MEE5114 Advanced Control for Robotics

Lecture 4: Exponential Coordinate of Rigid Body Configuration

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Outline

- Exponential Coordinate of $SO(3)$ Rotation matrix

- Euler Angles and Euler-Like Parameterizations

- Exponential Coordinate of SE(3) homogeneous transformation matrix

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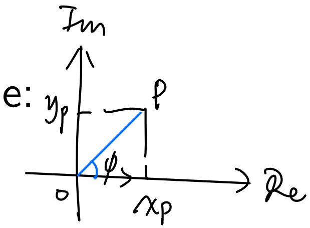
- Euler Angles and Euler-Like Parameterizations
- Exponential Coordinate of SE(3)

Towards Exponential Coordinate of $SO(3)$

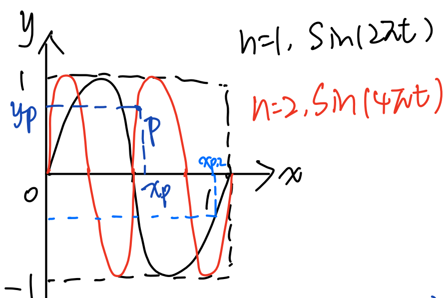


- Recall the polar coordinate system of the complex plane:
  - Every complex number $z = x + jy = \rho e^{j\phi}$
  - Cartesian coordinate $(x, y) \leftrightarrow$ polar coorindate (ρ, ϕ)
  - For some applications, polar coordinate is preferred due to its geometric meaning.

$p = (x_p, y_p) \xrightarrow{\text{polar}} (\rho_p, \phi_p)$

- Consider a set $M = \{(t, \sin(2n\pi t)) : t \in (0, 1), n = 1, 2, 3, \ldots\}$

- $M \subseteq \mathbb{R}^2$



coordinate of p (x_p, y_p)

$p_2 = (1, x_{p,2})$

take advantage of structure of M

coordinate of $p = (2, x_p) \leftarrow \sin(2n\pi t), n=2, t=x_p$

Exponential Coordinate of $SO(3)$

- **Proposition** [Exponential Coordinate $\leftrightarrow$ SO(3)]
  - For any unit vector $[\hat{\omega}] \in so(3)$ and any $\theta \in \mathbb{R}$,

    $\|\omega\| = 1$

    $$\underbrace{e^{[\hat{\omega}]\theta}}_{\in \mathbb{R}^{3\times 3}} \in \underbrace{SO(3)}$$

    R 与 $e^{[\hat{\omega}]\theta}$ 对应关系

  - For any $R \in SO(3)$, there exists $\hat{\omega} \in \mathbb{R}^3$ with $\|\hat{\omega}\| = 1$ and $\theta \in \mathbb{R}$ such that

    $$\underbrace{R = e^{[\hat{\omega}]\theta}}$$

    $\dot{p} = Ap$ solves linear diff equation

    $$\text{exp:} \quad [\hat{\omega}]\theta \in \underbrace{so(3)} \quad \xrightarrow{\exp(\,)} \quad R \in SO(3)$$

    $$\text{log:} \quad R \in SO(3) \quad \xrightarrow{\log(\,)} \quad [\hat{\omega}]\theta \in so(3)$$

    $R = \begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{bmatrix} \in \mathbb{R}^{3\times 3}$

- The vector $\hat{\omega}\theta$ is called the $\boxed{\textit{exponential coordinate}}$ for R

- The exponential coordinates are also called the canonical coordinates of the rotation group $SO(3)$

Rotation Matrix as Forward Exponential Map

- Exponential Map: By definition

$$R \leftarrow e^{[\omega]\theta} = I + \theta[\omega] + \frac{\theta^2}{2!}[\omega]^2 + \frac{\theta^3}{3!}[\omega]^3 + \cdots$$

- **Rodrigues' Formula**: Given any unit vector $[\hat{\omega}] \in so(3)$, we have

analytical

$$e^{[\hat{\omega}]\theta} = I + [\hat{\omega}]\sin(\theta) + [\hat{\omega}]^2(1 - \cos(\theta))$$

