Lecture

Navigation Mathematics: Kinematics (Angular Velocity: Quaternion Representation)

EE 570: Location and Navigation

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.1

Angular Velocity

- Since the relative and fixed axis rotations must be performed in a particular order, their derivatives are somewhat challenging
- The angle-axis format, however, is readily differentiable as we can encode the 3 parameters by

$$\vec{K} \equiv \vec{k}(t)\theta(t) = \begin{bmatrix} K_1(t) \\ K_2(t) \\ K_3(t) \end{bmatrix} \tag{1}$$

  where $\theta = \|\vec{K}\|$
- Hence,

$$\frac{d}{dt}\vec{K}(t) = \begin{bmatrix} \dot{K}_1(t) \\ \dot{K}_2(t) \\ \dot{K}_3(t) \end{bmatrix}$$

.2

Angular Velocity

- For a sufficiently "small" time interval we can often consider the axis of rotation to be $\approx$ constant (i.e.,$\vec{K}(t) = \vec{k}$)

$$\begin{aligned} \frac{d}{dt}\vec{K}(t) &= \frac{d}{dt}\left(\vec{k}\theta(t)\right) \\ &= \vec{k}\dot{\theta}(t) \end{aligned}$$

- This is referred to as the angular velocity ($\vec{\omega}(t)$) or the so called "body reference" angular velocity

  Angular Velocity

$$\vec{\omega}(t) \equiv \vec{k}\dot{\theta}(t) \tag{2}$$

.3

Quaternion Multiply

- Quaternion multiply

$$\bar{r} = \bar{q} \otimes \bar{p} = [\bar{q}\otimes]\bar{p} = \begin{bmatrix} q_s p_s - \vec{q} \cdot \vec{p} \\ q_s \vec{p} + p_s \vec{q} + \vec{q} \times \vec{p} \end{bmatrix}$$

  where

$$[\bar{q}\otimes] = \begin{bmatrix} q_s & -q_x & -q_y & -q_z \\ q_x & q_s & -q_z & q_y \\ q_y & q_z & q_s & -q_x \\ q_z & -q_y & q_x & q_s \end{bmatrix}$$

.4

Quaternion Multiply

- Quaternion multiply (corresponds to reverse order DCM)

$$\bar{r} = \bar{q} \circledast \bar{p} = [\bar{q}\circledast]\bar{p} = \begin{bmatrix} q_s p_s - \vec{q} \cdot \vec{p} \\ q_s \vec{p} + p_s \vec{q} - \vec{q} \times \vec{p} \end{bmatrix}$$

- $$\bar{q} \otimes \bar{p} = \bar{p} \circledast \bar{q}$$

  where

$$[\bar{q}\circledast] = \begin{bmatrix} q_s & -q_x & -q_y & -q_z \\ q_x & q_s & q_z & -q_y \\ q_y & -q_z & q_s & q_x \\ q_z & q_y & -q_x & q_s \end{bmatrix}$$

.5

Angular Velocity

- Recalling that

$$[\bar{q}\,{}^a_b(t)\otimes] = e^{\frac{1}{2}[\breve{k}^a_{ab}\otimes]\theta(t)} = \cos(\theta/2)\mathcal{I} + \frac{1}{2}[\breve{k}^a_{ab}\otimes]\frac{\sin(\theta/2)}{\theta/2}$$

  where

$$\breve{k} = \begin{bmatrix} 0 \\ \vec{k} \end{bmatrix}$$

- Hence,

$$\begin{aligned} \frac{d}{dt}[\bar{q}\,{}^a_b(t)\otimes] &= \frac{d}{dt} e^{\frac{1}{2}[\breve{k}^a_{ab}\otimes]\theta(t)} \\ &= \frac{\partial[\bar{q}\,{}^a_b(t)\otimes]}{\partial\theta}\frac{d\theta}{dt} \\ &= \frac{1}{2}[\breve{k}^a_{ab}\otimes]e^{\frac{1}{2}[\breve{k}^a_{ab}\otimes]\theta(t)}\dot{\theta}(t) \\ &= \frac{1}{2}\left([\breve{k}^a_{ab}\otimes]\dot{\theta}(t)\right)[\bar{q}\,{}^a_b(t)\otimes] \end{aligned}$$

.6

Angular Velocity

- let $W^a_{ab} = \left([\breve{k}^a_{ab}\otimes]\dot{\theta}(t)\right) = [\breve{\omega}^a_{ab}\otimes]$
- therefore,

$$W^a_{ab} = \begin{bmatrix} 0 & -\omega^a_{ab,x} & -\omega^a_{ab,y} & -\omega^a_{ab,z} \\ \omega^a_{ab,x} & 0 & -\omega^a_{ab,z} & \omega^a_{ab,y} \\ \omega^a_{ab,y} & \omega^a_{ab,z} & 0 & -\omega^a_{ab,x} \\ \omega^a_{ab,z} & -\omega^a_{ab,y} & \omega^a_{ab,x} & 0 \end{bmatrix}$$

- and consequently,

$$\dot{\bar{q}}^a_b(t) = \frac{1}{2}[\breve{\omega}^a_{ab}\otimes]\bar{q}\,{}^a_b(t)$$

.7

Angular Velocity

- Now,

$$\begin{aligned}
\dot{\bar{q}}_b^a(t) &= \frac{1}{2}[\breve{\omega}_{ab}^a \otimes]\bar{q}_{\,b}^{\,a}(t) = \frac{1}{2}\breve{\omega}_{ab}^a \otimes \bar{q}_{\,b}^{\,a}(t) \\
&= \frac{1}{2}\bar{q}_{\,b}^{\,a}(t) \otimes \breve{\omega}_{ab}^b \otimes \left(\bar{q}_{\,b}^{\,a}(t)\right)^{-1} \otimes \bar{q}_{\,b}^{\,a}(t) \\
&= \frac{1}{2}[\bar{q}_{\,b}^{\,a}(t) \otimes]\breve{\omega}_{ab}^b \\
&= \frac{1}{2}[\breve{\omega}_{ab}^b \circledast]\bar{q}_{\,b}^{\,a}(t)
\end{aligned}$$

  where $\breve{\omega}_{ab}^a = \bar{q}_{\,b}^{\,a}(t) \otimes \breve{\omega}_{ab}^b \otimes \left(\bar{q}_{\,b}^{\,a}(t)\right)^{-1}$ and $\left(\bar{q}_{\,b}^{\,a}(t)\right)^{-1} \otimes \bar{q}_{\,b}^{\,a}(t) = 1$.
- and consequently,

$$\dot{\bar{q}}_b^a(t) = \frac{1}{2}[\breve{\omega}_{ab}^a \otimes]\bar{q}_{\,b}^{\,a}(t) = \frac{1}{2}[\bar{q}_{\,b}^{\,a}(t) \otimes]\breve{\omega}_{ab}^b = \frac{1}{2}[\breve{\omega}_{ab}^b \circledast]\bar{q}_{\,b}^{\,a}(t) \tag{3}$$

.8