Sun-Avoidance Slew (SAS) Maneuver with Single Payload

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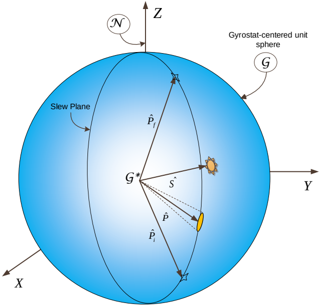
Sun-Avoidance Slew (SAS) Maneuver

Problem Statement:

Given: ${}_{\mathcal{N}}\hat{P}_i$, ${}_{\mathcal{N}}\hat{P}_f$, ${}_{\mathcal{N}}\hat{S}$, ${}_{\mathcal{G}}\hat{P}$, ϵ_p, ${}^{\mathcal{N}}q^{\mathcal{G}}$, ${}^{\mathcal{N}}_{\mathcal{G}}\omega^{\mathcal{G}}(t_i)$, and ${}^{\mathcal{N}}_{\mathcal{G}}\omega^{\mathcal{G}}(t_f)$.

Find:

1. A sequence of slew maneuvers to avoid sun vector.
2. the commanded angular velocity, angular acceleration, and quaternion profiles.



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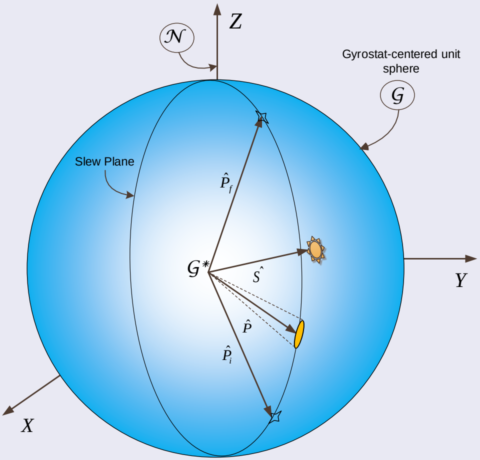


Figure: The gyrostat-centered unit sphere.

Nomenclature

- $\mathcal{G}$ frame: Unit sphere attached to the gyrostat.
- $\mathcal{N}$: frame: The Newtonian frame fixed in the inertial space.
- ${}_{\mathcal{G}}\hat{P}$: Unit vector along the bore sight of payload in the $\mathcal{G}$ frame.
- ${}_{\mathcal{G}}\hat{P}_i$: Unit vector of the initial point in the $\mathcal{G}$ frame.
- ${}_{\mathcal{G}}\hat{P}_f$: Unit vector of the final point in the $\mathcal{G}$ frame.
- ${}_{\mathcal{N}}\hat{S}$: Unit vector of the sun vector in the $\mathcal{N}$ frame.
- ϵ_p: Payload half-cone angle.

Check the Sun Vector Intrusion

1. Check the angular separation between the sun vector, $\hat{S}$, and the $\hat{P}_i - \hat{P}_f$ or "slew" plane.

$$\alpha = \frac{\pi}{2} - \cos^{-1}(\hat{S} \cdot_{\mathcal{N}} \hat{e}) \tag{1}$$

where the eigenaxis is determined by

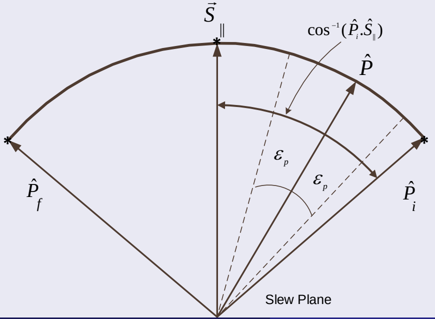
$$\hat{e} = \frac{\hat{P}_i \times \hat{P}_f}{|\hat{P}_i \times \hat{P}_f|} \tag{2}$$

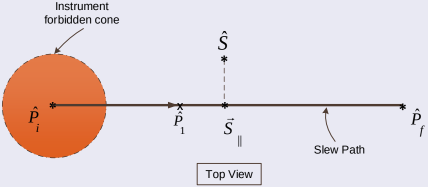
2. IF $|\alpha| < \epsilon_p$,THEN determine the projection of the sun vector into the slew plane.

