen grid has also been proposed as a means of producing control torques.[2] This discussion deals with a purely mechanical scheme where each thruster in an array has individual gimballing capability in two axes.

An idealized version of the spacecraft comprising a bus, solar arrays, and thruster array is shown in Fig. 1. Axes x, y, z are bus-fixed pitch, yaw, and roll, while axes X, Y, Z are solar array-fixed pitch, yaw, and roll. The offset between x, y, z and X, Y, Z is σ. The **n**'s and **N**'s are unit vectors. The thruster array consists of eight electric propulsion thrusters, each capable of gimballing in two axes. Figure 2 shows the thruster actuator concept. The symbols T, A_1, and A_2 denote thruster and actuators 1 and 2. Actuation of A_1 causes T to rotate through β about the z axis, whereas actuation of A_2 causes T to rotate through α about line b-b'. For small motions, these are essentially rotations about the bus roll and yaw axes.

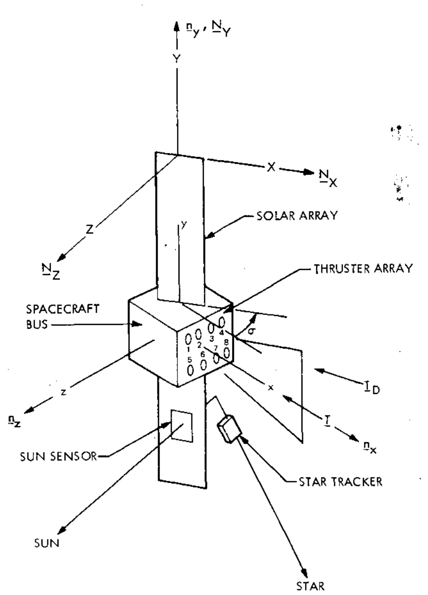

Fig. 1 Solar electric spacecraft.

For a single thruster, the type of gimbal motion described would produce torques about the bus roll and yaw axes. If two thrusters are symmetrically placed with respect to y or z, then equal and opposite gimballing of thrusters through $+\Delta$ and $-\Delta$ about z or through $+\delta$ and $-\delta$ about y would produce a torque about x. These torques can be used to control the spacecraft attitude.

If y- and z-axis symmetry is not observed for the thruster configuration, the thrust vector must be preaimed to insure that the thrusters exert no bias torque on the spacecraft. To insure, under these circumstances, that the thrust vector is properly oriented in inertial space, the vehicle must be reoriented. Such maneuvers will point the solar arrays, antenna, and other articulated instruments in the wrong direction. This can be corrected for by reorienting the articulated components with respect to the vehicle.

Letting y_1 be the y coordinate of thruster 1, z_1, z_2 the z coordinates of thrusters 1 and 2, L the distance from thruster array to origin of x, y, z axes, x_0, y_0, z_0 the location of the mass center with respect to origin of x, y, z axes, and δ_i and Δ_i the bus yaw and roll differential gimballing angles for thruster i, then the expression for the control torque **t** is

$$\mathbf{t} = t_x(\alpha, \beta, \delta_i, \Delta_i, y_1, z_1, z_2, x_0, y_0, z_0)\mathbf{n}_x + t_y(\delta_i, \alpha, z_1, z_2, x_0, y_0, z_0)\mathbf{n}_y + t_z(\Delta_i, \beta, y_1, x_0, y_0, z_0)\mathbf{n}_z$$

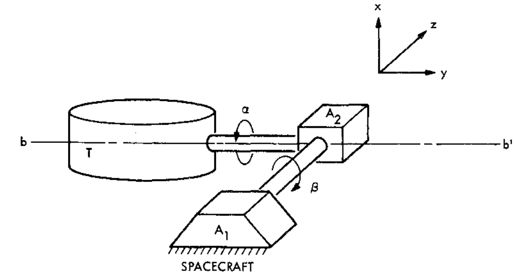

Fig. 2 Thruster actuator concept.

