

2.7 The determinant of a matrix is equal to the product of its eigenvalues. Thus

$$\det(\mathbf{I} + \mathbf{u}\mathbf{v}^T) = \det(\mathbf{T}) = \lambda_1\lambda_2\lambda_3 = 1 + \mathbf{v}^T\mathbf{u} = 1 + \mathbf{u} \cdot \mathbf{v}$$

2.8 From $\mathbf{Q} = \mathbf{R}_1\mathbf{R}_2$, we have

$$\mathbf{Q}\mathbf{Q}^T = \mathbf{R}_1\mathbf{R}_2(\mathbf{R}_1\mathbf{R}_2)^T = \mathbf{R}_1 \underbrace{\mathbf{R}_2\mathbf{R}_2^T}_{\mathbf{I}} \mathbf{R}_1^T = \mathbf{R}_1\mathbf{R}_1^T = \mathbf{I}$$

and thus $\mathbf{Q}$ is orthogonal. Moreover, we have

$$\det(\mathbf{Q}) = \det(\mathbf{R}_1)\det(\mathbf{R}_2) = (-1)(-1) = 1$$

Thus, $\mathbf{Q}$ is a rotation.

Let $\mathbf{u}$ and ϕ be the unit vector parallel to the axis of rotation and the angle of rotation, respectively; then,

$$\mathbf{Q} = (\mathbf{I} - 2\mathbf{e}\mathbf{e}^T)(\mathbf{I} - 2\mathbf{f}\mathbf{f}^T) = \mathbf{I} - 2\mathbf{e}\mathbf{e}^T - 2\mathbf{f}\mathbf{f}^T + 4(\mathbf{e}^T\mathbf{f})\mathbf{e}\mathbf{f}^T$$

Hence,

$$\text{vect}(\mathbf{Q}) = -\frac{1}{2}4(\mathbf{e}^T\mathbf{f})\mathbf{e} \times \mathbf{f} = \mathbf{u} \sin \phi$$

and

$$\text{tr}(\mathbf{Q}) = 3 - 2 - 2 + 4(\mathbf{e}^T\mathbf{f})^2 = 4(\mathbf{e}^T\mathbf{f})^2 - 1 = 1 + 2\cos \phi$$

Therefore,

$$\sin \phi = \|\text{vect}(\mathbf{Q})\| = 2|\mathbf{e}^T\mathbf{f}| \|\mathbf{e} \times \mathbf{f}\|, \quad 0 \leq \phi < \pi$$

whence

$$\mathbf{u} = -\frac{\mathbf{e} \times \mathbf{f}}{\|\mathbf{e} \times \mathbf{f}\|} \text{sign}(\mathbf{e}^T\mathbf{f})$$

where $\text{sign}(\mathbf{e}^T\mathbf{f})$ is the *signum function*, which is $+1$ if $\mathbf{e}^T\mathbf{f} > 0$, -1 if $\mathbf{e}^T\mathbf{f} < 0$, and undefined if $\mathbf{e}^T\mathbf{f} = 0$. Hence, $\mathbf{u}$ is undefined if $\mathbf{e}^T\mathbf{f} = 0$, which indicates that $\mathbf{Q} = \mathbf{I} - 2\mathbf{e}\mathbf{e}^T - 2\mathbf{f}\mathbf{f}^T$, in which case $\mathbf{Q}$ is symmetric, as in Exercise 2.13, and

$$\mathbf{u} = \mathbf{e} \times \mathbf{f}, \quad \phi = \pi$$

Hence, if $\mathbf{e}^T\mathbf{f} \neq 0$,

$$\cos \phi = 2(\mathbf{e}^T\mathbf{f})^2 - 1, \quad \Rightarrow \quad \phi = \tan^{-1} \left[\frac{2|\mathbf{e}^T\mathbf{f}| \|\mathbf{e} \times \mathbf{f}\|}{2(\mathbf{e}^T\mathbf{f})^2 - 1} \right]$$

2.9 The product $\mathbf{Q} = \mathbf{R}_1\mathbf{R}_2$ is readily computed as

$$\mathbf{Q} = (\mathbf{I} - 2\mathbf{e}\mathbf{e}^T)(\mathbf{I} - 2\mathbf{f}\mathbf{f}^T) = \mathbf{I} - 2\mathbf{e}\mathbf{e}^T - 2\mathbf{f}\mathbf{f}^T + 4(\mathbf{e}^T\mathbf{f})\mathbf{e}\mathbf{f}^T$$

Let ϕ be the angle of rotation of $\mathbf{Q}$, and hence,

$$\text{tr}(\mathbf{Q}) = 3 - 2 - 2 + 4(\mathbf{e}^T\mathbf{f})^2 = 4(\mathbf{e}^T\mathbf{f})^2 - 1 = 1 + 2\cos \phi$$

If $\mathbf{e}^T\mathbf{f} \neq 0$, then

$$\cos \phi = 2(\mathbf{e}^T\mathbf{f})^2 - 1.$$

Because $|\cos \phi| \leq 1$, we can write the above expression in the form

$$-1 \leq 2(\mathbf{e}^T\mathbf{f})^2 - 1 \leq 1 \quad \text{or} \quad 0 \leq |\mathbf{e}^T\mathbf{f}| \leq 1.$$

Since $\mathbf{e}$ and $\mathbf{f}$ are unit vectors, this condition is always respected for any $\mathbf{e}$ or $\mathbf{f}$. However,

$$\text{vect}(\mathbf{Q}) = 4(\mathbf{e}^T\mathbf{f})\text{vect}(\mathbf{e}\mathbf{f}^T) = -2(\mathbf{e}^T\mathbf{f})\mathbf{e} \times \mathbf{f}$$

where we have recalled relation (2.60). The axis of rotation of $\mathbf{Q}$ should thus be parallel to $\mathbf{e} \times \mathbf{f}$, which is the sole condition for $\mathbf{Q}$ to be factorable as $\mathbf{R}_1\mathbf{R}_2$.

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