Analytical Mechanics: Rigid Body Rotation

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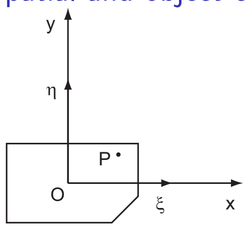
Agenda

Spatial and object coordinate systems



$O - xy$	spatial coordinate system
$O - \xi\eta$	object coordinate system
$\boldsymbol{a}$	unit vector along ξ-axis
$\boldsymbol{b}$	unit vector along η-axis

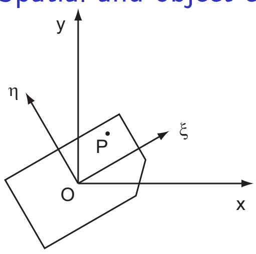
$$\|\boldsymbol{a}\| = 1 \;\rightarrow\; \boldsymbol{a}^{\mathrm{T}}\boldsymbol{a} = 1$$
$$\|\boldsymbol{b}\| = 1 \;\rightarrow\; \boldsymbol{b}^{\mathrm{T}}\boldsymbol{b} = 1$$
$$\boldsymbol{a} \perp \boldsymbol{b} \;\rightarrow\; \boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = \boldsymbol{b}^{\mathrm{T}}\boldsymbol{a} = 0$$

ξ, η: object coordinates of point P spatial coordinates of point P

$$\boldsymbol{x} = \xi\boldsymbol{a} + \eta\boldsymbol{b} = \underbrace{\left[\begin{array}{c|c} \boldsymbol{a} & \boldsymbol{b} \end{array}\right]}_{R} \underbrace{\left[\begin{array}{c} \xi \\ \eta \end{array}\right]}_{\boldsymbol{\xi}}$$

Note: $\boldsymbol{a}$ and $\boldsymbol{b}$ depend on time. ξ and η are independent of time.

Spatial and object coordinate systems



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Note: $\boldsymbol{a}$ and $\boldsymbol{b}$ depend on time. ξ and η are independent of time.

Angular velocity in planar rotation

differentiating relationships between $\boldsymbol{a}$ and $\boldsymbol{b}$ w.r.t time:

$$\boldsymbol{a}^{\mathrm{T}}\boldsymbol{a} = 1 \rightarrow \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{a}} = 0$$
$$\boldsymbol{b}^{\mathrm{T}}\boldsymbol{b} = 1 \rightarrow \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{b}} = 0$$
$$\boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = 0 \rightarrow \underbrace{\boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{b}}}_{-\omega} + \underbrace{\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}}}_{\omega} = 0$$

describing $\dot{\boldsymbol{a}}$ and $\dot{\boldsymbol{b}}$ in object coordinate system:

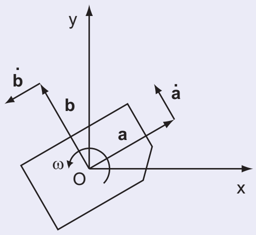
$$\dot{\boldsymbol{a}} = (\boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{a}})\boldsymbol{a} + (\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}})\boldsymbol{b} = \omega\boldsymbol{b}$$
$$\dot{\boldsymbol{b}} = (\boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{b}})\boldsymbol{a} + (\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{b}})\boldsymbol{b} = -\omega\boldsymbol{a}$$

velocity of point $\mathrm{P}(\xi, \eta)$

$$\dot{\boldsymbol{x}} = \xi\dot{\boldsymbol{a}} + \eta\dot{\boldsymbol{b}} = \omega(\xi\boldsymbol{b} - \eta\boldsymbol{a})$$

Angular velocity in planar rotation

interpretation



$\omega = \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}}$ angular velocity

$\|\boldsymbol{a}\| = 1 \;\rightarrow\; \dot{\boldsymbol{a}} \perp \boldsymbol{a} \rightarrow \dot{\boldsymbol{a}} \parallel \boldsymbol{b}$

$\|\boldsymbol{b}\| = 1 \;\rightarrow\; \dot{\boldsymbol{b}} \perp \boldsymbol{b} \rightarrow \dot{\boldsymbol{b}} \parallel \boldsymbol{a}$

$\|\boldsymbol{a}\| = 1 \;\rightarrow\; \|\dot{\boldsymbol{a}}\| = \omega$

$\|\boldsymbol{a}\| = 1 \;\rightarrow\; \|\dot{\boldsymbol{b}}\| = \omega$

Kinetic energy of rigid body

Divide a rigid body into a finite number of masses.

m_i	the i-th mass
(ξ_i, η_i)	object coordinates of the i-th mass

position of mass m_i $\quad \boldsymbol{x}_i = \xi_i\boldsymbol{a} + \eta_i\boldsymbol{b}$

velocity of mass m_i $\quad \dot{\boldsymbol{x}}_i = \xi_i\dot{\boldsymbol{a}} + \eta_i\dot{\boldsymbol{b}} = \omega(\xi_i\boldsymbol{b} - \eta_i\boldsymbol{a})$

kinetic energy of mass m_i

$$\frac{1}{2}m_i\dot{\boldsymbol{x}}_i^{\mathrm{T}}\dot{\boldsymbol{x}}_i = \frac{1}{2}m_i\,\omega^2(\xi_i\boldsymbol{b} - \eta_i\boldsymbol{a})^{\mathrm{T}}(\xi_i\boldsymbol{b} - \eta_i\boldsymbol{a}) = \frac{1}{2}m_i\,\omega^2(\xi_i^2 + \eta_i^2)$$

Kinetic energy of rigid body

kinetic energy of rigid body rotating on plane

$$\sum_i \frac{1}{2}m_i\dot{\boldsymbol{x}}_i^{\mathrm{T}}\dot{\boldsymbol{x}}_i = \sum_i \frac{1}{2}m_i\,\omega^2(\xi_i^2 + \eta_i^2) = \frac{1}{2}J\omega^2$$

where

$$J = \sum_i m_i\,(\xi_i^2 + \eta_i^2) \qquad \text{inertia of moment}$$

Note: J is constant (independent of time)

Computing Lagrange equation of planar rotation

description that satisfies relationships between $\boldsymbol{a}$ and $\boldsymbol{b}$

$$\boldsymbol{a} = \begin{bmatrix} C_\theta \\ S_\theta \end{bmatrix}, \qquad \boldsymbol{b} = \begin{bmatrix} -S_\theta \\ C_\theta \end{bmatrix}$$

angular velocity

$$\omega = \boldsymbol{b}^{\mathrm{T}} \dot{\boldsymbol{a}} = \begin{bmatrix} -S_\theta & C_\theta \end{bmatrix} \begin{bmatrix} -S_\theta \\ C_\theta \end{bmatrix} \dot{\theta} = \dot{\theta}$$

kinetic energy

$$T = \frac{1}{2} J \dot{\theta}^2$$

work done by external torque τ around point O

$$W = \tau \theta$$

Computing Lagrange equation of planar rotation

Lagrangian

$$L = \frac{1}{2} J \dot{\theta}^2 + \tau \theta$$

Lagrange equation of motion

$$\frac{\partial L}{\partial \theta} - \frac{\mathrm{d}}{\mathrm{d}t} \frac{\partial L}{\partial \dot{\theta}} = 0$$

$$\tau - J \ddot{\theta} = 0$$

$$J \ddot{\theta} = \tau$$

equation of planar rotation

Inertia of moment in rigid continuum

Let ρ be planar density of a rigid body.

$$m_i \to \rho \, \mathrm{d}\xi \mathrm{d}\eta$$

$$\sum_i \to \int_S$$

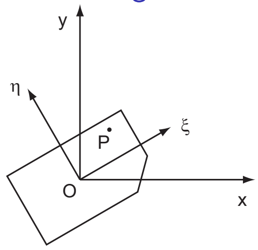
inertia of moment:

$$J = \sum_i m_i \, (\xi_i^2 + \eta_i^2)$$

$$\downarrow$$

$$J = \int_S \rho \, (\xi^2 + \eta^2) \, \mathrm{d}\xi \mathrm{d}\eta$$

Introducing rotation matrix



spatial coordinates of point $\mathrm{P}(\xi, \eta)$

$$\begin{aligned} \boldsymbol{x} &= \xi \boldsymbol{a} + \eta \boldsymbol{b} \\ &= \underbrace{\begin{bmatrix} \boldsymbol{a} & \boldsymbol{b} \end{bmatrix}}_{R} \underbrace{\begin{bmatrix} \xi \\ \eta \end{bmatrix}}_{\boldsymbol{\xi}} \\ &= R \boldsymbol{\xi} \end{aligned}$$

R rotation matrix

$$R^{\mathrm{T}} R = \begin{bmatrix} \boldsymbol{a}^{\mathrm{T}} \\ \boldsymbol{b}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \boldsymbol{a} & \boldsymbol{b} \end{bmatrix} = \begin{bmatrix} \boldsymbol{a}^{\mathrm{T}} \boldsymbol{a} & \boldsymbol{a}^{\mathrm{T}} \boldsymbol{b} \\ \boldsymbol{b}^{\mathrm{T}} \boldsymbol{a} & \boldsymbol{b}^{\mathrm{T}} \boldsymbol{b} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

R is an orthogonal matrix

$$R^{\mathrm{T}} R = R R^{\mathrm{T}} = I_{2\times 2} \quad \text{(unit matrix)}$$

Computing kinetic energy using rotation matrix

differentiating $R^{\mathrm{T}} R = I_{2\times 2}$ w.r.t time:

$$\dot{R}^{\mathrm{T}} R + R^{\mathrm{T}} \dot{R} = O_{2\times 2} \quad \text{(zero matrix)}$$

$$(R^{\mathrm{T}} \dot{R})^{\mathrm{T}} + (R^{\mathrm{T}} \dot{R}) = O_{2\times 2}$$

$R^{\mathrm{T}} \dot{R}$ is a skew-symmetric matrix:

$$R^{\mathrm{T}} \dot{R} = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}$$

$$\begin{aligned} (R^{\mathrm{T}} \dot{R})^{\mathrm{T}} (R^{\mathrm{T}} \dot{R}) &= \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} = \begin{bmatrix} \omega^2 & 0 \\ 0 & \omega^2 \end{bmatrix} \\ &= \omega^2 \, I_{2\times 2} \end{aligned}$$

Computing kinetic energy using rotation matrix

differentiating $\boldsymbol{x} = R \boldsymbol{\xi}$ with respect to time:

$$\dot{\boldsymbol{x}} = \dot{R} \boldsymbol{\xi}$$

quadratic form:

$$\begin{aligned} \dot{\boldsymbol{x}}^{\mathrm{T}} \dot{\boldsymbol{x}} &= \boldsymbol{\xi}^{\mathrm{T}} \dot{R}^{\mathrm{T}} \dot{R} \boldsymbol{\xi} \;=\; \boldsymbol{\xi}^{\mathrm{T}} \dot{R}^{\mathrm{T}} R R^{\mathrm{T}} \dot{R} \boldsymbol{\xi} \\ &= \boldsymbol{\xi}^{\mathrm{T}} \, (R^{\mathrm{T}} \dot{R})^{\mathrm{T}} (R^{\mathrm{T}} \dot{R}) \, \boldsymbol{\xi} \;=\; \boldsymbol{\xi}^{\mathrm{T}} \, \omega^2 I_{2\times 2} \, \boldsymbol{\xi} \\ &= \omega^2 \, \boldsymbol{\xi}^{\mathrm{T}} \boldsymbol{\xi} \end{aligned}$$