Fact: if $\|\hat{\omega}\|=1$, then we have the following $[\hat{\omega}] = -[\hat{\omega}]^T$, $[\hat{\omega}]^3 = -[\hat{\omega}]$, $[\hat{\omega}]^4 = -[\hat{\omega}]^2$

$$e^{[\hat{\omega}]\theta} = I + \theta[\hat{\omega}] + \frac{\theta^2}{2!}[\hat{\omega}]^2 + \frac{\theta^3}{3!}([\hat{\omega}]^3) + \frac{\theta^4}{4!}(-[\hat{\omega}]^2) + \cdots$$

$$= I + \left(\theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} + \cdots\right)[\hat{\omega}] + \left(\frac{\theta^2}{2!} - \frac{\theta^4}{4!} + \frac{\theta^6}{6!} - \cdots\right)[\hat{\omega}]^2$$

$$= I + [\hat{\omega}]\sin\theta + (1-\cos\theta)[\hat{\omega}]^2$$

Examples of Forward Exponential Map

- Rotation matrix $\underbrace{R_x(\theta)}_{\shortparallel}$ (corresponding to $\hat{x}\theta$)

$$R_x(\theta) \triangleq Rot(\hat{x}, \theta) = e^{[\hat{\omega}]\theta} = I + \sin\theta \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} + (1-\cos\theta) \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

If $\hat{\omega} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \Rightarrow [\hat{\omega}]$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

- Rotation matrix corresponding to $(1, 0, 1)^T$

$$\hat{\omega} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \frac{1}{\sqrt{2}}, \quad \theta = \sqrt{2}$$

$$R = e^{[\hat{\omega}]\theta} = \cdots$$

Logarithm of Rotations From $R \to \vec{w}$

① • If $R = I$, then $\theta = 0$ and $\hat{\omega}$ is undefined.

② • If $\mathrm{tr}(R) = -1$, then $\theta = \pi$ and set $\hat{\omega}$ equal to one of the following

$$\frac{1}{\sqrt{2(1+r_{33})}}\begin{bmatrix} r_{13} \\ r_{23} \\ 1+r_{33} \end{bmatrix}, \frac{1}{\sqrt{2(1+r_{22})}}\begin{bmatrix} r_{12} \\ 1+r_{22} \\ r_{32} \end{bmatrix}, \frac{1}{\sqrt{2(1+r_{11})}}\begin{bmatrix} 1+r_{11} \\ r_{21} \\ r_{31} \end{bmatrix}$$

③ • Otherwise, $\underline{\theta = \cos^{-1}\left(\frac{1}{2}(\mathrm{tr}(R) - 1)\right)} \in [0, \pi)$ and $\underline{[\hat{\omega}] = \frac{1}{2\sin(\theta)}(R - R^T)}$

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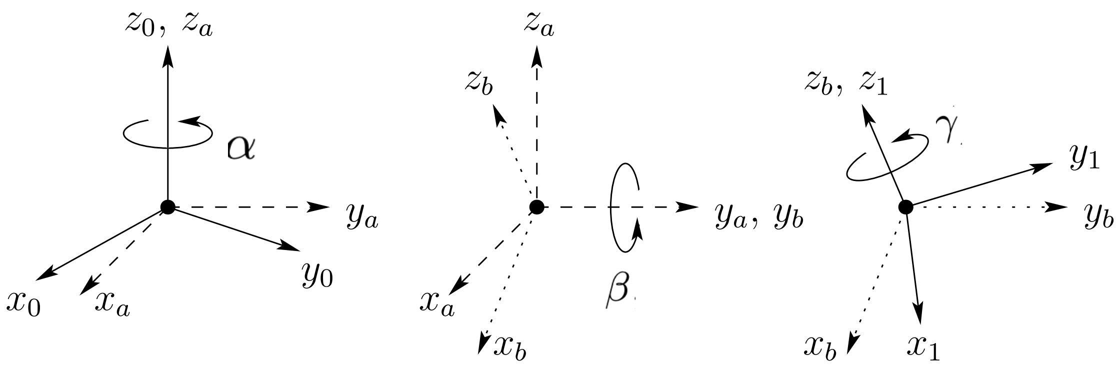
Euler Angle Representation of Rotation

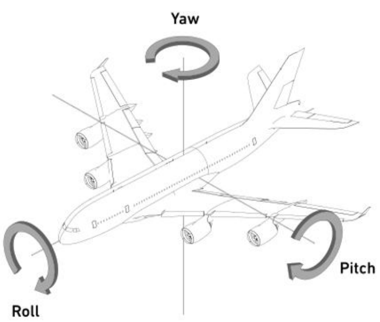


- A common method of specifying a rotation matrix is through three independent quantities called **Euler Angles**.
- Euler angle representation
  - Initially, frame $\{0\}$ coincides with frame $\{1\}$
  - Rotate $\{1\}$ about $\hat{\mathrm{z}}_0$ by an angle α, then rotate about $\hat{\mathrm{y}}_{\mathrm{a}}$ axis by β, and then rotate about the $\hat{\mathrm{z}}_{\mathrm{b}}$ axis by γ. This yields a net orientation ${}^0R_1(\alpha, \beta, \gamma)$ parameterized by the ZYZ angles (α, β, γ) $R_z(\gamma) = e^{[\hat{z}]\gamma}$
  - ${}^0R_1(\alpha, \beta, \gamma) = R_z(\alpha)R_y(\beta)R_z(\gamma)$
    $Rot(z,\alpha) \cdot Rot(y,\beta) \cdot Rot(z,\gamma)$

