

# EE 565: Position, Navigation and Timing

## Navigation Mathematics: Other Descriptions of Orientation

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- Notation to be adopted:
  - $C$  represents an orientation
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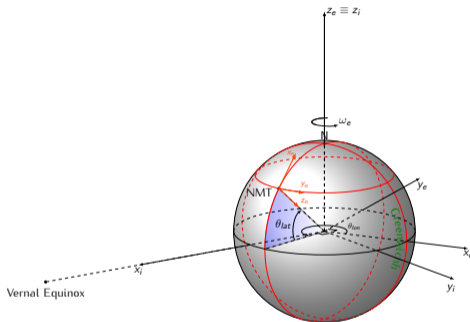
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$$C_{final} = RC_{initial}$$

- $3 \times 3 = 9$  elements with 6 constraints  $\Rightarrow$  3 parameters are sufficient to describe orientation

What is orientation of ECEF frame resolved in ECI frame, i.e.  $C_e^i$ ?

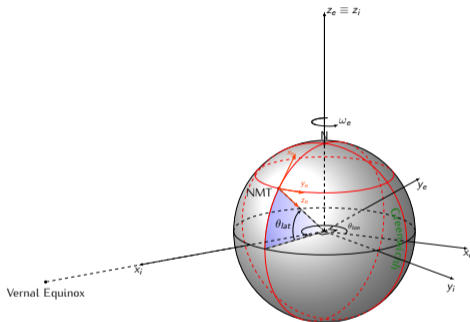
$$C_e^i = R_{z, \theta_{ie}} = \begin{bmatrix} \cos \theta_{ie} & -\sin \theta_{ie} & 0 \\ \sin \theta_{ie} & \cos \theta_{ie} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



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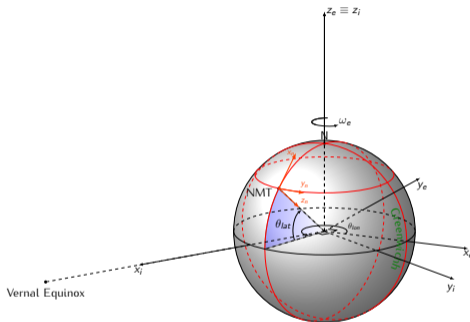
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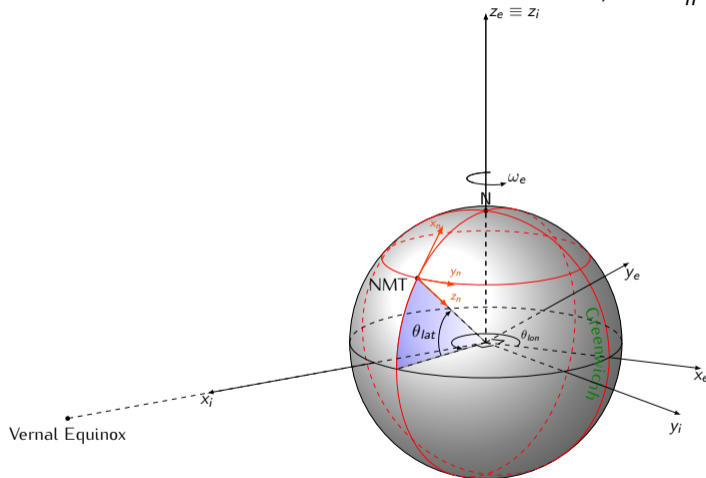
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What is  $\theta_{ie}$ ? angle from frame  $\{i\}$  to frame  $\{e\}$ ; here  $\theta_{ie} = \omega_{ie}(t - t_0)$



What is the nav frame resolved in the ECEF frame, i.e.  $C_n^e$ ?