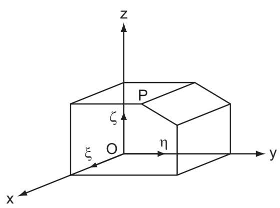
kinetic energy of a rigid body:

$$T = \sum_i \frac{1}{2} m_i \, \dot{\boldsymbol{x}}_i^{\mathrm{T}} \dot{\boldsymbol{x}}_i \;=\; \sum_i \frac{1}{2} m_i \, \omega^2 \, \boldsymbol{\xi}_i^{\mathrm{T}} \boldsymbol{\xi}_i \;=\; \frac{1}{2} J \omega^2$$

where

$$J = \sum_i m_i \, \boldsymbol{\xi}_i^{\mathrm{T}} \boldsymbol{\xi}_i = \sum_i m_i \, (\xi_i^2 + \eta_i^2)$$

Spatial and object coordinate systems



$O - xyz$ spatial coordinate system
$O - \xi\eta\zeta$ object coordinate system

$\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$ unit vectors along ξ-, η-, and ζ axes

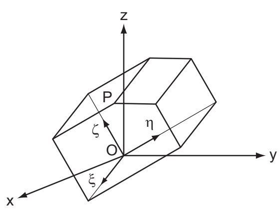
$\boldsymbol{a}^{\mathrm{T}} \boldsymbol{a} = \boldsymbol{b}^{\mathrm{T}} \boldsymbol{b} = \boldsymbol{c}^{\mathrm{T}} \boldsymbol{c} = 1$
$\boldsymbol{a}^{\mathrm{T}} \boldsymbol{b} = \boldsymbol{b}^{\mathrm{T}} \boldsymbol{c} = \boldsymbol{c}^{\mathrm{T}} \boldsymbol{a} = 0$

ξ, η, ζ: object coordinates of point P spatial coordinates of point P

$$\boldsymbol{x} = \xi \boldsymbol{a} + \eta \boldsymbol{b} + \zeta \boldsymbol{c} = \underbrace{\begin{bmatrix} \boldsymbol{a} & \boldsymbol{b} & \boldsymbol{c} \end{bmatrix}}_{R} \underbrace{\begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix}}_{\boldsymbol{\xi}} = R \boldsymbol{\xi}$$

Note: $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$ depend on time. ξ, η, ζ are independent of time.

Spatial and object coordinate systems



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Note: $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$ depend on time. ξ, η, ζ are independent of time.

Angular velocity vector in spatial rotation

rotation matrix R

$$R^{\mathrm{T}}R = \begin{bmatrix} \boldsymbol{a}^{\mathrm{T}} \\ \boldsymbol{b}^{\mathrm{T}} \\ \boldsymbol{c}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \boldsymbol{a} & \boldsymbol{b} & \boldsymbol{c} \end{bmatrix} = I_{3\times 3} \quad \text{(unit matrix)}$$

R is an orthogonal matrix

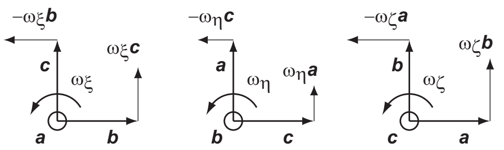
differentiating $R^{\mathrm{T}}R = I_{3\times 3}$ w.r.t time:

$$\dot{R}^{\mathrm{T}}R + R^{\mathrm{T}}\dot{R} = (R^{\mathrm{T}}\dot{R})^{\mathrm{T}} + (R^{\mathrm{T}}\dot{R}) = O_{3\times 3} \quad \text{(zero matrix)}$$

$R^{\mathrm{T}}\dot{R}$ is a skew-symmetric matrix:

$$R^{\mathrm{T}}\dot{R} = \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \\ \omega_\zeta & 0 & -\omega_\xi \\ -\omega_\eta & \omega_\xi & 0 \end{bmatrix}$$

Angular velocity vector in spatial rotation



$$\omega_\xi = \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}} \qquad \omega_\eta = \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}} \qquad \omega_\zeta = \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}}$$

$$R^{\mathrm{T}}\dot{R} = \begin{bmatrix} \boldsymbol{a}^{\mathrm{T}} \\ \boldsymbol{b}^{\mathrm{T}} \\ \boldsymbol{c}^{\mathrm{T}} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{a}} & \dot{\boldsymbol{b}} & \dot{\boldsymbol{c}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{a}} & \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{b}} & \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}} \\ \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}} & \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{b}} & \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{c}} \\ \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{a}} & \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}} & \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{c}} \end{bmatrix}$$

$$\begin{aligned} \dot{\boldsymbol{a}} &= (\boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{a}})\boldsymbol{a} + (\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}})\boldsymbol{b} + (\boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{a}})\boldsymbol{c} &= \omega_\zeta\boldsymbol{b} - \omega_\eta\boldsymbol{c} \\ \dot{\boldsymbol{b}} &= (\boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{b}})\boldsymbol{a} + (\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{b}})\boldsymbol{b} + (\boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}})\boldsymbol{c} &= \omega_\xi\boldsymbol{c} - \omega_\zeta\boldsymbol{a} \\ \dot{\boldsymbol{c}} &= (\boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}})\boldsymbol{a} + (\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{c}})\boldsymbol{b} + (\boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{c}})\boldsymbol{c} &= \omega_\eta\boldsymbol{a} - \omega_\xi\boldsymbol{b} \end{aligned}$$

Angular velocity vector in spatial rotation

angular velocity vector:

$$\boldsymbol{\omega} \triangleq \begin{bmatrix} \omega_\xi \\ \omega_\eta \\ \omega_\zeta \end{bmatrix}$$

Note that $\boldsymbol{\omega}$ is defined on object coordinate system.

$$\begin{aligned} (R^{\mathrm{T}}\dot{R})\,\boldsymbol{\xi} &= \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \\ \omega_\zeta & 0 & -\omega_\xi \\ -\omega_\eta & \omega_\xi & 0 \end{bmatrix} \begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} = \begin{bmatrix} \omega_\eta\zeta - \omega_\zeta\eta \\ \omega_\zeta\xi - \omega_\xi\zeta \\ \omega_\xi\eta - \omega_\eta\xi \end{bmatrix} \\ &= \begin{bmatrix} \omega_\xi \\ \omega_\eta \\ \omega_\zeta \end{bmatrix} \times \begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} = \boldsymbol{\omega} \times \boldsymbol{\xi} \end{aligned}$$

Computing kinetic energy in spacial rotation

differentiating $\boldsymbol{x} = R\boldsymbol{\xi}$ with respect to time:

$$\dot{\boldsymbol{x}} = \dot{R}\boldsymbol{\xi}$$

quadratic form:

$$\begin{aligned} \dot{\boldsymbol{x}}^{\mathrm{T}}\dot{\boldsymbol{x}} &= \boldsymbol{\xi}^{\mathrm{T}}\dot{R}^{\mathrm{T}}\dot{R}\boldsymbol{\xi} = \boldsymbol{\xi}^{\mathrm{T}}\dot{R}^{\mathrm{T}}RR^{\mathrm{T}}\dot{R}\boldsymbol{\xi} \\ &= (\boldsymbol{\omega}\times\boldsymbol{\xi})^{\mathrm{T}}(\boldsymbol{\omega}\times\boldsymbol{\xi}) = (-\boldsymbol{\xi}\times\boldsymbol{\omega})^{\mathrm{T}}(-\boldsymbol{\xi}\times\boldsymbol{\omega}) \\ &= (\boldsymbol{\xi}\times\boldsymbol{\omega})^{\mathrm{T}}(\boldsymbol{\xi}\times\boldsymbol{\omega}) = ([\,\boldsymbol{\xi}\times\,]\,\boldsymbol{\omega})^{\mathrm{T}}([\,\boldsymbol{\xi}\times\,]\,\boldsymbol{\omega}) \\ &= \boldsymbol{\omega}^{\mathrm{T}}\,[\,\boldsymbol{\xi}\times\,]^{\mathrm{T}}\,[\,\boldsymbol{\xi}\times\,]\,\boldsymbol{\omega} \end{aligned}$$

where

$$[\,\boldsymbol{\xi}\times\,] \triangleq \begin{bmatrix} 0 & -\zeta & \eta \\ \zeta & 0 & -\xi \\ -\eta & \xi & 0 \end{bmatrix}$$

Computing kinetic energy in spacial rotation

$$\begin{aligned} [\,\boldsymbol{\xi}\times\,]^{\mathrm{T}}[\,\boldsymbol{\xi}\times\,] &= \begin{bmatrix} 0 & \zeta & -\eta \\ -\zeta & 0 & \xi \\ \eta & -\xi & 0 \end{bmatrix} \begin{bmatrix} 0 & -\zeta & \eta \\ \zeta & 0 & -\xi \\ -\eta & \xi & 0 \end{bmatrix} \\ &= \begin{bmatrix} \eta^2+\zeta^2 & -\xi\eta & -\xi\zeta \\ -\eta\xi & \zeta^2+\xi^2 & -\eta\zeta \\ -\zeta\xi & -\zeta\eta & \xi^2+\eta^2 \end{bmatrix} \end{aligned}$$

kinetic energy of a rigid body:

$$\begin{aligned} T &= \sum_i \frac{1}{2} m_i\,\dot{\boldsymbol{x}}_i^{\mathrm{T}}\dot{\boldsymbol{x}}_i = \sum_i \frac{1}{2} m_i\,\boldsymbol{\omega}^{\mathrm{T}}\,[\,\boldsymbol{\xi}_i\times\,]^{\mathrm{T}}\,[\,\boldsymbol{\xi}_i\times\,]\,\boldsymbol{\omega} \\ &= \frac{1}{2}\,\boldsymbol{\omega}^{\mathrm{T}} J\,\boldsymbol{\omega} \end{aligned}$$

Computing kinetic energy in spacial rotation

inertia matrix

$$J \triangleq \sum_i m_i\,[\,\boldsymbol{\xi}_i\times\,]^{\mathrm{T}}\,[\,\boldsymbol{\xi}_i\times\,] = \begin{bmatrix} J_\xi & J_{\xi\eta} & J_{\zeta\xi} \\ J_{\xi\eta} & J_\eta & J_{\eta\zeta} \\ J_{\zeta\xi} & J_{\eta\zeta} & J_\zeta \end{bmatrix}$$

where

$$J_\xi = \sum_i m_i\,(\eta_i^2+\zeta_i^2), \quad J_\eta = \sum_i m_i\,(\zeta_i^2+\xi_i^2),$$

$$J_\zeta = \sum_i m_i\,(\xi_i^2+\eta_i^2),$$

$$J_{\xi\eta} = -\sum_i m_i\,\xi_i\eta_i, \quad J_{\eta\zeta} = -\sum_i m_i\,\eta_i\zeta_i, \quad J_{\zeta\xi} = -\sum_i m_i\,\zeta_i\xi_i$$