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The total torque exerted on the spacecraft is $\mathbf{t}+\tau$, where τ is the disturbance torque from all sources other than the thrusters. The attitude control objective is to balance τ with $\mathbf{t}$ and reduce the net torque on the vehicle to zero and simultaneously drive the attitude errors to zero. A desirable feature would be to produce a torque about a particular axis by variation of either α, β, δ_i, Δ_i, or δ_i and Δ_i, without introducing bias torques about any other axis. In this manner, any axis is controlled independently of any other.

Since α is a rotation about the bus yaw axis, it should be used for yaw-axis control and, similarly, β for bus roll-axis control. Differential gimballing, i.e., changes in δ_i and/or Δ_i, can be used for bus pitch-axis control. Thus, the desire is to have

$$t_x = t_x(\delta_i, \Delta_i); \quad t_y = t_y(\alpha); \quad t_z = t_z(\beta)$$

To avoid thruster bias torques on the spacecraft, the thrusters must be preaimed before startup. The preaim angles can be calculated by setting t_y and t_z equal to zero, and letting $\alpha = \alpha_p + \alpha_c$ and $\beta = \beta_p + \beta_c$. If the control angles α_c, β_c, δ_i, and Δ_i are set to zero, then the preaim angles α_p and β_p are

$$\alpha_p = \Big[-(F_1n_1+F_5n_5)(z_1-z_0)-(F_2n_2+F_6n_6)(z_2-z_0)+(F_3n_3+F_7n_7)(z_2+z_0)+(F_4n_4+F_8n_8)(z_1+z_0)\Big] \Big/ \sum_{i=1}^{8} F_i n_i (L-x_0)$$

$$\beta_p = \left[\sum_{i=1}^{4} F_i n_i (y_1 - y_0) - \sum_{i=5}^{8} F_i n_i (y_1+y_0)\right] \Big/ \sum_{i=1}^{8} F_i n_i (L-x_0)$$

where F_i is thruster i thrust level and n_i is either 0 or 1 depending on whether or not thruster i is on or off. The equation $t_x = 0$ is satisfied by these values of α_p and β_p. When the thrusters are preaimed according to these formulas and if: 1) the thrusters operate in symmetric pairs; 2) for odd numbers k of thrusters, $k-1$ thrusters are arranged in symmetric pairs and used for roll, yaw, and pitch control; 3) for the unsymmetric thruster, δ_i and Δ_i are set equal to zero; then the final forms for t_x, t_y, and t_z are

$$t_x = -\Big[-\sum_{i=1}^{4} F_i n_i \delta_i (y_1-y_0) + \sum_{i=5}^{8} F_i n_i \delta_i (y_1+y_0) - (F_1n_1\Delta_1+F_5n_5\Delta_5)(z_1-z_0) - (F_2n_2\Delta_2+F_6n_6\Delta_6)(z_2-z_0) + (F_3n_3\Delta_3+F_7n_7\Delta_7)(z_2+z_0) + (F_4n_4\Delta_4+F_8n_8\Delta_8)(z_1+z_0)\Big]$$

$$t_y = -\sum_{i=1}^{8} F_i n_i (L-x_0)\alpha_c$$

$$t_z = -\sum_{i=1}^{8} F_i n_i (L-x_0)\beta_c$$

Scrutiny of these equations clearly indicates the capability for independent three-axis control by thruster gimballing.

Generally, during an electric propulsion spacecraft mission, the thrust vector $\mathbf{T}$ must be reoriented periodically for trajectory control. Simultaneously, the solar arrays must maintain sun orientation to insure an adequate power supply. These two requirements can be made compatible by providing for solar array and star tracker gimballing. Thrust vector reorientation is achieved by a Z-Y axis rotation sequence. In Fig. 1, the sun sensor senses errors about the X and Y axes, while the star tracker senses errors about the Z axis. To obtain the Z-axis rotation, the star tracker is gimballed about Z. To obtain the Y-axis rotation, the solar arrays are articulated about Y. Errors are registered by both sun and star sensors. They are nulled when the thrust vector coincides with the desired thrust vector $\mathbf{T}_D$.