## Roll-Pitch-Yaw angles

- often used to represent orientation of aircraft
- three angles  $(\phi, \theta, \psi)$  that represent the sequence of rotations about the  $x$ -,  $y$ - and  $z$ -axes of a fixed frame
- given angles  $(\phi, \theta, \psi)$ , equivalent rotation matrix can be found via

$$\begin{aligned}
 C_{RPY} &= R_{z,\psi} R_{y,\theta} R_{x,\phi} \\
 &= \begin{bmatrix} c_\psi & -s_\psi & 0 \\ s_\psi & c_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_\theta & 0 & s_\theta \\ 0 & 1 & 0 \\ -s_\theta & 0 & c_\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi & c_\phi \end{bmatrix} \\
 &= \begin{bmatrix} c_\theta c_\psi & c_\psi s_\theta s_\phi - c_\phi s_\psi & c_\phi c_\psi s_\theta + s_\phi s_\psi \\ c_\theta s_\psi & c_\phi c_\psi + s_\theta s_\phi s_\psi & c_\phi s_\theta s_\psi - c_\psi s_\phi \\ -s_\theta & c_\theta s_\phi & c_\theta c_\phi \end{bmatrix}
 \end{aligned}$$

Given a rotation matrix that describes a desired orientation

$$C_{desired} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

Roll-Pitch-Yaw angles ( $\phi$ ,  $\theta$ ,  $\psi$ ) can be found (the inverse solution) by equating combinations of terms

$$\begin{bmatrix} \boxed{C_{\theta} C_{\psi}} & C_{\psi} S_{\theta} S_{\phi} - C_{\phi} S_{\psi} & C_{\phi} C_{\psi} S_{\theta} + S_{\phi} S_{\psi} \\ \boxed{C_{\theta} S_{\psi}} & C_{\phi} C_{\psi} + S_{\theta} S_{\phi} S_{\psi} & C_{\phi} S_{\theta} S_{\psi} - C_{\psi} S_{\phi} \\ -S_{\theta} & C_{\theta} S_{\phi} & C_{\theta} C_{\phi} \end{bmatrix} = \begin{bmatrix} \boxed{C_{11}} & C_{12} & C_{13} \\ \boxed{C_{21}} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}$$

$$\frac{C_{21}}{C_{11}} = \frac{C_{\theta} S_{\psi}}{C_{\theta} C_{\psi}} = \tan(\psi)$$

$$\begin{bmatrix} c_\theta c_\psi & c_\psi s_\theta s_\phi - c_\phi s_\psi & c_\phi c_\psi s_\theta + s_\phi s_\psi \\ c_\theta s_\psi & c_\phi c_\psi + s_\theta s_\phi s_\psi & c_\phi s_\theta s_\psi - c_\psi s_\phi \\ -s_\theta & \boxed{c_\theta s_\phi} & \boxed{c_\theta c_\phi} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & \boxed{C_{32}} & \boxed{C_{33}} \end{bmatrix}$$

$$\frac{C_{32}}{C_{33}} = \frac{c_\theta s_\phi}{c_\theta c_\phi} = \tan(\phi)$$

$$\begin{bmatrix} c_\theta c_\psi & c_\psi s_\theta s_\phi - c_\phi s_\psi & c_\phi c_\psi s_\theta + s_\phi s_\psi \\ c_\theta s_\psi & c_\phi c_\psi + s_\theta s_\phi s_\psi & c_\phi s_\theta s_\psi - c_\psi s_\phi \\ -s_\theta & \boxed{c_\theta s_\phi} & \boxed{c_\theta c_\phi} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & \boxed{C_{32}} & \boxed{C_{33}} \end{bmatrix}$$

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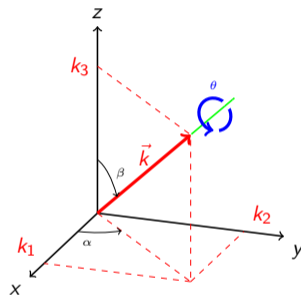
$$\frac{-C_{31}}{\sqrt{C_{32}^2 + C_{33}^2}} = \frac{-(-s_\theta)}{\sqrt{c_\theta^2 (s_\phi^2 + c_\phi^2)}} = \frac{s_\theta}{c_\theta} = \tan(\theta)$$

## Angle-Axis

- one rotation about general axis will be used to describe orientation, so **does not** have the “rotation in sequence” issue
- rotation matrix  $C$  can be realized via rotation away from initial frame by angle  $\theta$  about appropriately chosen axis  $\vec{k} = [k_1, k_2, k_3]^T$  of rotation
- assume  $\vec{k}$  is a unit vector