Note: inertia matrix is constant (independent of time)

Lagrange equation of spatial rotation

generalized coordinates describing spatial rotation:

$$\boldsymbol{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}, \quad \boldsymbol{b} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}, \quad \boldsymbol{c} = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix}$$

under geometric constraints:

$$R_1 = \boldsymbol{a}^{\mathrm{T}}\boldsymbol{a} - 1 = 0, \quad R_2 = \boldsymbol{b}^{\mathrm{T}}\boldsymbol{b} - 1 = 0, \quad R_3 = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{c} - 1 = 0,$$
$$Q_1 = \boldsymbol{b}^{\mathrm{T}}\boldsymbol{c} = 0, \quad Q_2 = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{a} = 0, \quad Q_3 = \boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = 0$$

kinetic energy

$$T = \frac{1}{2}\,\boldsymbol{\omega}^{\mathrm{T}} J\,\boldsymbol{\omega}$$

where

$$\omega_\xi = \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}}, \quad \omega_\eta = \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}}, \quad \omega_\zeta = \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}}$$

Lagrange equation of spatial rotation

Lagrangian

$$L = T + \lambda_1 R_1 + \lambda_2 R_2 + \lambda_3 R_3 + \mu_1 Q_1 + \mu_2 Q_2 + \mu_3 Q_3$$

(λ_1, λ_2, λ_3, μ_1, μ_2, μ_3: Lagrange multipliers)

Lagrange equations of spacial rotation

$$\frac{\partial L}{\partial \boldsymbol{a}} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{\boldsymbol{a}}} = \boldsymbol{0},$$
$$\frac{\partial L}{\partial \boldsymbol{b}} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{\boldsymbol{b}}} = \boldsymbol{0},$$
$$\frac{\partial L}{\partial \boldsymbol{c}} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{\boldsymbol{c}}} = \boldsymbol{0}$$

Computing Lagrange equation of spatial rotation

kinetic energy

$$T = \frac{1}{2}\boldsymbol{\omega}^{\mathrm{T}} J \boldsymbol{\omega}$$

derivative

$$\frac{\mathrm{d}T}{\mathrm{d}\boldsymbol{\omega}} = J\boldsymbol{\omega}$$

$$\frac{\mathrm{d}T}{\mathrm{d}\boldsymbol{\omega}} = \begin{bmatrix} \dfrac{\partial T}{\partial \omega_\xi} \\ \dfrac{\partial T}{\partial \omega_\eta} \\ \dfrac{\partial T}{\partial \omega_\zeta} \end{bmatrix}$$

Computing Lagrange equation of spatial rotation

angular velocities

$$\omega_\xi = \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}}, \quad \omega_\eta = \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}}, \quad \omega_\zeta = \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}}$$

partial derivatives

$$\frac{\partial \omega_\xi}{\partial \boldsymbol{a}} = \mathbf{0}, \quad \frac{\partial \omega_\eta}{\partial \boldsymbol{a}} = \dot{\boldsymbol{c}}, \quad \frac{\partial \omega_\zeta}{\partial \boldsymbol{a}} = \mathbf{0}$$
$$\frac{\partial \omega_\xi}{\partial \dot{\boldsymbol{a}}} = \mathbf{0}, \quad \frac{\partial \omega_\eta}{\partial \dot{\boldsymbol{a}}} = \mathbf{0}, \quad \frac{\partial \omega_\zeta}{\partial \dot{\boldsymbol{a}}} = \boldsymbol{b}$$

Computing Lagrange equation of spatial rotation

angular velocities

$$\omega_\xi = \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}}, \quad \omega_\eta = \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}}, \quad \omega_\zeta = \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}}$$

partial derivatives

$$\frac{\partial \omega_\xi}{\partial \boldsymbol{a}} = \mathbf{0}, \quad \frac{\partial \omega_\eta}{\partial \boldsymbol{a}} = \dot{\boldsymbol{c}}, \quad \frac{\partial \omega_\zeta}{\partial \boldsymbol{a}} = \mathbf{0}, \quad \frac{\partial \omega_\xi}{\partial \dot{\boldsymbol{a}}} = \mathbf{0}, \quad \frac{\partial \omega_\eta}{\partial \dot{\boldsymbol{a}}} = \mathbf{0}, \quad \frac{\partial \omega_\zeta}{\partial \dot{\boldsymbol{a}}} = \boldsymbol{b}$$
$$\frac{\partial \omega_\xi}{\partial \boldsymbol{b}} = \mathbf{0}, \quad \frac{\partial \omega_\eta}{\partial \boldsymbol{b}} = \mathbf{0}, \quad \frac{\partial \omega_\zeta}{\partial \boldsymbol{b}} = \dot{\boldsymbol{a}}, \quad \frac{\partial \omega_\xi}{\partial \dot{\boldsymbol{b}}} = \boldsymbol{c}, \quad \frac{\partial \omega_\eta}{\partial \dot{\boldsymbol{b}}} = \mathbf{0}, \quad \frac{\partial \omega_\zeta}{\partial \dot{\boldsymbol{b}}} = \mathbf{0}$$
$$\frac{\partial \omega_\xi}{\partial \boldsymbol{c}} = \dot{\boldsymbol{b}}, \quad \frac{\partial \omega_\eta}{\partial \boldsymbol{c}} = \mathbf{0}, \quad \frac{\partial \omega_\zeta}{\partial \boldsymbol{c}} = \mathbf{0}, \quad \frac{\partial \omega_\xi}{\partial \dot{\boldsymbol{c}}} = \mathbf{0}, \quad \frac{\partial \omega_\eta}{\partial \dot{\boldsymbol{c}}} = \boldsymbol{a}, \quad \frac{\partial \omega_\zeta}{\partial \dot{\boldsymbol{c}}} = \mathbf{0}$$

Computing Lagrange equation of spatial rotation

dependency

$$T \leftarrow \omega_\xi, \omega_\eta, \omega_\zeta \leftarrow \boldsymbol{a}$$
$$\Downarrow$$

$$\begin{aligned}
\frac{\partial T}{\partial \boldsymbol{a}} &= \frac{\partial T}{\partial \omega_\xi}\frac{\partial \omega_\xi}{\partial \boldsymbol{a}} + \frac{\partial T}{\partial \omega_\eta}\frac{\partial \omega_\eta}{\partial \boldsymbol{a}} + \frac{\partial T}{\partial \omega_\zeta}\frac{\partial \omega_\zeta}{\partial \boldsymbol{a}} \\
&= \left[\begin{array}{c|c|c} \dfrac{\partial \omega_\xi}{\partial \boldsymbol{a}} & \dfrac{\partial \omega_\eta}{\partial \boldsymbol{a}} & \dfrac{\partial \omega_\zeta}{\partial \boldsymbol{a}} \end{array} \right] \begin{bmatrix} \dfrac{\partial T}{\partial \omega_\xi} \\ \dfrac{\partial T}{\partial \omega_\eta} \\ \dfrac{\partial T}{\partial \omega_\zeta} \end{bmatrix} \\
&= \begin{bmatrix} \mathbf{0} & \dot{\boldsymbol{c}} & \mathbf{0} \end{bmatrix} J\boldsymbol{\omega}
\end{aligned}$$

Computing Lagrange equation of spatial rotation

dependency

$$T \leftarrow \omega_\xi, \omega_\eta, \omega_\zeta \leftarrow \dot{\boldsymbol{a}}$$
$$\Downarrow$$

$$\begin{aligned}
\frac{\partial T}{\partial \dot{\boldsymbol{a}}} &= \frac{\partial T}{\partial \omega_\xi}\frac{\partial \omega_\xi}{\partial \dot{\boldsymbol{a}}} + \frac{\partial T}{\partial \omega_\eta}\frac{\partial \omega_\eta}{\partial \dot{\boldsymbol{a}}} + \frac{\partial T}{\partial \omega_\zeta}\frac{\partial \omega_\zeta}{\partial \dot{\boldsymbol{a}}} \\
&= \left[\begin{array}{c|c|c} \dfrac{\partial \omega_\xi}{\partial \dot{\boldsymbol{a}}} & \dfrac{\partial \omega_\eta}{\partial \dot{\boldsymbol{a}}} & \dfrac{\partial \omega_\zeta}{\partial \dot{\boldsymbol{a}}} \end{array} \right] \begin{bmatrix} \dfrac{\partial T}{\partial \omega_\xi} \\ \dfrac{\partial T}{\partial \omega_\eta} \\ \dfrac{\partial T}{\partial \omega_\zeta} \end{bmatrix} \\
&= \begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\boldsymbol{\omega}
\end{aligned}$$

Computing Lagrange equation of spatial rotation

partial derivative

$$\frac{\partial T}{\partial \dot{\boldsymbol{a}}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\boldsymbol{\omega}$$

time derivative:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial T}{\partial \dot{\boldsymbol{a}}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \mathbf{0} & \mathbf{0} & \dot{\boldsymbol{b}} \end{bmatrix} J\boldsymbol{\omega}$$

Computing Lagrange equation of spatial rotation

geometric constraints

$$R_1 = \boldsymbol{a}^{\mathrm{T}}\boldsymbol{a} - 1 = 0, \quad R_2 = \boldsymbol{b}^{\mathrm{T}}\boldsymbol{b} - 1 = 0, \quad R_3 = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{c} - 1 = 0,$$
$$Q_1 = \boldsymbol{b}^{\mathrm{T}}\boldsymbol{c} = 0, \quad Q_2 = \boldsymbol{c}^{\mathrm{T}}\boldsymbol{a} = 0, \quad Q_3 = \boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = 0$$

partial derivatives

$$\frac{\partial R_1}{\partial \boldsymbol{a}} = 2\boldsymbol{a}, \quad \frac{\partial R_2}{\partial \boldsymbol{a}} = \mathbf{0}, \quad \frac{\partial R_3}{\partial \boldsymbol{a}} = \mathbf{0}$$
$$\frac{\partial Q_1}{\partial \boldsymbol{a}} = \mathbf{0}, \quad \frac{\partial Q_2}{\partial \boldsymbol{a}} = \boldsymbol{c}, \quad \frac{\partial Q_3}{\partial \boldsymbol{a}} = \boldsymbol{b}$$