The thrust vector reorientation geometry is shown in Fig. 3. The geometry differs slightly from that shown in Fig. 1, where

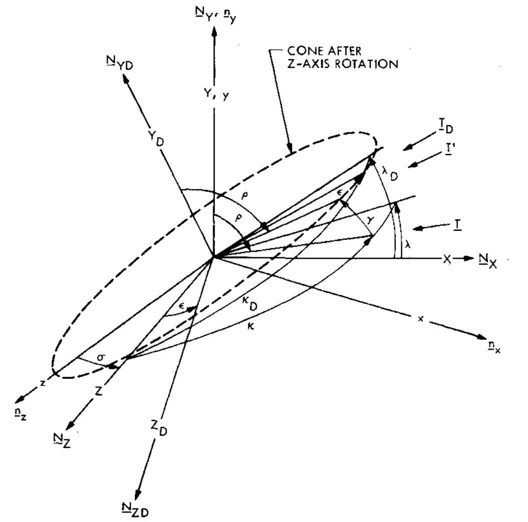

Fig. 3 Thrust vector reorientation geometry.

$\mathbf{T}$ is shown parallel to the bus pitch axis. In general, α_p and β_p will not be zero, and Fig. 3 reflects this by showing $\mathbf{T}$ not parallel to x. Cone and clock angles for a line with respect to solar array coordinates are defined as the angle between Z and the line, and the angle between X and a plane formed by Z and the line. The cone and clock angles for $\mathbf{T}$ are κ and λ, whereas those for $\mathbf{T}_D$ are κ_D and λ_D. Note that $\mathbf{T}$ is parallel to a line which is an element of a cone having half-cone angle ρ and axis Y. Rotation of the spacecraft about Z reorients this cone in space. Subsequent reorientation about the new Y axis, say Y_D, relocates the thrust vector so that it is now parallel to a new element of the reoriented cone. Cognizance of this basic geometry suggests a scheme for reorienting the thrust vector from $\mathbf{T}$ to $\mathbf{T}_D$. The scheme is to first rotate about Z through an angle γ, which will insure that both $\mathbf{T}_D$ and $\mathbf{T}'$ (the intermediate thrust vector) lie on the same cone having cone angle ρ, and then to rotate about Y_D through ε so that the thrust vector coincides with $\mathbf{T}_D$.

To obtain the solar array roll (Z axis)-yaw (Y axis) maneuver for reorienting $\mathbf{T}$, the star tracker first gimbals through $-\gamma$. An error of $-\gamma$ is registered and the spacecraft rotates about Z through γ to reacquire the reference star. Note that the solar arrays are still sun-oriented and that the sun sensors register no errors. Next, the solar arrays are rotated through $-\varepsilon$ about Y_D. An error $-\varepsilon$ is read in the Y-axis sun sensor. Furthermore, the panel rotation causes loss of the star reference, and consequently, the star tracker also registers an error. The torque supplied by thruster gimballing rotates the spacecraft through ε and nulls out the tracker errors. In this configuration, the thrust vector is pointing in the desired direction and the solar panels are sun-oriented. Expressions for obtaining γ and ε in terms of the known angles κ, κ_D, λ_D, λ are

$$\sin^2\kappa_D \sin^2\gamma + 2\sin\kappa\sin\lambda\sin\kappa_D\cos\lambda_D\sin\gamma + \sin^2\kappa\sin^2\lambda - \sin^2\kappa_D\sin^2\lambda_D = 0$$

$$\cos\varepsilon = \sin\kappa\sin\kappa_D[\cos\lambda_D(\cos\lambda\cos\gamma - \sin\lambda\sin\gamma) + \sin\lambda_D(\cos\lambda\sin\gamma + \sin\lambda\cos\gamma)] + \cos\kappa\cos\kappa_D$$

References

[1] Perkins, G. S. et al., "A Mechanism for Three Axis Control of an Ion Thruster Array," *Journal of Spacecraft and Rockets*, Vol. 9, No. 3, March 1972, pp. 218–220.

[2] King, H. J., Collett, C. R., and Schnelker, D. E., "Thrust Vectoring Systems, Part I-5, CM Systems," CR-72677, 1971, NASA.