- Rotation matrix can be derived by rotating one of the principal axis (x, y, or z) onto the vector  $\vec{k}$ , performing a rotation of  $\theta$ , and finally undoing the original changes.
- Common sequence is

$$R_{\vec{k},\theta} = \underbrace{R_{z,\alpha} R_{y,\beta}}_{\text{align z with } \vec{k}} R_{z,\theta} \underbrace{R_{y,-\beta} R_{z,-\alpha}}_{\text{put frame back relative to } \vec{k}}$$



Noting

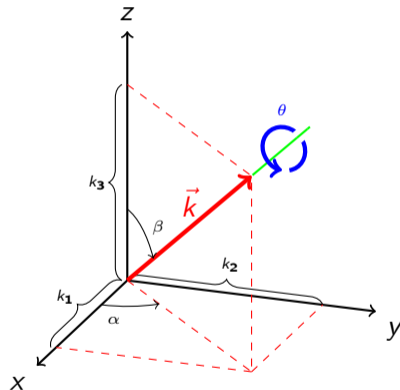
$$\sin \alpha = \frac{k_2}{\sqrt{k_1^2 + k_2^2}}, \quad \cos \alpha = \frac{k_1}{\sqrt{k_1^2 + k_2^2}}$$

$$\sin \beta = \frac{k_3}{\sqrt{k_1^2 + k_2^2 + k_3^2}}, \quad \cos \beta = \frac{\sqrt{k_1^2 + k_2^2}}{\sqrt{k_1^2 + k_2^2 + k_3^2}}$$

the composition of rotations becomes

$$R_{\vec{k}, \theta} = \begin{bmatrix} k_1^2 V_\theta + c_\theta & k_1 k_2 V_\theta - k_3 s_\theta & k_1 k_3 V_\theta + k_2 s_\theta \\ k_1 k_2 V_\theta + k_3 s_\theta & k_2^2 V_\theta + c_\theta & k_2 k_3 V_\theta - k_1 s_\theta \\ k_1 k_3 V_\theta - k_2 s_\theta & k_2 k_3 V_\theta + k_1 s_\theta & k_3^2 V_\theta + c_\theta \end{bmatrix} \quad (1)$$

where  $\text{versin}(\theta) = V_\theta \equiv 1 - c_\theta$ .





Alternate approach to development of angle-axis is to relate rotation matrix to its equivalent angle-axis pair by

$$R_{\vec{k},\theta(t)} = e^{\kappa\theta(t)}$$

where

skew-symmetric

$$\kappa = [\vec{k} \times] = \begin{bmatrix} 0 & -k_3 & k_2 \\ k_3 & 0 & -k_1 \\ -k_2 & k_1 & 0 \end{bmatrix}$$

is the skew-symmetric matrix version of the axis vector  $\vec{k} = [k_1 \quad k_2 \quad k_3]^T$  and  $\kappa^T = -\kappa$ .

- Using Taylor expansion of matrix-exponential

$$R_{\vec{k},\theta(t)} = e^{\kappa\theta(t)} = \mathcal{I} + \kappa\theta(t) + \frac{\kappa^2\theta^2(t)}{2!} + \frac{\kappa^3\theta^3(t)}{3!} + \dots$$

which, after a bit of manipulation (recalling Taylor series of sine and cosine and noting  $\kappa^3 = -\kappa$ ), can be shown to be

## Rodrigues Formula

$$R_{\vec{k},\theta(t)} = \mathcal{I} + \sin(\theta(t))\kappa + [1 - \cos(\theta(t))] \kappa^2$$

- Multiplying out the right hand side of the above equation gives us the same rotation matrix as that in Eq. 1 shown previously.

Desired rotation matrix to  $(\vec{k}, \theta)$  - the inverse problem

$$R_{\vec{k}, \theta} = \begin{bmatrix} k_1^2 V_\theta + c_\theta & k_1 k_2 V_\theta - k_3 s_\theta & k_1 k_3 V_\theta + k_2 s_\theta \\ k_1 k_2 V_\theta + k_3 s_\theta & k_2^2 V_\theta + c_\theta & k_2 k_3 V_\theta - k_1 s_\theta \\ k_1 k_3 V_\theta - k_2 s_\theta & k_2 k_3 V_\theta + k_1 s_\theta & k_3^2 V_\theta + c_\theta \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = R_{desired}$$

- find angle-axis pair  $(\vec{k}, \theta)$  needed to realize desired rotation matrix