Computing Lagrange equation of spatial rotation

contributions to Lagrange equation of motion w.r.t. $\boldsymbol{a}$:

$$\begin{aligned}
\frac{\partial L}{\partial \boldsymbol{a}} &= \frac{\partial T}{\partial \boldsymbol{a}} + \lambda_1\frac{\partial R_1}{\partial \boldsymbol{a}} + \cdots + \mu_3\frac{\partial Q_3}{\partial \boldsymbol{a}} \\
&= \begin{bmatrix} \mathbf{0} & \dot{\boldsymbol{c}} & \mathbf{0} \end{bmatrix} J\boldsymbol{\omega} + 2\lambda_1\boldsymbol{a} + \mu_2\boldsymbol{c} + \mu_3\boldsymbol{b} \\
\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{\boldsymbol{a}}} &= \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial T}{\partial \dot{\boldsymbol{a}}} \\
&= \begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \mathbf{0} & \mathbf{0} & \dot{\boldsymbol{b}} \end{bmatrix} J\boldsymbol{\omega}
\end{aligned}$$

Lagrange equation of motion w.r.t. $\boldsymbol{a}$:

$$\begin{bmatrix} \mathbf{0} & \dot{\boldsymbol{c}} & \mathbf{0} \end{bmatrix} J\boldsymbol{\omega} - \begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\dot{\boldsymbol{\omega}} - \begin{bmatrix} \mathbf{0} & \mathbf{0} & \dot{\boldsymbol{b}} \end{bmatrix} J\boldsymbol{\omega}$$
$$+2\lambda_1\boldsymbol{a} + \mu_2\boldsymbol{c} + \mu_3\boldsymbol{b} = \mathbf{0}$$

Computing Lagrange equation of spatial rotation

Lagrange equation of motion w.r.t. $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$:

$$\begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \mathbf{0} & -\dot{\boldsymbol{c}} & \dot{\boldsymbol{b}} \end{bmatrix} J\boldsymbol{\omega} - 2\lambda_1 \boldsymbol{a} - \mu_2 \boldsymbol{c} - \mu_3 \boldsymbol{b} = \mathbf{0}$$
$$\begin{bmatrix} \boldsymbol{c} & \mathbf{0} & \mathbf{0} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \dot{\boldsymbol{c}} & \mathbf{0} & -\dot{\boldsymbol{a}} \end{bmatrix} J\boldsymbol{\omega} - 2\lambda_2 \boldsymbol{b} - \mu_3 \boldsymbol{a} - \mu_1 \boldsymbol{c} = \mathbf{0}$$
$$\begin{bmatrix} \mathbf{0} & \boldsymbol{a} & \mathbf{0} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} -\dot{\boldsymbol{b}} & \dot{\boldsymbol{a}} & \mathbf{0} \end{bmatrix} J\boldsymbol{\omega} - 2\lambda_3 \boldsymbol{c} - \mu_1 \boldsymbol{b} - \mu_2 \boldsymbol{a} = \mathbf{0}$$

$\boldsymbol{c}^{\mathrm{T}}$(2nd eq.) (note: $\boldsymbol{c}^{\mathrm{T}}\boldsymbol{c} = 1$, $\boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{c}} = 0$, and $-\boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{a}} = \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}} = \omega_\eta$)

$$\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} 0 & 0 & \omega_\eta \end{bmatrix} J\boldsymbol{\omega} - \mu_1 = 0$$

$\boldsymbol{b}^{\mathrm{T}}$(3rd eq.) (note: $\boldsymbol{b}^{\mathrm{T}}\boldsymbol{a} = 0$, $\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{b}} = 0$, and $\boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}} = \omega_\zeta$)

$$\begin{bmatrix} 0 & 0 & 0 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} 0 & \omega_\zeta & 0 \end{bmatrix} J\boldsymbol{\omega} - \mu_1 = 0$$

$\boldsymbol{c}^{\mathrm{T}}$(2nd eq.) $-$ $\boldsymbol{b}^{\mathrm{T}}$(3rd eq.)

$$\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \end{bmatrix} J\boldsymbol{\omega} = 0$$

Computing Lagrange equation of spatial rotation

$\boldsymbol{c}^{\mathrm{T}}$(2nd eq.) $-$ $\boldsymbol{b}^{\mathrm{T}}$(3rd eq.)

$$\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \end{bmatrix} J\boldsymbol{\omega} = 0$$

$\boldsymbol{a}^{\mathrm{T}}$(3rd eq.) $-$ $\boldsymbol{c}^{\mathrm{T}}$(1st eq.)

$$\begin{bmatrix} 0 & 1 & 0 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \omega_\zeta & 0 & -\omega_\xi \end{bmatrix} J\boldsymbol{\omega} = 0$$

$\boldsymbol{b}^{\mathrm{T}}$(1st eq.) $-$ $\boldsymbol{a}^{\mathrm{T}}$(2nd eq.)

$$\begin{bmatrix} 0 & 0 & 1 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} -\omega_\eta & \omega_\xi & 0 \end{bmatrix} J\boldsymbol{\omega} = 0$$

Euler's equation of rotation

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \\ \omega_\zeta & 0 & -\omega_\xi \\ -\omega_\eta & \omega_\xi & 0 \end{bmatrix} J\boldsymbol{\omega} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$
$$J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \boldsymbol{\omega}\times \end{bmatrix} J\boldsymbol{\omega} = \mathbf{0}$$

Euler's equation of rotation

$$J\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times J\boldsymbol{\omega} = \mathbf{0}$$

Dynamic equations describing spacial rotation

12 state variables

$$\boldsymbol{\omega} = \begin{bmatrix} \omega_\xi \\ \omega_\eta \\ \omega_\zeta \end{bmatrix}, \quad \boldsymbol{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}, \quad \boldsymbol{b} = \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}, \quad \boldsymbol{c} = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix}$$

12 equations (6 differential eqs. and 6 algebraic eqs.)

$$J\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega} \times J\boldsymbol{\omega},$$
$$\boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}} = \omega_\xi, \quad \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}} = \omega_\eta, \quad \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}} = \omega_\zeta,$$
$$\boldsymbol{a}^{\mathrm{T}}\boldsymbol{a} = 1, \quad \boldsymbol{b}^{\mathrm{T}}\boldsymbol{b} = 1, \quad \boldsymbol{c}^{\mathrm{T}}\boldsymbol{c} = 1,$$
$$\boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = 0, \quad \boldsymbol{b}^{\mathrm{T}}\boldsymbol{c} = 0, \quad \boldsymbol{c}^{\mathrm{T}}\boldsymbol{a} = 0$$

Lagrange equation of forced spatial rotation

external force $\boldsymbol{f}$ is applied to point $\mathrm{P}(\xi, \eta, \zeta)$:

$$W = \boldsymbol{f}^{\mathrm{T}} R\boldsymbol{\xi} \qquad (R\boldsymbol{\xi} \text{ denotes displacement vector of point P})$$

$$\frac{\partial W}{\partial a_x} = \boldsymbol{f}^{\mathrm{T}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \boldsymbol{\xi} = \boldsymbol{f}^{\mathrm{T}} \begin{bmatrix} \xi \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \xi & 0 & 0 \end{bmatrix} \boldsymbol{f}$$
$$\frac{\partial W}{\partial a_y} = \boldsymbol{f}^{\mathrm{T}} \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \boldsymbol{\xi} = \boldsymbol{f}^{\mathrm{T}} \begin{bmatrix} 0 \\ \xi \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & \xi & 0 \end{bmatrix} \boldsymbol{f}$$
$$\frac{\partial W}{\partial a_z} = \boldsymbol{f}^{\mathrm{T}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \boldsymbol{\xi} = \boldsymbol{f}^{\mathrm{T}} \begin{bmatrix} 0 \\ 0 \\ \xi \end{bmatrix} = \begin{bmatrix} 0 & 0 & \xi \end{bmatrix} \boldsymbol{f}$$
$$\Longrightarrow \quad \frac{\partial W}{\partial \boldsymbol{a}} = \xi \boldsymbol{f}$$

Lagrange equation of forced spatial rotation

partial derivatives of W w.r.t. $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{c}$:

$$\frac{\partial W}{\partial \boldsymbol{a}} = \xi \boldsymbol{f}, \quad \frac{\partial W}{\partial \boldsymbol{b}} = \eta \boldsymbol{f}, \quad \frac{\partial W}{\partial \boldsymbol{c}} = \zeta \boldsymbol{f}$$

Lagrangian

$$L = T + \lambda_1 R_1 + \lambda_2 R_2 + \lambda_3 R_3 + \mu_1 Q_1 + \mu_2 Q_2 + \mu_3 Q_3 + W$$

Lagrange equation of motion w.r.t. $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{c}$:

$$\begin{bmatrix} \mathbf{0} & \mathbf{0} & \boldsymbol{b} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \mathbf{0} & -\dot{\boldsymbol{c}} & \dot{\boldsymbol{b}} \end{bmatrix} J\boldsymbol{\omega} - 2\lambda_1 \boldsymbol{a} - \mu_2 \boldsymbol{c} - \mu_3 \boldsymbol{b} = \xi \boldsymbol{f}$$
$$\begin{bmatrix} \boldsymbol{c} & \mathbf{0} & \mathbf{0} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} \dot{\boldsymbol{c}} & \mathbf{0} & -\dot{\boldsymbol{a}} \end{bmatrix} J\boldsymbol{\omega} - 2\lambda_2 \boldsymbol{b} - \mu_3 \boldsymbol{a} - \mu_1 \boldsymbol{c} = \eta \boldsymbol{f}$$
$$\begin{bmatrix} \mathbf{0} & \boldsymbol{a} & \mathbf{0} \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} -\dot{\boldsymbol{b}} & \dot{\boldsymbol{a}} & \mathbf{0} \end{bmatrix} J\boldsymbol{\omega} - 2\lambda_3 \boldsymbol{c} - \mu_1 \boldsymbol{b} - \mu_2 \boldsymbol{a} = \zeta \boldsymbol{f}$$

Lagrange equation of forced spatial rotation

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} J\dot{\boldsymbol{\omega}} + \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \\ \omega_\zeta & 0 & -\omega_\xi \\ -\omega_\eta & \omega_\xi & 0 \end{bmatrix} J\boldsymbol{\omega} = \begin{bmatrix} \eta \boldsymbol{c}^{\mathrm{T}}\boldsymbol{f} - \zeta \boldsymbol{b}^{\mathrm{T}}\boldsymbol{f} \\ \zeta \boldsymbol{a}^{\mathrm{T}}\boldsymbol{f} - \xi \boldsymbol{c}^{\mathrm{T}}\boldsymbol{f} \\ \xi \boldsymbol{b}^{\mathrm{T}}\boldsymbol{f} - \eta \boldsymbol{a}^{\mathrm{T}}\boldsymbol{f} \end{bmatrix}$$

external torque:

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_\xi \\ \tau_\eta \\ \tau_\zeta \end{bmatrix} \triangleq \begin{bmatrix} \eta \boldsymbol{c}^{\mathrm{T}}\boldsymbol{f} - \zeta \boldsymbol{b}^{\mathrm{T}}\boldsymbol{f} \\ \zeta \boldsymbol{a}^{\mathrm{T}}\boldsymbol{f} - \xi \boldsymbol{c}^{\mathrm{T}}\boldsymbol{f} \\ \xi \boldsymbol{b}^{\mathrm{T}}\boldsymbol{f} - \eta \boldsymbol{a}^{\mathrm{T}}\boldsymbol{f} \end{bmatrix} = \begin{bmatrix} \eta f_\zeta - \zeta f_\eta \\ \zeta f_\xi - \xi f_\zeta \\ \xi f_\eta - \eta f_\xi \end{bmatrix} = \begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix} \times \begin{bmatrix} f_\xi \\ f_\eta \\ f_\zeta \end{bmatrix}$$

Euler's equation of rotation with external torque

$$J\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times J\boldsymbol{\omega} = \boldsymbol{\tau}$$

Rotation matrix using quaternion

Definition of quaternion

$$\boldsymbol{q} = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

where

$$\boldsymbol{q}^{\mathrm{T}}\boldsymbol{q} = q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1$$

Rotation matrix using quaternion

$$R(\boldsymbol{q}) = \begin{bmatrix} 2(q_0^2 + q_1^2) - 1 & 2(q_1 q_2 - q_0 q_3) & 2(q_1 q_3 + q_0 q_2) \\ 2(q_1 q_2 + q_0 q_3) & 2(q_0^2 + q_2^2) - 1 & 2(q_2 q_3 - q_0 q_1) \\ 2(q_1 q_3 - q_0 q_2) & 2(q_2 q_3 + q_0 q_1) & 2(q_0^2 + q_3^2) - 1 \end{bmatrix}$$

Describing column vectors of rotation matrix

column vectors $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{c}$ of rotation matrix $R(\boldsymbol{q})$:

$$\boldsymbol{a} = \begin{bmatrix} 2(q_0^2+q_1^2)-1 \\ 2(q_1q_2+q_0q_3) \\ 2(q_1q_3-q_0q_2) \end{bmatrix} = \begin{bmatrix} q_0 & q_1 & -q_2 & -q_3 \\ q_3 & q_2 & q_1 & q_0 \\ -q_2 & q_3 & -q_0 & q_1 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \triangleq A\boldsymbol{q}$$

$$\boldsymbol{b} = \begin{bmatrix} 2(q_1q_2-q_0q_3) \\ 2(q_0^2+q_2^2)-1 \\ 2(q_2q_3+q_0q_1) \end{bmatrix} = \begin{bmatrix} -q_3 & q_2 & q_1 & -q_0 \\ q_0 & -q_1 & q_2 & -q_3 \\ q_1 & q_0 & q_3 & q_2 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \triangleq B\boldsymbol{q}$$

$$\boldsymbol{c} = \begin{bmatrix} 2(q_1q_3+q_0q_2) \\ 2(q_2q_3-q_0q_1) \\ 2(q_0^2+q_3^2)-1 \end{bmatrix} = \begin{bmatrix} q_2 & q_3 & q_0 & q_1 \\ -q_1 & -q_0 & q_3 & q_2 \\ q_0 & -q_1 & -q_2 & q_3 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \triangleq C\boldsymbol{q}$$

Describing column vectors of rotation matrix

$$A^{\mathrm{T}}A = \begin{bmatrix} 1-q_1^2 & q_0q_1 & q_1q_3 & -q_1q_2 \\ q_0q_1 & 1-q_0^2 & -q_0q_3 & q_0q_2 \\ q_1q_3 & -q_0q_3 & 1-q_3^2 & q_2q_3 \\ -q_1q_2 & q_0q_2 & q_2q_3 & 1-q_2^2 \end{bmatrix}, \quad (A^{\mathrm{T}}A)\boldsymbol{q} = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

$$B^{\mathrm{T}}B = \begin{bmatrix} 1-q_2^2 & -q_2q_3 & q_0q_2 & q_1q_2 \\ -q_2q_3 & 1-q_3^2 & q_0q_3 & q_1q_3 \\ q_0q_2 & q_0q_3 & 1-q_0^2 & -q_0q_1 \\ q_1q_2 & q_1q_3 & -q_0q_1 & 1-q_1^2 \end{bmatrix}, \quad (B^{\mathrm{T}}B)\boldsymbol{q} = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

$$C^{\mathrm{T}}C = \begin{bmatrix} 1-q_3^2 & q_2q_3 & -q_1q_3 & q_0q_3 \\ q_2q_3 & 1-q_2^2 & q_1q_2 & -q_0q_2 \\ -q_1q_3 & q_1q_2 & 1-q_1^2 & q_0q_1 \\ q_0q_3 & -q_0q_2 & q_0q_1 & 1-q_0^2 \end{bmatrix}, \quad (C^{\mathrm{T}}C)\boldsymbol{q} = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

Describing column vectors of rotation matrix

$$A^{\mathrm{T}}B = \begin{bmatrix} -q_1q_2 & -q_1q_3 & q_0q_1 & q_1^2-1 \\ q_0q_2 & q_0q_3 & 1-q_0^2 & -q_0q_1 \\ q_2q_3 & q_3^2-1 & -q_0q_3 & -q_1q_3 \\ 1-q_2^2 & -q_2q_3 & q_0q_2 & q_1q_2 \end{bmatrix}, \quad (A^{\mathrm{T}}B)\boldsymbol{q} = \begin{bmatrix} -q_3 \\ q_2 \\ -q_1 \\ q_0 \end{bmatrix}$$

$$B^{\mathrm{T}}C = \begin{bmatrix} -q_2q_3 & q_2^2-1 & -q_1q_2 & q_0q_2 \\ 1-q_3^2 & q_2q_3 & -q_1q_3 & q_0q_3 \\ q_0q_3 & -q_0q_2 & q_0q_1 & 1-q_0^2 \\ q_1q_3 & -q_1q_2 & q_1^2-1 & -q_0q_1 \end{bmatrix}, \quad (B^{\mathrm{T}}C)\boldsymbol{q} = \begin{bmatrix} -q_1 \\ q_0 \\ q_3 \\ -q_2 \end{bmatrix}$$

$$C^{\mathrm{T}}A = \begin{bmatrix} -q_1q_3 & q_0q_3 & q_3^2-1 & -q_2q_3 \\ q_1q_2 & -q_0q_2 & -q_2q_3 & q_2^2-1 \\ 1-q_1^2 & q_0q_1 & q_1q_3 & -q_1q_2 \\ q_0q_1 & 1-q_0^2 & -q_0q_3 & q_0q_2 \end{bmatrix}, \quad (C^{\mathrm{T}}A)\boldsymbol{q} = \begin{bmatrix} -q_2 \\ -q_3 \\ q_0 \\ q_1 \end{bmatrix}$$

Describing column vectors of rotation matrix

$$\boldsymbol{a}^{\mathrm{T}}\boldsymbol{a} = (A\boldsymbol{q})^{\mathrm{T}}(A\boldsymbol{q}) = \boldsymbol{q}^{\mathrm{T}}A^{\mathrm{T}}A\boldsymbol{q} = \boldsymbol{q}^{\mathrm{T}}\boldsymbol{q} = 1$$

$$\boldsymbol{b}^{\mathrm{T}}\boldsymbol{b} = (B\boldsymbol{q})^{\mathrm{T}}(B\boldsymbol{q}) = \boldsymbol{q}^{\mathrm{T}}B^{\mathrm{T}}B\boldsymbol{q} = \boldsymbol{q}^{\mathrm{T}}\boldsymbol{q} = 1$$

...

$$\boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = (A\boldsymbol{q})^{\mathrm{T}}(B\boldsymbol{q}) = \boldsymbol{q}^{\mathrm{T}}A^{\mathrm{T}}B\boldsymbol{q} = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \end{bmatrix} \begin{bmatrix} -q_3 \\ q_2 \\ -q_1 \\ q_0 \end{bmatrix} = 0$$

$$\boldsymbol{b}^{\mathrm{T}}\boldsymbol{c} = (B\boldsymbol{q})^{\mathrm{T}}(C\boldsymbol{q}) = \boldsymbol{q}^{\mathrm{T}}B^{\mathrm{T}}C\boldsymbol{q} = \begin{bmatrix} q_0 & q_1 & q_2 & q_3 \end{bmatrix} \begin{bmatrix} -q_1 \\ q_0 \\ q_3 \\ -q_2 \end{bmatrix} = 0$$

...

Describing column vectors of rotation matrix

Assume that $\boldsymbol{q}$ depends on time.
time derivative of quaternion:

$$\dot{\boldsymbol{q}} = \begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix}$$

Note that matrices $R(\boldsymbol{q})$, A, B, and C depend on time.

Describing angular velocity vector using quaternion

time derivatives of column vectors $\boldsymbol{a}$, $\boldsymbol{b}$, and $\boldsymbol{c}$:

$$\begin{aligned} \dot{\boldsymbol{a}} &= \dot{A}\boldsymbol{q} + A\dot{\boldsymbol{q}} = A\dot{\boldsymbol{q}} + A\dot{\boldsymbol{q}} &= 2A\dot{\boldsymbol{q}} \\ \dot{\boldsymbol{b}} &= \dot{B}\boldsymbol{q} + B\dot{\boldsymbol{q}} = B\dot{\boldsymbol{q}} + B\dot{\boldsymbol{q}} &= 2B\dot{\boldsymbol{q}} \\ \dot{\boldsymbol{c}} &= \dot{C}\boldsymbol{q} + C\dot{\boldsymbol{q}} = C\dot{\boldsymbol{q}} + C\dot{\boldsymbol{q}} &= 2C\dot{\boldsymbol{q}} \end{aligned}$$

angular velocities:

$$\begin{aligned} \omega_\xi &= \boldsymbol{c}^{\mathrm{T}}\dot{\boldsymbol{b}} &= \boldsymbol{q}^{\mathrm{T}}C^{\mathrm{T}}2B\dot{\boldsymbol{q}} &= 2(B^{\mathrm{T}}C\boldsymbol{q})^{\mathrm{T}}\dot{\boldsymbol{q}} \\ \omega_\eta &= \boldsymbol{a}^{\mathrm{T}}\dot{\boldsymbol{c}} &= \boldsymbol{q}^{\mathrm{T}}A^{\mathrm{T}}2C\dot{\boldsymbol{q}} &= 2(C^{\mathrm{T}}A\boldsymbol{q})^{\mathrm{T}}\dot{\boldsymbol{q}} \\ \omega_\zeta &= \boldsymbol{b}^{\mathrm{T}}\dot{\boldsymbol{a}} &= \boldsymbol{q}^{\mathrm{T}}B^{\mathrm{T}}2A\dot{\boldsymbol{q}} &= 2(A^{\mathrm{T}}B\boldsymbol{q})^{\mathrm{T}}\dot{\boldsymbol{q}} \end{aligned}$$