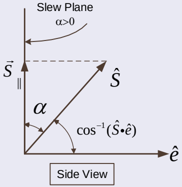
$$\vec{S}_{||} = \hat{S}\cos\alpha \tag{3}$$

1. The 1^{st} slew around the eigenaxis, $\hat{e}$, through angle:

$$\phi_1 = \begin{cases} \cos^{-1}(\hat{P}_i \cdot_G \hat{S}_{||}) - \epsilon_p & \textit{when} \ \cos^{-1}(\hat{P}_i \cdot_G \hat{S}_{||}) - \epsilon_p \leq \pi \\ \cos^{-1}(\hat{P}_i \cdot_G \hat{S}_{||}) - \epsilon_p - 2\pi & \textit{when} \ \cos^{-1}(\hat{P}_i \cdot_G \hat{S}_{||}) - \epsilon_p > \pi \end{cases} \tag{4}$$



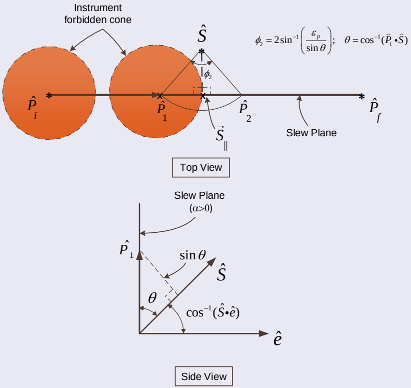




Slew Maneuvers

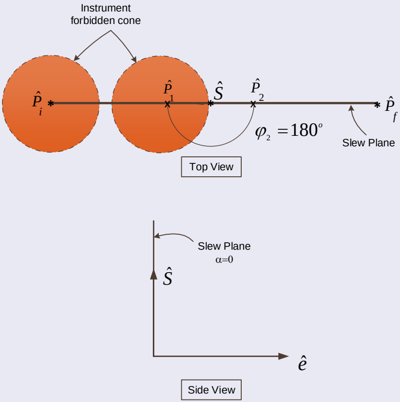
2. The 2^{nd} slew around the unit sun vector, $\hat{S}$, via ϕ_2.
   a. when $\alpha \neq 0$

$$\phi_2 = 2\sin^{-1}\left(\frac{\sin\epsilon_p}{\sin\theta}\right), \ \theta = \cos^{-1}(\hat{P}_1 \cdot \hat{S}) \tag{5}$$



Slew Maneuvers

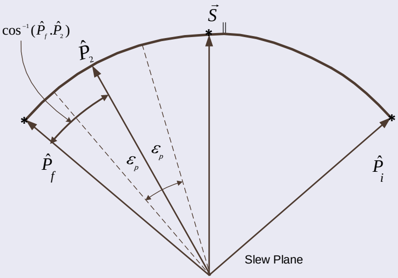
2. The 2^{nd} slew around the unit sun vector, $\hat{S}$, via $\phi_2 = 180°$.
   b) when $\alpha = 0$



Slew Maneuvers

3. The 3^{rd} slew about the $\hat{e}$ through angle:

$$\phi_3 = \begin{cases} \cos^{-1}({}_G\hat{P}_f.\hat{P}_2) & when\ {}_G\hat{P}_f.\hat{P}_2 \geq 0 \\ \cos^{-1}({}_G\hat{P}_f.\hat{P}_2) - 2\pi & when\ {}_G\hat{P}_f.\hat{P}_2 < 0 \end{cases} \tag{6}$$