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- find angle-axis pair  $(\vec{k}, \theta)$  needed to realize desired rotation matrix
- look at trace of rotation matrix and recall  $V_\theta \equiv 1 - \cos \theta$

$$\text{Tr} \left( R_{\vec{k}, \theta} \right) = [k_1^2 + k_2^2 + k_3^2] (1 - \cos \theta) + 3 \cos \theta = 1 + 2 \cos \theta$$

$$\Rightarrow \theta = \cos^{-1} \left( \frac{\text{Tr} \left( R_{\vec{k}, \theta} \right) - 1}{2} \right) = \cos^{-1} \left( \frac{r_{11} + r_{22} + r_{33} - 1}{2} \right)$$

Now for the axis of rotation; a review of the structure suggests

$$r_{32} - r_{23} = 2k_1 s_\theta$$

$$r_{13} - r_{31} = 2k_2 s_\theta$$

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$$\Rightarrow \vec{k} = \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} = \frac{1}{2s_\theta} \begin{bmatrix} r_{32} - r_{23} \\ r_{13} - r_{31} \\ r_{21} - r_{12} \end{bmatrix}$$

A satellite orbiting the earth can be made to point it's telescope at a desired star by performing the following motions

- 1 Rotate about it's  $x$ -axis by  $-30^\circ$ , then
- 2 Rotate about it's new  $z$ -axis by  $50^\circ$ , then finally
- 3 Rotate about it's initial  $y$ -axis by  $40^\circ$ .



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What is its final orientation *wrt* the starting orientation?

$$C_{final}^{start} = R_{(\vec{y}, 40^\circ)} R_{(\vec{x}, -30^\circ)} R_{(\vec{z}, 50^\circ)}$$

$$= \begin{bmatrix} 0.766044 & 0 & 0.642788 \\ 0 & 1 & 0 \\ -0.642788 & 0 & 0.766044 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.866025 & 0.5 \\ 0 & -0.5 & 0.866025 \end{bmatrix} \begin{bmatrix} 0.642788 & -0.766044 & 0 \\ 0.766044 & 0.642788 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0.246202 & -0.793412 & 0.55667 \\ 0.663414 & 0.663414 & 0.5 \\ -0.706588 & 0.246202 & 0.246202 \end{bmatrix}$$

- In order to save energy it is desirable to perform this change in orientation with only one rotation — How?

- In order to save energy it is desirable to perform this change in orientation with only one rotation — How?
- Perform a single, equivalent angle-axis rotation with

$$\theta = \cos^{-1} \left( \frac{\text{Tr}(C_{final}^{start}) - 1}{2} \right) = 76.5^\circ$$

$$\vec{k} = \frac{1}{2s_\theta} \begin{bmatrix} r_{32} - r_{23} \\ r_{13} - r_{31} \\ r_{21} - r_{12} \end{bmatrix} = \begin{bmatrix} -0.130495 \\ 0.649529 \\ 0.749055 \end{bmatrix}$$

Angle-Axis representation can be made three parameters via

$$\vec{K} = \theta \vec{k}$$

such that

$$\theta = \|\vec{K}\|$$

and

$$\vec{k} = \frac{\vec{K}}{\|\vec{K}\|}$$

Euler angles, RPY angles and angle-axis consist three elements, but they are not unique, e.g., there are orientations that are represented by different Euler angles, RYP angles and angle-axis.

## Quaternion

- Quaternions are 4-element representation of the rotation vectors where the additional element makes quaternions unique.
- With 4 elements quaternions have the lowest dimensionality possible for a globally nonsingular attitude representation.

Given an angle-axis pair  $(\theta, \vec{k})$  or the corresponding rotation vector  $\vec{K} = \theta \vec{k}$ , a quaternion is defined as

$$\bar{q} = \begin{bmatrix} q_s \\ \vec{q} \end{bmatrix} = \begin{bmatrix} q_s \\ q_x \\ q_y \\ q_z \end{bmatrix} = \begin{bmatrix} \cos(\frac{\theta}{2}) \\ \vec{k} \sin(\frac{\theta}{2}) \end{bmatrix}$$

where

- $q_s = \cos(\frac{\theta}{2})$  is the scalar component
- $\vec{q} = [q_x, q_y, q_z]^T = \vec{k} \sin(\frac{\theta}{2})$  is the vector component
- $|\bar{q}| = \sqrt{q_s^2 + q_x^2 + q_y^2 + q_z^2} = \sqrt{(\cos(\frac{\theta}{2}))^2 + (k_1 \sin(\frac{\theta}{2}))^2 + (k_2 \sin(\frac{\theta}{2}))^2 + (k_3 \sin(\frac{\theta}{2}))^2} = 1 \Rightarrow$  a unit quaternion