Describing angular velocity vector using quaternion

angular velocities:

$$\begin{aligned} \omega_\xi &= 2\begin{bmatrix} -q_1 & q_0 & q_3 & -q_2 \end{bmatrix}\dot{\boldsymbol{q}} \\ \omega_\eta &= 2\begin{bmatrix} -q_2 & -q_3 & q_0 & q_1 \end{bmatrix}\dot{\boldsymbol{q}} \\ \omega_\zeta &= 2\begin{bmatrix} -q_3 & q_2 & -q_1 & q_0 \end{bmatrix}\dot{\boldsymbol{q}} \end{aligned}$$

angular velocity vector

$$\boldsymbol{\omega} = 2H\dot{\boldsymbol{q}}$$

where

$$H \triangleq \begin{bmatrix} -q_1 & q_0 & q_3 & -q_2 \\ -q_2 & -q_3 & q_0 & q_1 \\ -q_3 & q_2 & -q_1 & q_0 \end{bmatrix}$$

Describing Lagrangian using quaternion

Lagrangian

$$L = T + \lambda_{\mathrm{quat}} Q_{\mathrm{quat}}$$

kinetic energy of a rotating rigid body:

$$T = \frac{1}{2}\boldsymbol{\omega}^{\mathrm{T}}J\boldsymbol{\omega} = \frac{1}{2}(2H\dot{\boldsymbol{q}})^{\mathrm{T}}J(2H\dot{\boldsymbol{q}}) = 2\dot{\boldsymbol{q}}^{\mathrm{T}}(H^{\mathrm{T}}JH)\dot{\boldsymbol{q}}$$

or

$$T = \frac{1}{2}\boldsymbol{\omega}^{\mathrm{T}}J\boldsymbol{\omega} = \frac{1}{2}(-2\dot{H}\boldsymbol{q})^{\mathrm{T}}J(-2\dot{H}\boldsymbol{q}) = 2\boldsymbol{q}^{\mathrm{T}}(\dot{H}^{\mathrm{T}}J\dot{H})\boldsymbol{q}$$

constraint on quaternion:

$$Q_{\mathrm{quat}} = \boldsymbol{q}^{\mathrm{T}}\boldsymbol{q} - 1$$

λ_{quat}: Lagrange multiplier

Computing Lagrange equation

partial derivatives of T w.r.t. $\dot{\boldsymbol{q}}$ and $\boldsymbol{q}$:

$$\frac{\partial T}{\partial \dot{\boldsymbol{q}}} = 4(H^{\mathrm{T}}JH)\dot{\boldsymbol{q}}, \qquad \frac{\partial T}{\partial \boldsymbol{q}} = 4(\dot{H}^{\mathrm{T}}J\dot{H})\boldsymbol{q}$$

since $\dot{H}\boldsymbol{q} = -H\dot{\boldsymbol{q}}$

$$\frac{\partial T}{\partial \boldsymbol{q}} = 4(\dot{H}^{\mathrm{T}}J)\dot{H}\boldsymbol{q} = 4(\dot{H}^{\mathrm{T}}J)(-H\dot{\boldsymbol{q}}) = -4(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}$$

time derivative of $\partial T/\partial \dot{\boldsymbol{q}}$:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial T}{\partial \dot{\boldsymbol{q}}} = 4(H^{\mathrm{T}}JH)\ddot{\boldsymbol{q}} + 4(\dot{H}^{\mathrm{T}}JH + H^{\mathrm{T}}J\dot{H})\dot{\boldsymbol{q}}$$

since $H\dot{\boldsymbol{q}} = \mathbf{0}$ yields $(H^{\mathrm{T}}J\dot{H})\dot{\boldsymbol{q}} = (H^{\mathrm{T}}J)\dot{H}\dot{\boldsymbol{q}} = \mathbf{0}$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial T}{\partial \dot{\boldsymbol{q}}} = 4(H^{\mathrm{T}}JH)\ddot{\boldsymbol{q}} + 4(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}$$

Computing Lagrange equation

contribution of kinetic energy T to Lagrange equation:

$$\begin{aligned}\frac{\partial T}{\partial \boldsymbol{q}} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial T}{\partial \dot{\boldsymbol{q}}} &= -4(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} - \left\{4(H^{\mathrm{T}}JH)\ddot{\boldsymbol{q}} + 4(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}\right\} \\ &= -4(H^{\mathrm{T}}JH)\ddot{\boldsymbol{q}} - 8(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}\end{aligned}$$

contribution of constraint Q_{quat} to Lagrange equation:

$$\frac{\partial Q_{\mathrm{quat}}}{\partial \boldsymbol{q}} - \frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial Q_{\mathrm{quat}}}{\partial \dot{\boldsymbol{q}}} = 2\boldsymbol{q}$$

Lagrange equation of motion

$$-4(H^{\mathrm{T}}JH)\ddot{\boldsymbol{q}} - 8(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} + 2\lambda_{\mathrm{quat}}\boldsymbol{q} = \mathbf{0}_4$$

Dynamic equations describing spatial rotation

multiply H to Lagrange equation of motion:

$$-4H(H^{\mathrm{T}}JH)\ddot{\boldsymbol{q}} - 8H(\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} + 2\lambda_{\mathrm{quat}}H\boldsymbol{q} = \mathbf{0}_3$$

since $HH^{\mathrm{T}} = I_{3\times 3}$ and $H\boldsymbol{q} = \mathbf{0}$:

$$JH\ddot{\boldsymbol{q}} + 2(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} = \mathbf{0}_3$$

matrix J is regular:

$$H\ddot{\boldsymbol{q}} = -2J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}$$

since $\dot{Q}_{\mathrm{quat}} = 2\boldsymbol{q}^{\mathrm{T}}\dot{\boldsymbol{q}}$ and $\ddot{Q}_{\mathrm{quat}} = 2\boldsymbol{q}^{\mathrm{T}}\ddot{\boldsymbol{q}} + 2\dot{\boldsymbol{q}}^{\mathrm{T}}\dot{\boldsymbol{q}}$, equation for stabilizing constraint $Q_{\mathrm{quat}} = 0$ is given by

$$-\boldsymbol{q}^{\mathrm{T}}\ddot{\boldsymbol{q}} = r(\boldsymbol{q}, \dot{\boldsymbol{q}})$$

where

$$r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \triangleq \dot{\boldsymbol{q}}^{\mathrm{T}}\dot{\boldsymbol{q}} + 2\nu\boldsymbol{q}^{\mathrm{T}}\dot{\boldsymbol{q}} + \frac{1}{2}\nu^2(\boldsymbol{q}^{\mathrm{T}}\boldsymbol{q} - 1) \quad (\nu\text{: positive constant})$$

Dynamic equations describing spatial rotation

differential equations:

$$\begin{aligned}-\boldsymbol{q}^{\mathrm{T}}\ddot{\boldsymbol{q}} &= r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \\ H\ddot{\boldsymbol{q}} &= -2J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}\end{aligned}$$

combining the two equations:

$$\begin{aligned}\begin{bmatrix} -\boldsymbol{q}^{\mathrm{T}} \\ H \end{bmatrix}\ddot{\boldsymbol{q}} &= \begin{bmatrix} r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \\ -2J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} \end{bmatrix} \\ \hat{H}\ddot{\boldsymbol{q}} &= \begin{bmatrix} r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \\ -2J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} \end{bmatrix}\end{aligned}$$

where

$$\hat{H} \triangleq \begin{bmatrix} -\boldsymbol{q}^{\mathrm{T}} \\ H \end{bmatrix}$$

Dynamic equations describing spatial rotation

$$\begin{aligned}\hat{H}\hat{H}^{\mathrm{T}} &= \begin{bmatrix} -\boldsymbol{q}^{\mathrm{T}} \\ H \end{bmatrix}\begin{bmatrix} -\boldsymbol{q} & H^{\mathrm{T}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{q}^{\mathrm{T}}\boldsymbol{q} & -(H\boldsymbol{q})^{\mathrm{T}} \\ -H\boldsymbol{q} & HH^{\mathrm{T}} \end{bmatrix} \\ &= \begin{bmatrix} 1 & \mathbf{0}_3^{\mathrm{T}} \\ \mathbf{0}_3 & I_{3\times 3} \end{bmatrix} = I_{4\times 4}\end{aligned}$$

matrix $\hat{H}$ is orthogonal:

$$\begin{aligned}\ddot{\boldsymbol{q}} &= \hat{H}^{\mathrm{T}}\begin{bmatrix} r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \\ -2J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} \end{bmatrix} \\ &= \begin{bmatrix} -\boldsymbol{q} & H^{\mathrm{T}} \end{bmatrix}\begin{bmatrix} r(\boldsymbol{q}, \dot{\boldsymbol{q}}) \\ -2J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}} \end{bmatrix} \\ &= -r(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{q} - 2H^{\mathrm{T}}J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}\end{aligned}$$

Dynamic equations describing spatial rotation

$$\begin{aligned}2H\dot{H}^{\mathrm{T}} &= 2\begin{bmatrix} -q_1 & q_0 & q_3 & -q_2 \\ -q_2 & -q_3 & q_0 & q_1 \\ -q_3 & q_2 & -q_1 & q_0 \end{bmatrix}\begin{bmatrix} -\dot{q}_1 & -\dot{q}_2 & -\dot{q}_3 \\ \dot{q}_0 & -\dot{q}_3 & \dot{q}_2 \\ \dot{q}_3 & \dot{q}_0 & -\dot{q}_1 \\ -\dot{q}_2 & \dot{q}_1 & \dot{q}_0 \end{bmatrix} \\ &= \begin{bmatrix} 0 & -\omega_\zeta & \omega_\eta \\ \omega_\zeta & 0 & -\omega_\xi \\ -\omega_\eta & \omega_\xi & 0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{\omega}\times \end{bmatrix} = \begin{bmatrix} (2H\dot{\boldsymbol{q}})\times \end{bmatrix}\end{aligned}$$

matrix $H\dot{H}^{\mathrm{T}}$ represents outer product with $H\dot{\boldsymbol{q}}$

$$\ddot{\boldsymbol{q}} = -r(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{q} - 2H^{\mathrm{T}}J^{-1}(H\dot{H}^{\mathrm{T}}JH)\dot{\boldsymbol{q}}$$

$$\Downarrow$$

$$\ddot{\boldsymbol{q}} = -r(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{q} - 2H^{\mathrm{T}}J^{-1}\left\{(H\dot{\boldsymbol{q}}) \times (JH\dot{\boldsymbol{q}})\right\}$$

Dynamic equations describing spatial rotation

Equation of rotation

4 generalized coordinates:

$$\boldsymbol{q} = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

4 differential equations:

$$\ddot{\boldsymbol{q}} = -r(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{q} - 2H^{\mathrm{T}}J^{-1}\left\{(H\dot{\boldsymbol{q}}) \times (JH\dot{\boldsymbol{q}})\right\}$$

Dynamic equations describing spatial rotation

Canonical form for numerical computation

$$\begin{aligned}\dot{\boldsymbol{q}} &= \boldsymbol{p} \\ \dot{\boldsymbol{p}} &= -r(\boldsymbol{q}, \boldsymbol{p})\boldsymbol{q} - 2H^{\mathrm{T}}J^{-1}\left\{(H\boldsymbol{p}) \times (JH\boldsymbol{p})\right\}\end{aligned}$$

state variable vector

$$\boldsymbol{s} = \begin{bmatrix} \boldsymbol{q} \\ \boldsymbol{p} \end{bmatrix}$$