4. The final slew is about the instrument boresight axis to go to the final attitude.

Summary of the Algorithm

1. Slew around the eigenaxis, $\hat{e}$, through angle:

$$\phi_1 = \begin{cases} \cos^{-1}(\hat{P}_i \cdot_{\mathcal{G}} \hat{S}_{||}) - \epsilon_p & when \;\; \cos^{-1}(\hat{P}_i \cdot_{\mathcal{G}} \hat{S}_{||}) - \epsilon_p \leq \pi \\ \cos^{-1}(\hat{P}_i \cdot_{\mathcal{G}} \hat{S}_{||}) - \epsilon_p - 2\pi & when \;\; \cos^{-1}(\hat{P}_i \cdot_{\mathcal{G}} \hat{S}_{||}) - \epsilon_p > \pi \end{cases} \tag{7}$$

2. Slew around the $\hat{S}$ via:

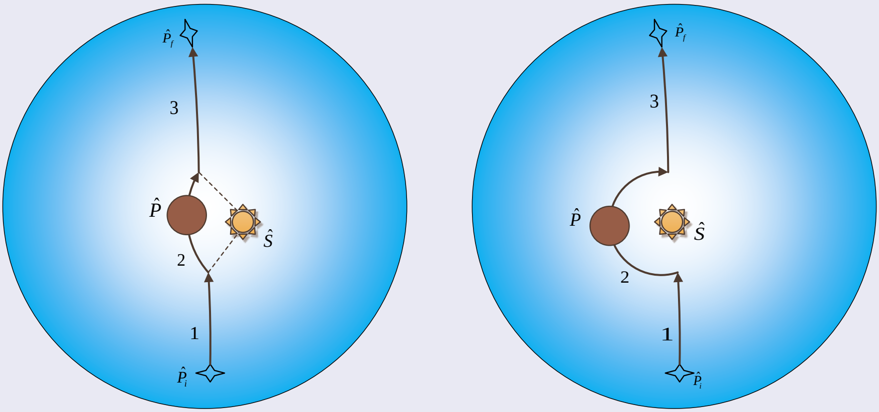
$$\phi_2 = \begin{cases} 2\sin^{-1}\left(\frac{\sin \epsilon_p}{\sin \theta}\right), \;\; \theta = \cos^{-1}(\hat{P}_1 \cdot \hat{S}) & when \;\; \alpha \neq 0 \\ \pi & when \;\; \alpha = 0 \end{cases} \tag{8}$$

3. Slew about the $\hat{e}$ through angle:

$$\phi_3 = \begin{cases} \cos^{-1}({}_{\mathcal{G}}\hat{P}_f . \hat{P}_2) & when \;\; {}_{\mathcal{G}}\hat{P}_f . \hat{P}_2 \geq 0 \\ \cos^{-1}({}_{\mathcal{G}}\hat{P}_f . \hat{P}_2) - 2\pi & when \;\; {}_{\mathcal{G}}\hat{P}_f . \hat{P}_2 < 0 \end{cases} \tag{9}$$

4. Perform the final rotation, ϕ_4, about the instrument boresight axis to adjust the attitude.

Summary of the Algorithm



$\alpha > 0$ $\alpha = 0$

Computing the Steering Profiles

- Case 1) Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints.

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

Problem Statement:

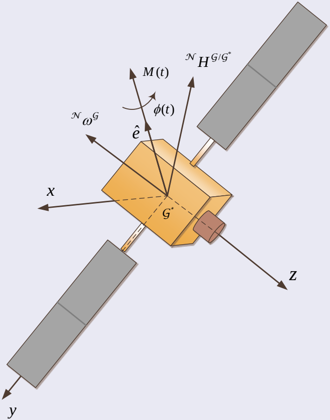
Consider the motion of a rigid spacecraft around a given inertially-fixed axis, ${}_G\hat{e} = [e_x, e_y, e_z]^T$. The problem of minimum-time slew maneuver around the $\hat{e}$ axis can be formulated as

$$\underset{u}{Minimze}\ J[x(.), u(.), t_f] = \int_{t0}^{t_f} dt, \quad (10)$$

subject to the following dynamic constraint

$$\Sigma : \begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = M/I_{\hat{e}}^{G/G*} = u, \end{cases} \quad (11)$$

where $x_1 \triangleq \phi$ and $x_2 = \dot{\phi}$.



Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

The boundary conditions are

$$BCs: \begin{cases} \phi(t_0) = 0, \phi(t_f) = \phi_f, \\ \dot{\phi}(t_0) = \dot{\phi}_0, \dot{\phi}(t_f) = \dot{\phi}_f, \end{cases} \tag{12}$$

and velocity (state) and acceleration (control) constraints are

$$C_1: \begin{cases} |x_2 = \dot{\phi}| \leq \dot{\phi}_{max}, \\ |u = \ddot{\phi}| \leq \ddot{\phi}_{max}, \end{cases} \tag{13}$$

in which

$$\dot{\phi}_{max} = [I^{w/w^*}]^{-1}[{}^N H^{G/G*} - (I^{G/G*} + I^{w/w*})^N \omega^G]/(e_x + e_y + e_z), \tag{14}$$

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

and

$$\ddot{\phi}_{max} = {}_B\hat{e}^T \; {}_BM_{max}/I_{\hat{e}}^{G/G*}, \tag{15}$$

where ${}^NH^{G/G*}$ is the total angular momentum of the gyrostat with respect to its center of mass, G^*, in the N-frame. I^{G/G^*} and $I^{w/w*}$ represent the inertia dyadic of the gyrostat and reaction wheel with respect to their center of masses, respectively. ${}_BM_{max}$ is the maximum generated torque along the body-axes in the body frame.

Find: $\phi(t)$, $\dot{\phi}(t)$, and $\ddot{\phi}(t)$.

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

Using the Pontryagin's minimum principle (PMP), we derive the necessary conditions for the optimal solution as follows:

1. State Eqs.:

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = u, \\ \dot{x}_3 = (x_2 + \dot{\phi}_{max})^2 \mathbb{U}(-x_2 - \dot{\phi}_{max}) + (\dot{\phi}_{max} - x_2)^2 \mathbb{U}(x_2 - \dot{\phi}_{max}), \end{cases} \tag{16}$$

   where the unit step function, $\mathbb{U}$, is defined as

$$\mathbb{U}(X) = \begin{cases} 1, & X > 0, \\ 0, & X \leq 0. \end{cases} \tag{17}$$

   Note: $(x_3(t_0) = x_3(t_f) = 0 \ \& \ x_3(t) \geq 0\ ) \rightarrow x_3(t) = 0, t \in [t_0, t_f]$.

2. Hamlitonian:

$$\begin{aligned} \mathscr{H} =& 1 + \lambda_1 x_2 + \lambda_2 u + \lambda_3 \Big[(x_2 + \dot{\phi}_{max})^2 \mathbb{U}(-x_2 - \dot{\phi}_{max}) \\ & (\dot{\phi}_{max} - x_2)^2 \mathbb{U}(x_2 - \dot{\phi}_{max}) \Big] \end{aligned} \tag{18}$$

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

3. Costate Eqs.:

$$\begin{cases} \dot{\lambda}_1 = -\frac{\partial \mathscr{H}}{\partial x_1} = 0, \\ \dot{\lambda}_2 = -\frac{\partial \mathscr{H}}{\partial x_2} = -\lambda_1 - 2\lambda_3(x_2 + \dot{\phi}_{max})\mathbb{U}(-x_2 - \dot{\phi}_{max}) \\ +2\lambda_3(\dot{\phi}_{max} - x_2)\mathbb{U}(x_2 - \dot{\phi}_{max}), \\ \dot{\lambda}_3 = -\frac{\partial \mathscr{H}}{\partial x_3} = 0. \end{cases} \tag{19}$$