Trig identities can be applied term-by-term to  $R_{\vec{k},\theta}$  to find  $R_{\vec{q}}$ .

$$\begin{aligned}
 r_{11} &= k_1^2 V_\theta + c_\theta \\
 &= k_1^2(1 - \cos(\theta)) + \cos(\theta) \\
 &= 2k_1^2 \underbrace{\left(\frac{1 - \cos(\theta)}{2}\right)}_{\sin^2(\frac{\theta}{2})} + \underbrace{\cos(\theta)}_{\cos^2(\frac{\theta}{2}) - \sin^2(\frac{\theta}{2})} \\
 &= \cos^2\left(\frac{\theta}{2}\right) + (2k_1^2 - \underbrace{1}_{k_1^2 + k_2^2 + k_3^2}) \sin^2\left(\frac{\theta}{2}\right) \\
 &= \cos^2\left(\frac{\theta}{2}\right) + (2k_1^2 - k_1^2 - k_2^2 - k_3^2) \sin^2\left(\frac{\theta}{2}\right) \\
 &= \cos^2\left(\frac{\theta}{2}\right) + (k_1^2 - k_2^2 - k_3^2) \sin^2\left(\frac{\theta}{2}\right) \\
 &= \underbrace{\cos^2\left(\frac{\theta}{2}\right)}_{q_s^2} + \underbrace{k_1^2 \sin^2\left(\frac{\theta}{2}\right)}_{q_x^2} - \underbrace{k_2^2 \sin^2\left(\frac{\theta}{2}\right)}_{q_y^2} - \underbrace{k_3^2 \sin^2\left(\frac{\theta}{2}\right)}_{q_z^2} \\
 &= q_s^2 + q_x^2 - q_y^2 - q_z^2
 \end{aligned}$$

$$R_{\bar{q}} = \begin{bmatrix} q_s^2 + q_x^2 - q_y^2 - q_z^2 & & & \\ & & & \\ & & & \\ & & & \end{bmatrix}$$



$$\begin{aligned}
 r_{12} &= k_1 k_2 V_\theta - k_3 s_\theta \\
 &= k_1 k_2 (1 - \cos(\theta)) - k_3 \sin(\theta) \\
 &= 2k_1 k_2 \underbrace{\left(\frac{1 - \cos(\theta)}{2}\right)}_{\sin^2\left(\frac{\theta}{2}\right)} - k_3 \underbrace{\sin(\theta)}_{2 \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{\theta}{2}\right)} \\
 &= 2 \underbrace{k_1 \sin\left(\frac{\theta}{2}\right)}_{q_x} \underbrace{k_2 \sin\left(\frac{\theta}{2}\right)}_{q_y} - 2 \underbrace{\cos\left(\frac{\theta}{2}\right)}_{q_s} \underbrace{k_3 \sin\left(\frac{\theta}{2}\right)}_{q_z} \\
 &= 2(q_x q_y - q_s q_z)
 \end{aligned}$$

$$R_{\bar{q}} = \begin{bmatrix} q_s^2 + q_x^2 - q_y^2 - q_z^2 & 2(q_x q_y - q_s q_z) & & \\ & & & \\ & & & \\ & & & \end{bmatrix}$$

and so on ...