Comparison summary

- a set of rotation matrix elements
  - 12 state variables (9 for orientation and 3 for angular velocity)
  - 12 equations (6 differential + 6 algebraic)
- quaternion
  - 4 generalized coordinates (8 state variables)
  - quadratic expressions, no trigonometric functions
  - no singularity, implying no gimbal lock or no instability
- a set of Euler angles
  - 3 generalized coordinates (6 state variables)
  - trigonometric functions
  - singularity, causing gimbal lock or instability

Lagrange equation of forced spatial rotation

$\boldsymbol{\tau}_{\rm quat} = [\,\tau_0,\ \tau_1,\ \tau_2,\ \tau_3\,]^{\rm T}$ a set of generalized torques corresponding to quaternion $\boldsymbol{q} = [\,q_0,\ q_1,\ q_2,\ q_3\,]^{\rm T}$

$$W = \boldsymbol{\tau}_{\rm quat}^{\rm T}\boldsymbol{q} = \tau_0 q_0 + \tau_1 q_1 + \tau_2 q_2 + \tau_3 q_3$$

contribution of work W to Lagrange equation:

$$\frac{\partial W}{\partial \boldsymbol{q}} - \frac{\rm d}{{\rm d}t}\frac{\partial W}{\partial \dot{\boldsymbol{q}}} = \boldsymbol{\tau}_{\rm quat}$$

Lagrange equation of motion:

$$-4(H^{\rm T}JH)\ddot{\boldsymbol{q}} - 8(\dot{H}^{\rm T}JH)\dot{\boldsymbol{q}} + 2\lambda_{\rm quat}\boldsymbol{q} + \boldsymbol{\tau}_{\rm quat} = \boldsymbol{0}_4$$

$$\ddot{\boldsymbol{q}} = -r(\boldsymbol{q},\dot{\boldsymbol{q}})\boldsymbol{q} - 2H^{\rm T}J^{-1}\left\{(H\dot{\boldsymbol{q}}) \times (JH\dot{\boldsymbol{q}}) - \frac{1}{8}H\boldsymbol{\tau}_{\rm quat}\right\}$$

Lagrange equation of forced spatial rotation

Principle of virtual works

$$\boldsymbol{\omega} = 2H\dot{\boldsymbol{q}} \quad \Rightarrow \quad \boldsymbol{\tau}_{\rm quat} = (2H)^{\rm T}\boldsymbol{\tau}$$

since $H\boldsymbol{\tau}_{\rm quat} = 2HH^{\rm T}\boldsymbol{\tau} = 2\boldsymbol{\tau}$, equation of rotation turns into:

$$\ddot{\boldsymbol{q}} = -r(\boldsymbol{q},\dot{\boldsymbol{q}})\boldsymbol{q} - 2H^{\rm T}J^{-1}\left\{(H\dot{\boldsymbol{q}}) \times (JH\dot{\boldsymbol{q}}) - \frac{1}{4}\boldsymbol{\tau}\right\}$$

Lagrange equation of forced spatial rotation

Canonical form for numerical computation

$$\dot{\boldsymbol{q}} = \boldsymbol{p}$$

$$\dot{\boldsymbol{p}} = -r(\boldsymbol{q},\boldsymbol{p})\boldsymbol{q} - 2H^{\rm T}J^{-1}\left\{(H\boldsymbol{p}) \times (JH\boldsymbol{p}) - \frac{1}{4}\boldsymbol{\tau}\right\}$$

state variable vector

$$\boldsymbol{s} = \begin{bmatrix} \boldsymbol{q} \\ \boldsymbol{p} \end{bmatrix}$$

Summary

Planar rotation

- described by angle θ and angular velocity ω
- Lagrangian formulation yields equation of planar rotation

Spatial rotation

- described by rotation matrix R under geometric constraints
- Lagrangian approach derives Euler's equation of rotation
- equation of forced rotation

Quaternion

- a set of four variables under one constraint
- differential eq. w.r.t. quaternion describing spacial rotation

Quaternion

Report #4 due date : Dec. 14 (Mon.)

(1) Show that $R(\boldsymbol{q})$ is orthogonal.
(2) Show $\dot{A}\boldsymbol{q} = A\dot{\boldsymbol{q}}$, $\dot{B}\boldsymbol{q} = B\dot{\boldsymbol{q}}$, and $\dot{C}\boldsymbol{q} = C\dot{\boldsymbol{q}}$.
(3) Show $H\boldsymbol{q} = \boldsymbol{0}$.
(4) Show $\dot{H}\dot{\boldsymbol{q}} = \boldsymbol{0}$.
(5) Show $H\dot{\boldsymbol{q}} = -\dot{H}\boldsymbol{q}$ and $\boldsymbol{\omega} = -2\dot{H}\boldsymbol{q}$.
(6) Show $HH^{\rm T} = I_{3\times 3}$.
(7) Show $H^{\rm T}H\dot{\boldsymbol{q}} = \dot{\boldsymbol{q}}$ and $\dot{\boldsymbol{q}} = (1/2)H^{\rm T}\boldsymbol{\omega}$.

Dynamic Simulation of Rotation

Report #5 due date : Dec. 28 (Mon.)

Let us compute rotation of a rigid cylindrical body of which inertia matrix is given by $J = {\rm diag}\{\,2.00,\ 100.00,\ 100.00\,\}$. The rigid body remains still at $t = 0$. External torque $\tau_\xi = 10.00$ is applied to the rigid body during $t \in [\,0,\ 5\,]$, then external torque $\tau_\eta = 4.00$ is applied to the rigid body during $t \in [\,5,\ 10\,]$. Simulate the rotation of the body to show how quaternions change according to time during $t \in [\,0,\ 20\,]$. Illustrate how the direction of the central axis of the cylindrial body (ζ-axis) changes according to time.

Appendix: Vector Calculus

Let $\boldsymbol{x}$ and $\boldsymbol{y}$ are three-dimensional vectors given as

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}, \quad \boldsymbol{y} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix}$$

Inner product between $\boldsymbol{x}$ and $\boldsymbol{y}$ is described as

$$\boldsymbol{x}^{\rm T}\boldsymbol{y} = x_1 y_1 + x_2 y_2 + x_3 y_3$$

Thus, partial derivatives of the inner product with respect to column vectors $\boldsymbol{x}$ and $\boldsymbol{y}$ are given as follows:

$$\frac{\partial(\boldsymbol{x}^{\rm T}\boldsymbol{y})}{\partial \boldsymbol{x}} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \boldsymbol{y}, \quad \frac{\partial(\boldsymbol{x}^{\rm T}\boldsymbol{y})}{\partial \boldsymbol{y}} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \boldsymbol{x}$$

Since the inner product is a scalar, the above derivatives are three-dimensional column vectors.

Appendix: Vector Calculus

Outer product between $\boldsymbol{x}$ and $\boldsymbol{y}$:

$$\boldsymbol{x}\times\boldsymbol{y} = \begin{bmatrix} x_2y_3 - x_3y_2 \\ x_3y_1 - x_1y_3 \\ x_1y_2 - x_2y_1 \end{bmatrix} = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \triangleq \left[\ \boldsymbol{x}\times\ \right]\boldsymbol{y}$$

Note that $\left[\ \boldsymbol{x}\times\ \right]$ is a 3×3 skew-symmetric matrix.

$$\left[\ \boldsymbol{x}\times\ \right] = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix}$$

Appendix: Vector Calculus

Partial derivatives of the outer product with respect to row vectors $\boldsymbol{x}^{\mathrm{T}}$ and $\boldsymbol{y}^{\mathrm{T}}$:

$$\frac{\partial(\boldsymbol{x}\times\boldsymbol{y})}{\partial\boldsymbol{x}^{\mathrm{T}}} = \begin{bmatrix} 0 & y_3 & -y_2 \\ -y_3 & 0 & y_1 \\ y_2 & -y_1 & 0 \end{bmatrix} = \left[\ -\boldsymbol{y}\times\ \right],$$

$$\frac{\partial(\boldsymbol{x}\times\boldsymbol{y})}{\partial\boldsymbol{y}^{\mathrm{T}}} = \begin{bmatrix} 0 & -x_3 & x_2 \\ x_3 & 0 & -x_1 \\ -x_2 & x_1 & 0 \end{bmatrix} = \left[\ \boldsymbol{x}\times\ \right]$$

Since the outer product is a three-dimensional column vector, the above derivatives are 3×3 matrices.

Appendix: Vector Calculus

Let $\boldsymbol{x}$ be a three-dimensional vector and A be a 3×3 symmetric matrix independent of $\boldsymbol{x}$. Quadratic form is described as:

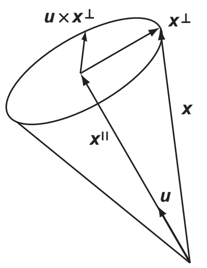
$$\boldsymbol{x}^{\mathrm{T}}A\boldsymbol{x} = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + 2a_{12}x_1x_2 + 2a_{13}x_1x_3 + 2a_{23}x_2x_3$$

Partial derivatie of the quadratic form with respect to $\boldsymbol{x}$ is:

$$\frac{\partial\boldsymbol{x}^{\mathrm{T}}A\boldsymbol{x}}{\partial\boldsymbol{x}} = \begin{bmatrix} 2a_{11}x_1 + 2a_{12}x_2 + 2a_{13}x_3 \\ 2a_{22}x_2 + 2a_{12}x_1 + 2a_{23}x_3 \\ 2a_{33}x_3 + 2a_{13}x_3 + 2a_{23}x_3 \end{bmatrix} = 2A\boldsymbol{x}$$

Since the quadratic form is a scalar, the above derivative is a three-dimensional column vector.