4. Applying the Pontryagin's minimum principle (PMP),

$$u^* = arg \min_{u \in \mathcal{U}} \mathscr{H}, \tag{20}$$

where $\mathcal{U}$ defines the domain of feasible controls. The optimal control can be determined as

$$u^*(t) = \begin{cases} \ddot{\phi}_{max} & \lambda_2 < 0, \\ ? & \lambda_2 = 0, \\ -\ddot{\phi}_{max} & \lambda_2 > 0. \end{cases} \tag{21}$$

This is a *singular arc* optimal control problem.

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

5. Determining the optimal control in the singular arc:

$$\frac{d^2}{dt^2}\left(\frac{\partial \mathscr{H}}{\partial u}\right) = \ddot{\lambda}_2 = 0 \rightarrow \dot{x}_2 = 0 \rightarrow u^* = 0 \tag{22}$$

6. Checking the Generalized Legendre-Clebsch condition for optimality:

$$(-1)^2 \frac{\partial}{\partial u}\left[\frac{d^2}{dt^2}\left(\frac{\partial \mathscr{H}}{\partial u}\right)\right] = 1 \geq 0 \tag{23}$$

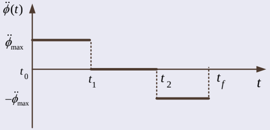
7. The transversality condition:

$$\mathscr{H}\big|_{(*,t_f)} = 0 \text{ and } \mathscr{H} \neq \mathscr{H}(t) \rightarrow \mathscr{H} = 0, \forall t \in [t_0, t_f]. \tag{24}$$

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

- Angular acceleration profile (bang-off-bang):

$$\ddot{\phi}(t) = u = \begin{cases} \ddot{\phi}_{max} & \text{when } t_0 \leq t \leq t_1, \\ 0 & \text{when } t_1 \leq t \leq t_2, \\ -\ddot{\phi}_{max} & \text{when } t_2 \leq t \leq t_f. \end{cases} \tag{25}$$



- Angular velocity profile:

$$\dot{\phi}(t) = \begin{cases} \dot{\phi}_0 + \ddot{\phi}_{max}(t - t_0) & \text{when } t_0 \leq t \leq t_1, \\ \dot{\phi}_{max} & \text{when } t_1 \leq t \leq t_2, \\ \dot{\phi}_{max} - \ddot{\phi}_{max}(t - t_2) & \text{when } t_2 \leq t \leq t_f. \end{cases} \tag{26}$$

- Angular position profile:

$$\phi(t) = \begin{cases} \dot{\phi}_0(t - t_0) + \frac{1}{2}\ddot{\phi}_{max}(t - t_0)^2 & \text{when } t_0 \leq t \leq t_1, \\ \phi(t_1) + \dot{\phi}_{max}(t - t_1) & \text{when } t_1 \leq t \leq t_2, \\ \phi(t_2) + \dot{\phi}_{max}(t - t_2) - \frac{1}{2}\ddot{\phi}_{max}(t - t_2)^2 & \text{when } t_2 \leq t \leq t_f. \end{cases} \tag{27}$$

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

- Using the conditions, $\dot{\phi}(t_1) = \dot{\phi}_{max}$, $\dot{\phi}(t_f) = \dot{\phi}_f$, $\phi(t_f) = \phi_f$, we can determine switching times t_1, t_2, and final time t_f as:

$$t_1 = t_0 + \frac{\dot{\phi}_{max} - \dot{\phi}_0}{\ddot{\phi}_{max}}, \tag{28}$$