Other Euler-Like Parameterizations

- Other types of Euler angle parameterization can be devised using different ordered sets of rotation axes

- Common choices include:
  - ZYX Euler angles: also called *Fick angles* or yaw, pitch and roll angles
  - YZX Euler angles (Helmholtz angles)



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Exponential Map of $se(3)$: From Twist to Rigid Motion

Theorem 1 [Exponential Map of $se(3)$]: For any $\boxed{\mathcal{V} = (\omega, v)}$ and $\theta \in \mathbb{R}$, we have $e^{[\mathcal{V}]\theta} \in SE(3)$ → Homogeneous transformation matrix

- Case 1 ($\omega = 0$): $e^{[\mathcal{V}]\theta} = \begin{bmatrix} I & v\theta \\ 0 & 1 \end{bmatrix}$
- Case 2 ($\omega \neq 0$): without loss of generality assume $\|\omega\| = 1$. Then

$$e^{[\mathcal{V}]\theta} = \begin{bmatrix} e^{[\omega]\theta} & G(\theta)v \\ 0 & 1 \end{bmatrix}, \text{ with } G(\theta) = I\theta + (1-\cos(\theta))[\omega] + (\theta - \sin(\theta))[\omega]^2 \quad (1)$$

$$\mathcal{V} \in \mathbb{R}^6 = \begin{bmatrix} \omega \\ v \end{bmatrix}, \quad [\mathcal{V}] = \begin{array}{cc} 3\times3 & 3\times1 \\ \begin{bmatrix} [\omega] & v \\ 0 & 0 \end{bmatrix} \end{array} \in \mathbb{R}^{4\times4}$$

From exp map from $se(3) \longrightarrow SE(3)$

Log of $SE(3)$: from Rigid-Body Motion to Twist

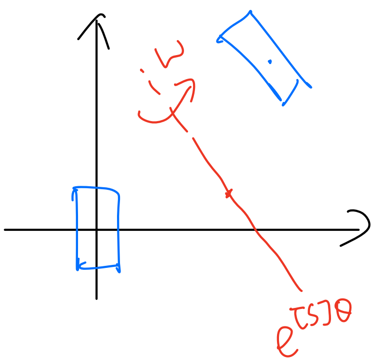
Theorem 2 [Log of $SE(3)$]: Given any $T = (R, p) \in SE(3)$, one can always find twist $\mathcal{S} = (\omega, v)$ and a scalar θ such that

$$e^{[\mathcal{S}]\theta} = T = \begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix}$$

Matrix Logarithm Algorithm:

- If $R = I$, then set $\omega = 0$, $v = p/\|p\|$, and $\theta = \|p\|$.
- Otherwise, use matrix logarithm on $SO(3)$ to determine ω and θ from R. Then v is calculated as $v = G^{-1}(\theta)p$, where

$$G^{-1}(\theta) = \frac{1}{\theta}I - \frac{1}{2}[\omega] + \left(\frac{1}{\theta} - \frac{1}{2}\cos\frac{\theta}{2}\right)[\omega]^2$$



Exponential Coordinates of Rigid Transformation

- To sum up, screw axis $\mathcal{S} = \overset{=(\hat{s},q,h)}{(\omega, v)}$ can be expressed as a normalized twist; its matrix representation is

$$[\mathcal{S}] = \begin{array}{c} \begin{array}{cc} 3\times3 & 3\times1 \end{array} \\ \left[\begin{array}{cc} [\omega] & v \\ 0 & 0 \end{array}\right] \\ \begin{array}{cc} 1\times3 & 1\times1 \end{array} \end{array} \in se(3)$$

- A point started at $p(0)$ at time zero, travel along screw axis $\mathcal{S}$ at unit speed for time t will end up at $\tilde{p}(t) = e^{[\mathcal{S}]t}\tilde{p}(0)$

$$\underset{4\times1}{\dot{\tilde{p}}} = \underset{4\times4}{[S]}\ \underset{4\times1}{\tilde{p}}$$

- Given $\mathcal{S}$ we can use Theorem 1 to compute $e^{[\mathcal{S}]t} \in SE(3)$;

- Given $T \in SE(3)$, we can use Theorem 2 to find $\mathcal{S} = (\omega, v)$ and θ such that $e^{[\mathcal{S}]\theta} = T$.

- We call $\mathcal{S}\theta$ the **Exponential Coordinate** of the homogeneous transformation $T \in SE(3)$

More Space

More Space