Appendix: deriving quaternion description



$\boldsymbol{u} = [\,u_x,\ u_y,\ u_z\,]^{\mathrm{T}}$ unit vector

$R(\boldsymbol{u},\alpha)$ rotation around $\boldsymbol{u}$ by angle α

$\boldsymbol{x}$ arbitrary vector

decompose $\boldsymbol{x}$ into two components

$$\boldsymbol{x} = \boldsymbol{x}^{\parallel} + \boldsymbol{x}^{\perp}$$
$$\boldsymbol{x}^{\parallel} \parallel \boldsymbol{u}, \quad \boldsymbol{x}^{\perp} \perp \boldsymbol{u}$$

$\boldsymbol{x}^{\parallel}$ is the projection of $\boldsymbol{x}$ to a line specified by unit vector $\boldsymbol{u}$:

$$\boldsymbol{x}^{\parallel} = (\boldsymbol{u}^{\mathrm{T}}\boldsymbol{x})\boldsymbol{u} = (\boldsymbol{u}\boldsymbol{u}^{\mathrm{T}})\boldsymbol{x},$$
$$\boldsymbol{x}^{\perp} = \boldsymbol{x} - \boldsymbol{x}^{\parallel} = (I_{3\times 3} - \boldsymbol{u}\boldsymbol{u}^{\mathrm{T}})\boldsymbol{x}$$

vectors $\boldsymbol{u}$, $\boldsymbol{x}^{\perp}$, and $\boldsymbol{u}\times\boldsymbol{x}^{\perp}$ form a right-handed coordinate system

Appendix: deriving quaternion description

rotation $R(\boldsymbol{u},\alpha)$ transforms $\boldsymbol{x}^{\parallel}$ into itself:

$$R\boldsymbol{x}^{\parallel} = \boldsymbol{x}^{\parallel}.$$

rotation $R(\boldsymbol{u},\alpha)$ transforms $\boldsymbol{x}^{\perp}$ into $C_\alpha\boldsymbol{x}^{\perp} + S_\alpha\boldsymbol{u}\times\boldsymbol{x}^{\perp}$:

$$R\boldsymbol{x}^{\perp} = C_\alpha\boldsymbol{x}^{\perp} + S_\alpha\boldsymbol{u}\times\boldsymbol{x}^{\perp}$$

Thus

$$R\boldsymbol{x} = R(\boldsymbol{x}^{\parallel} + \boldsymbol{x}^{\perp}) = \boldsymbol{x}^{\parallel} + C_\alpha\boldsymbol{x}^{\perp} + S_\alpha\boldsymbol{u}\times\boldsymbol{x}^{\perp}.$$

since $\boldsymbol{u}\times\boldsymbol{x}^{\parallel} = \boldsymbol{0}$

$$\boldsymbol{u}\times\boldsymbol{x}^{\perp} = \boldsymbol{u}\times(\boldsymbol{x}^{\parallel} + \boldsymbol{x}^{\perp}) = \boldsymbol{u}\times\boldsymbol{x} = \left[\ \boldsymbol{u}\times\ \right]\boldsymbol{x}$$

$$R\boldsymbol{x} = (\boldsymbol{u}\boldsymbol{u}^{\mathrm{T}})\boldsymbol{x} + C_\alpha(I_{3\times 3} - \boldsymbol{u}\boldsymbol{u}^{\mathrm{T}})\boldsymbol{x} + S_\alpha\left[\ \boldsymbol{u}\times\ \right]\boldsymbol{x} = \left\{C_\alpha I_{3\times 3} + (1 - C_\alpha)\boldsymbol{u}\boldsymbol{u}^{\mathrm{T}} + S_\alpha\left[\ \boldsymbol{u}\times\ \right]\right\}\boldsymbol{x}.$$

Appendix: deriving quaternion description

rotation around unit vector $\boldsymbol{u}$ by angle α:

$$R = C_\alpha I_{3\times 3} + (1 - C_\alpha)\boldsymbol{u}\boldsymbol{u}^{\mathrm{T}} + S_\alpha\left[\ \boldsymbol{u}\times\ \right] = \begin{bmatrix} C_\alpha + \overline{C}_\alpha u_x^2 & \overline{C}_\alpha u_x u_y - S_\alpha u_z & \overline{C}_\alpha u_x u_z + S_\alpha u_y \\ \overline{C}_\alpha u_y u_x + S_\alpha u_z & C_\alpha + \overline{C}_\alpha u_y^2 & \overline{C}_\alpha u_y u_z - S_\alpha u_x \\ \overline{C}_\alpha u_z u_x - S_\alpha u_y & \overline{C}_\alpha u_z u_y + S_\alpha u_x & C_\alpha + \overline{C}_\alpha u_z^2 \end{bmatrix}$$

where $\overline{C}_\alpha = 1 - C_\alpha$

Define $q_0 = \cos(\alpha/2)$:

$$C_\alpha = 2q_0^2 - 1, \quad \overline{C}_\alpha = 2\sin^2\frac{\alpha}{2}, \quad S_\alpha = 2q_0\sin\frac{\alpha}{2}$$

Define $[\,q_1,\ q_2,\ q_3\,]^{\mathrm{T}} = \sin(\alpha/2)[\,u_x,\ u_y,\ u_z\,]^{\mathrm{T}}$:

$$R = \begin{bmatrix} 2(q_0^2 + q_1^2) - 1 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & 2(q_0^2 + q_2^2) - 1 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & 2(q_0^2 + q_3^2) - 1 \end{bmatrix}$$

Appendix: algebraic description of quaternion

R : a sequence of rotations P followed by Q

P, Q, R : denoted by quaternions

$\boldsymbol{p} = [\,p_0,\ p_1,\ p_2,\ p_3\,]^{\mathrm{T}}$, $\boldsymbol{q} = [\,q_0,\ q_1,\ q_2,\ q_3\,]^{\mathrm{T}}$, $\boldsymbol{r} = [\,r_0,\ r_1,\ r_2,\ r_3\,]^{\mathrm{T}}$

$$R(\boldsymbol{r}) = R(\boldsymbol{p})R(\boldsymbol{q}),$$

$$\Updownarrow$$

$$\begin{bmatrix} r_0 \\ r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} p_0q_0 - p_1q_1 - p_2q_2 - p_3q_3 \\ p_0q_1 + p_1q_0 + p_2q_3 - p_3q_2 \\ p_0q_2 + p_2q_0 + p_3q_1 - p_1q_3 \\ p_0q_3 + p_3q_0 + p_1q_2 - p_2q_1 \end{bmatrix} \quad (1)$$

Appendix: algebraic description of quaternion

Define numbers of which units are given by 1, i, j, and k.
Four units satisfy:

$$i^2 = j^2 = k^2 = -1,$$
$$ij = k, \quad jk = i, \quad ki = j,$$
$$ji = -k, \quad kj = -i, \quad ik = -j$$

Multiplication among i, j, and k circulates but does not commute.
Numbers p, q, r:

$$p = p_0 + p_1 i + p_2 j + p_3 k,$$
$$q = q_0 + q_1 i + q_2 j + q_3 k,$$
$$r = r_0 + r_1 i + r_2 j + r_3 k$$

Appendix: algebraic description of quaternion

Product pq:

$$
\begin{aligned}
r = pq &= (p_0 + p_1 i + p_2 j + p_3 k)(q_0 + q_1 i + q_2 j + q_3 k) \\
&= (p_0 q_0 - p_1 q_1 - p_2 q_2 - p_3 q_3) \\
&+ (p_0 q_1 + p_1 q_0 + p_2 q_3 - p_3 q_2) i \\
&+ (p_0 q_2 + p_2 q_0 + p_3 q_1 - p_1 q_3) j \\
&+ (p_0 q_3 + p_3 q_0 + p_1 q_2 - p_2 q_1) k
\end{aligned}
$$

$$\Updownarrow$$

$$
\begin{bmatrix} r_0 \\ r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} p_0 q_0 - p_1 q_1 - p_2 q_2 - p_3 q_3 \\ p_0 q_1 + p_1 q_0 + p_2 q_3 - p_3 q_2 \\ p_0 q_2 + p_2 q_0 + p_3 q_1 - p_1 q_3 \\ p_0 q_3 + p_3 q_0 + p_1 q_2 - p_2 q_1 \end{bmatrix} \quad (2)
$$

(1) and (2) are equivalent each other.

Appendix: Euler angles

a set of 3-2-3 Euler angles:

$$
\begin{aligned}
R(\phi, \theta, \psi) &= R_3(\phi) R_2(\theta) R_3(\psi) \\
&= \begin{bmatrix} C_\phi & -S_\phi & \\ S_\phi & C_\phi & \\ & & 1 \end{bmatrix} \begin{bmatrix} C_\theta & & S_\theta \\ & 1 & \\ -S_\theta & & C_\theta \end{bmatrix} \begin{bmatrix} C_\psi & -S_\psi & \\ S_\psi & C_\psi & \\ & & 1 \end{bmatrix}
\end{aligned}
$$

Rotation matrix

$$
\begin{bmatrix} 1/\sqrt{2} & -1/\sqrt{2} & \\ 1/\sqrt{2} & 1/\sqrt{2} & \\ & & 1 \end{bmatrix}
$$

corresponds to an infinite number of sets of Euler angles satisfying $\theta = 0$ and $\phi + \psi = \pi/4$. This singularity causes

- gimbal lock
- instability in solving equation of rotation

Appendix: Euler angles

a set of 1-2-3 Euler angles:

$$
\begin{aligned}
R(\phi, \theta, \psi) &= R_1(\phi) R_2(\theta) R_3(\psi) \\
&= \begin{bmatrix} 1 & & \\ & C_\phi & -S_\phi \\ & S_\phi & C_\phi \end{bmatrix} \begin{bmatrix} C_\theta & & S_\theta \\ & 1 & \\ -S_\theta & & C_\theta \end{bmatrix} \begin{bmatrix} C_\psi & -S_\psi & \\ S_\psi & C_\psi & \\ & & 1 \end{bmatrix}
\end{aligned}
$$

Rotation matrix

$$
\begin{bmatrix} & & 1 \\ 1/\sqrt{2} & 1/\sqrt{2} & \\ -1/\sqrt{2} & 1/\sqrt{2} & \end{bmatrix}
$$

corresponds to an infinite number of sets of Euler angles satisfying $\theta = \pi/2$ and $\phi + \psi = \pi/4$.

Any set of Euler angles has singularity.

Appendix: Euler angles

computing angular velocity vector for a set of 3-2-3 Euler angles:

$$
\begin{aligned}
R^{\mathrm{T}} &= R_3^{\mathrm{T}}(\psi) R_2^{\mathrm{T}}(\theta) R_3^{\mathrm{T}}(\phi) \\
\dot{R} &= \dot{R}_3(\phi) R_2(\theta) R_3(\psi) + R_3(\phi) \dot{R}_2(\theta) R_3(\psi) + R_3(\phi) R_2(\theta) \dot{R}_3(\psi)
\end{aligned}
$$

$$
\begin{aligned}
[\, \boldsymbol{\omega} \times \,] &= R^{\mathrm{T}} \dot{R} \\
&= R_3^{\mathrm{T}}(\psi) R_2^{\mathrm{T}}(\theta) R_3^{\mathrm{T}}(\phi) \dot{R}_3(\phi) R_2(\theta) R_3(\psi) \\
&+ R_3^{\mathrm{T}}(\psi) R_2^{\mathrm{T}}(\theta) \dot{R}_2(\theta) R_3(\psi) \\
&+ R_3^{\mathrm{T}}(\psi) \dot{R}_3(\psi)
\end{aligned}
$$

angular velocity vector:

$$
\begin{bmatrix} \omega_\xi \\ \omega_\eta \\ \omega_\zeta \end{bmatrix} = \begin{bmatrix} -S_\theta C_\psi \\ S_\theta S_\psi \\ C_\theta \end{bmatrix} \dot{\phi} + \begin{bmatrix} S_\psi \\ C_\psi \\ 0 \end{bmatrix} \dot{\theta} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \dot{\psi}
$$