$$\begin{aligned} t_2 = &t_1 + \frac{1}{\dot{\phi}_{max}} \Big[\phi_f - \dot{\phi}_0(t_1 - t_0) - \frac{1}{2}\ddot{\phi}_{max}(t_1 - t_0)^2 \\ &- \frac{\dot{\phi}_{max}(\dot{\phi}_{max} - \dot{\phi}_f)}{\ddot{\phi}_{max}} + \frac{(\dot{\phi}_{max} - \dot{\phi}_f)^2}{2\ddot{\phi}_{max}} \Big], \end{aligned} \tag{29}$$

and

$$t_f = t_1 + \frac{1}{\dot{\phi}_{max}} \Big[\phi_f - \dot{\phi}_0(t_1 - t_0) - \frac{1}{2}\ddot{\phi}_{max}(t_1 - t_0)^2 + \frac{(\dot{\phi}_{max} - \dot{\phi}_f)^2}{2\ddot{\phi}_{max}} \Big]. \tag{30}$$

Single-Axis, Agile Slew Maneuver with Velocity and Acceleration Constraints

- Steering profiles:

$$^{N}q^{D}(t) = [e_x \sin\frac{\phi(t)}{2}, e_y \sin\frac{\phi(t)}{2}, e_z \sin\frac{\phi(t)}{2}, \cos\frac{\phi(t)}{2}]^T \tag{31}$$

$$^{N}_{G}\omega^{D}(t) = \dot{\phi}(t)_G\hat{e} \tag{32}$$

$$^{N}_{G}\alpha^{D}(t) = \ddot{\phi}(t)_G\hat{e} \tag{33}$$

Computing the Steering Profiles

- Case 2) Single-Axis, Agile Slew Maneuver with Acceleration Constraint.

Single-Axis, Agile Slew Maneuver with Acceleration Constraint

Problem Statement:

Consider the optimal control problem described by Eqs.(10), (11), (12), and subject to control constraint

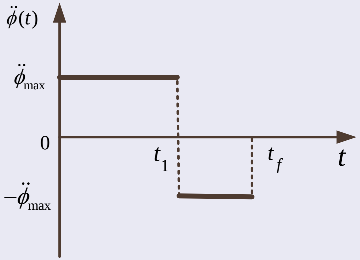
$$C_2: \ |u = \ddot{\phi}| \leq \ddot{\phi}_{max}. \tag{34}$$

Find: $\phi(t)$, $\dot{\phi}(t)$, and $\ddot{\phi}(t)$.

Single-Axis, Agile Slew Maneuver with Acceleration Constraint

- Angular acceleration about the $\hat{e}$ axis:

$$\ddot{\phi}(t) = \ddot{\phi}_{max}\mathbb{U}(t_0) - 2\ddot{\phi}_{max}\mathbb{U}(t - t_1) \tag{35}$$



where the switching and the final times are given by

$$t_1 = t_0 - \frac{\dot{\phi}_0}{\ddot{\phi}_{max}} + \frac{\sqrt{\ddot{\phi}_{max}^2(2\ddot{\phi}_{max}\phi_f + \dot{\phi}_f^2 + \dot{\phi}_0^2)}}{\sqrt{2}\ddot{\phi}_{max}^2} \tag{36}$$

Single-Axis, Agile Slew Maneuver with Acceleration Constraint

and

$$t_f = t_0 - \frac{\dot{\phi}_f + \dot{\phi}_0}{\ddot{\phi}_{max}} + \frac{\sqrt{2}\sqrt{\ddot{\phi}_{max}^2(2\ddot{\phi}_{max}\phi_f + \dot{\phi}_{ef}^2 + \dot{\phi}_0^2)}}{\ddot{\phi}_{max}^2} \quad (37)$$

- Angular velocity about the $\hat{e}$ axis:

$$\dot{\phi}(t) = \dot{\phi}_0 + \ddot{\phi}_{max}(t - t_0)\mathbb{U}(t_0) - 2\ddot{\phi}_{max}(t - t_1)\mathbb{U}(t - t_1) \quad (38)$$