Rotation matrix from given quaternion

$$R_{\bar{q}} = \begin{bmatrix} q_s^2 + q_x^2 - q_y^2 - q_z^2 & 2(q_x q_y - q_s q_z) & 2(q_x q_z + q_s q_y) \\ 2(q_x q_y + q_s q_z) & q_s^2 - q_x^2 + q_y^2 - q_z^2 & 2(q_y q_z - q_s q_x) \\ 2(q_x q_z - q_s q_y) & 2(q_y q_z + q_s q_x) & q_s^2 - q_x^2 - q_y^2 + q_z^2 \end{bmatrix}$$

## Quaternion from given rotation matrix

$$R_{\vec{q}} = \begin{bmatrix} q_s^2 + q_x^2 - q_y^2 - q_z^2 & 2(q_x q_y - q_s q_z) & 2(q_x q_z + q_s q_y) \\ 2(q_x q_y + q_s q_z) & q_s^2 - q_x^2 + q_y^2 - q_z^2 & 2(q_y q_z - q_s q_x) \\ 2(q_x q_z - q_s q_y) & 2(q_y q_z + q_s q_x) & q_s^2 - q_x^2 - q_y^2 + q_z^2 \end{bmatrix}$$

$$= \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = R_{desired}$$

$$\Rightarrow q_s = \frac{1}{2} \sqrt{1 + r_{11} + r_{22} + r_{33}} \text{ and } \vec{q} = \frac{1}{4q_s} \begin{bmatrix} r_{32} - r_{23} \\ r_{13} - r_{31} \\ r_{21} - r_{12} \end{bmatrix}$$

where we have to be careful when  $\theta = 180^\circ$  and  $q_s = 0$ . Note issue is with conversion rather than quaternions or rotation matrices.

Quaternions can be used to describe orientation and compose rotations like rotation matrices

- $C_b^a \Leftrightarrow \bar{q}_b^a$
- $C_f^i = R_2 R_1 R_3 \Leftrightarrow \bar{q}_f^i = \bar{q}_2 \otimes \bar{q}_1 \otimes \bar{q}_3$

- Quaternion inverse or conjugate

$$\bar{q}^{-1} = \bar{q}^* = \begin{bmatrix} q_s \\ -q_x \\ -q_y \\ -q_z \end{bmatrix}$$

- Vector transformation (change of coordinates)

Define a “pure” vector

$$\check{v} = \begin{bmatrix} 0 \\ \vec{v} \end{bmatrix}$$

then a vector  $\vec{v}^P$  written in the  $p$ -frame may be transformed to the  $i$ -frame using

$$\check{v}^i = \bar{q} \otimes \check{v}^P \otimes \bar{q}^{-1}$$

Quaternion multiplication - first type  $\otimes$

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

where implementation via matrix multiplication achieved by defining

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

Note multiplication does not commute.

Quaternion multiplication - second type  $\circledast$  (useful to re-order multiplication when certain factorizations and coordinatizations needed)

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

where

$$\vec{q} \otimes \vec{p} = \vec{p} \circledast \vec{q}$$

and

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



## Identities for quaternions

$$[\bar{q}^{-1} \otimes] = [\bar{q} \otimes]^{-1} = [\bar{q} \otimes]^T$$

$$[\bar{q}^{-1} \circledast] = [\bar{q} \circledast]^{-1} = [\bar{q} \circledast]^T$$

$$[\bar{q} \otimes] = e^{\frac{1}{2}[\check{k} \otimes]} = \cos(\theta/2)\mathcal{I} + \frac{1}{2}[\check{k} \otimes] \frac{\sin(\theta/2)}{\theta/2}$$

$$[\bar{q} \circledast] = e^{\frac{1}{2}[\check{k} \circledast]} = \cos(\theta/2)\mathcal{I} + \frac{1}{2}[\check{k} \circledast] \frac{\sin(\theta/2)}{\theta/2}$$

$$[\bar{q} \otimes][\bar{q} \circledast]^{-1} = [\bar{q} \circledast]^{-1}[\bar{q} \otimes] = \begin{bmatrix} 1 & 0 \\ 0 & \mathcal{T}(\bar{q}) \end{bmatrix}$$

$$\bar{q} \otimes \bar{p} \otimes \bar{r} = (\bar{q} \otimes \bar{p}) \otimes \bar{r} = \bar{q} \otimes (\bar{p} \otimes \bar{r})$$

$$\bar{q} * \bar{p} * \bar{r} = (\bar{q} * \bar{p}) * \bar{r} = \bar{q} * (\bar{p} * \bar{r})$$

$$(\bar{q} * \bar{p}) \otimes \bar{r} \neq \bar{q} * (\bar{p} \otimes \bar{r})$$

$$(\bar{q} \otimes \bar{p}) * \bar{r} \neq \bar{q} \otimes (\bar{p} * \bar{r})$$