- Angular position about the $\hat{e}$ axis:

$$\begin{aligned}\phi(t) = \dot{\phi}_0(t - t_0) + \ddot{\phi}_{max}\frac{(t - t_0)^2}{2}\mathbb{U}(t_0) \\ - 2\ddot{\phi}_{max}\frac{(t - t_1)^2}{2}\mathbb{U}(t - t_1)\end{aligned} \quad (39)$$

The Agile Sun-Avoidance Slew Maneuver

The First Slew Maneuver: A single-axis nonrest-to-rest maneuver around the $\hat{e}$

- The BCs:

$$\dot{\phi}(t_0) = \dot{\phi}_0, \phi(t_0) = 0, \dot{\phi}(t_{f1}) = 0, \phi(t_{f1}) = \phi_1. \tag{40}$$

The switching time, t_{11}, and minimum-time, t_{f1}, are

$$t_{11} = t_0 - \frac{\dot{\phi}_0}{\ddot{\phi}_{max}} + \frac{\sqrt{\ddot{\phi}_{max}^2(2\ddot{\phi}_{max}\phi_1 + \dot{\phi}_0^2)}}{\sqrt{2}\ddot{\phi}_{max}^2} \tag{41}$$

$$t_{f1} = t_0 - \frac{\dot{\phi}_0}{\ddot{\phi}_{max}} + \frac{\sqrt{2\ddot{\phi}_{max}^2(2\ddot{\phi}_{max}\phi_1 + \dot{\phi}_0^2)}}{\ddot{\phi}_{max}^2} \tag{42}$$

The $\ddot{\phi}(t)$, $\dot{\phi}(t)$, and $\phi(t)$, can be found by substituting the boundary conditions given by (40) and t_{11} and t_{f1} in to Eqs. (35), (38), and (39), respectively.

The Agile Sun-Avoidance Slew Maneuver

The Second Slew Maneuver: A rest-to-rest maneuver around the sun vector

- The BCs:

$$\dot{\phi}(t_0) = 0, \phi(t_0) = 0, \dot{\phi}(t_{f2}) = 0, \phi(t_{f2}) = \phi_2. \tag{43}$$

The switching time, t_{12}, and the minimum-time, t_{f2}, are

$$t_{12} = t_0 - \frac{\sqrt{\phi_2}}{\ddot{\phi}_{max}} \tag{44}$$

$$t_{f2} = t_0 - \frac{2\sqrt{\phi_2}}{\ddot{\phi}_{max}} \tag{45}$$

The $\ddot{\phi}(t)$, $\dot{\phi}(t)$, and $\phi(t)$, can be found by substituting the boundary conditions given by (43) and t_{12} and t_{f2} in to Eqs. (35), (38), and (39), respectively.

The Third Slew Maneuver: A single-axis rest-to-nonrest maneuver around the $\hat{e}$

- The BCs:

$$\dot{\phi}(t_0) = 0, \phi(t_0) = 0, \dot{\phi}(t_{f3}) = \dot{\phi}_f, \phi(t_{f3}) = \phi_3. \tag{46}$$

The switching time, t_{13}, and the minimum-time, t_{f3}, are

$$t_{13} = t_0 + \frac{\sqrt{\ddot{\phi}_{max}^2(2\ddot{\phi}_{max}\phi_3 + \dot{\phi}_f^2)}}{\sqrt{2}\ddot{\phi}_{max}^2} \tag{47}$$

$$t_{f3} = t_0 - \frac{\dot{\phi}_f}{\ddot{\phi}_{max}} + \frac{\sqrt{2\ddot{\phi}_{max}^2(2\ddot{\phi}_{max}\phi_3 + \dot{\phi}_f^2)}}{\ddot{\phi}_{max}^2} \tag{48}$$

The $\ddot{\phi}(t)$, $\dot{\phi}(t)$, and $\phi(t)$, can be found by substituting the boundary conditions given by (46) and t_{13} and t_{f3} in to Eqs. (35), (38), and (39), respectively.