Quaternion Algebra and Calculus

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This document provides a mathematical summary of quaternion algebra and calculus and how they relate to rotations and interpolation of rotations. The ideas are based on the article [1].

1 Quaternion Algebra

A *quaternion* is given by $q = w + xi + yj + zk$ where w, x, y, and z are real numbers. Define $q_n = w_n + x_n i + y_n j + z_n k$ ($n = 0, 1$). *Addition* and *subtraction* of quaternions is defined by

$$
\begin{aligned}
q_0 \pm q_1 &= (w_0 + x_0 i + y_0 j + z_0 k) \pm (w_1 + x_1 i + y_1 j + z_1 k) \\
&= (w_0 \pm w_1) + (x_0 \pm x_1)i + (y_0 \pm y_1)j + (z_0 \pm z_1)k.
\end{aligned}
\tag{1}
$$

Multiplication for the primitive elements i, j, and k is defined by $i^2 = j^2 = k^2 = -1$, $ij = -ji = k$, $jk = -kj = i$, and $ki = -ik = j$. *Multiplication* of quaternions is defined by

$$
\begin{aligned}
q_0 q_1 &= (w_0 + x_0 i + y_0 j + z_0 k)(w_1 + x_1 i + y_1 j + z_1 k) \\
&= (w_0 w_1 - x_0 x_1 - y_0 y_1 - z_0 z_1) \\
&\quad (w_0 x_1 + x_0 w_1 + y_0 z_1 - z_0 y_1)i+ \\
&\quad (w_0 y_1 - x_0 z_1 + y_0 w_1 + z_0 x_1)j+ \\
&\quad (w_0 z_1 + x_0 y_1 - y_0 x_1 + z_0 w_1)k.
\end{aligned}
\tag{2}
$$

Multiplication is not commutative in that the products $q_0 q_1$ and $q_1 q_0$ are not necessarily equal.

The *conjugate* of a quaternion is defined by

$$
q^* = (w + xi + yj + zk)^* = w - xi - yj - zk.
\tag{3}
$$

The conjugate of a product of quaternions satisfies the properties $(p^*)^* = p$ and $(pq)^* = q^* p^*$.

The *norm* of a quaternion is defined by

$$
N(q) = N(w + xi + yj + zk) = w^2 + x^2 + y^2 + z^2.
\tag{4}
$$

The norm is a real–valued function and the norm of a product of quaternions satisfies the properties $N(q^*) = N(q)$ and $N(pq) = N(p)N(q)$.

The *multiplicative inverse* of a quaternion q is denoted q^{-1} and has the property $qq^{-1} = q^{-1}q = 1$. It is constructed as

$$q^{-1} = q^*/N(q) \tag{5}$$

where the division of a quaternion by a real–valued scalar is just componentwise division. The inverse operation satisfies the properties $(p^{-1})^{-1} = p$ and $(pq)^{-1} = q^{-1}p^{-1}$.

A simple but useful function is the *selection* function

$$W(q) = W(w + xi + yj + zk) = w \tag{6}$$

which selects the "real part" of the quaternion. This function satisfies the property $W(q) = (q + q^*)/2$.

The quaternion $q = w + xi + yj + zk$ may also be viewed as $q = w + \hat{v}$ where $\hat{v} = xi + yj + zk$. If we identify $\hat{v}$ with the 3D vector (x, y, z), then quaternion multiplication can be written using vector dot product ($\bullet$) and cross product ($\times$) as

$$(w_0 + \hat{v}_0)(w_1 + \hat{v}_1) = (w_0 w_1 - \hat{v}_0 \bullet \hat{v}_1) + w_0 \hat{v}_1 + w_1 \hat{v}_0 + \hat{v}_0 \times \hat{v}_1. \tag{7}$$

In this form it is clear that $q_0 q_1 = q_1 q_0$ if and only if $\hat{v}_0 \times \hat{v}_1 = 0$ (these two vectors are parallel).

A quaternion q may also be viewed as a 4D vector (w, x, y, z). The *dot product* of two quaternions is

$$q_0 \bullet q_1 = w_0 w_1 + x_0 x_1 + y_0 y_1 + z_0 z_1 = W(q_0 q_1^*). \tag{8}$$

A *unit quaternion* is a quaternion q for which $N(q) = 1$. The inverse of a unit quaternion and the product of unit quaternions are themselves unit quaternions. A unit quaternion can be represented by

$$q = \cos\theta + \hat{u}\sin\theta \tag{9}$$

where $\hat{u}$ as a 3D vector has length 1. However, observe that the quaternion product $\hat{u}\hat{u} = -1$. Note the similarity to unit length complex numbers $\cos\theta + i\sin\theta$. In fact, Euler's identity for complex numbers generalizes to quaternions,

$$\exp(\hat{u}\theta) = \cos\theta + \hat{u}\sin\theta, \tag{10}$$

where the exponential on the left–hand side is evaluated by symbolically substituting $\hat{u}\theta$ into the power series representation for $\exp(x)$ and replacing products $\hat{u}\hat{u}$ by -1. From this identity it is possible to define the *power* of a unit quaternion,

$$q^t = (\cos\theta + \hat{u}\sin\theta)^t = \exp(\hat{u}t\theta) = \cos(t\theta) + \hat{u}\sin(t\theta). \tag{11}$$

It is also possible to define the *logarithm* of a unit quaternion,

$$\log(q) = \log(\cos\theta + \hat{u}\sin\theta) = \log(\exp(\hat{u}\theta)) = \hat{u}\theta. \tag{12}$$

It is important to note that the noncommutativity of quaternion multiplication disallows the standard identities for exponential and logarithm functions. The quaternions $\exp(p)\exp(q)$ and $\exp(p + q)$ are not necessarily equal. The quaternions $\log(pq)$ and $\log(p) + \log(q)$ are not necessarily equal.

2 Relationship of Quaternions to Rotations

A unit quaternion $q = \cos\theta + \hat{u}\sin\theta$ represents the rotation of the 3D vector $\hat{v}$ by an angle 2θ about the 3D axis $\hat{u}$. The rotated vector, represented as a quaternion, is $R(\hat{v}) = q\hat{v}q^*$. The proof requires showing that $R(\hat{v})$ is a 3D vector, a length–preserving function of 3D vectors, a linear transformation, and does not have a reflection component.

To see that $R(\hat{v})$ is a 3D vector,

$$
\begin{aligned}
W(R(\hat{v})) &= W(q\hat{v}q^*) \\
&= [(q\hat{v}q^*) + (q\hat{v}q^*)^*]/2 \\
&= [q\hat{v}q^* + q\hat{v}^*q^*]/2 \\
&= q[(\hat{v} + \hat{v}^*)/2]q^* \\
&= qW(\hat{v})q^* \\
&= W(\hat{v}) \\
&= 0.
\end{aligned}
$$

To see that $R(\hat{v})$ is length–preserving,

$$
\begin{aligned}
N(R(\hat{v})) &= N(q\hat{v}q^*) \\
&= N(q)N(\hat{v})N(q^*) \\
&= N(q)N(\hat{v})N(q) \\
&= N(\hat{v}).
\end{aligned}
$$

To see that $R(\hat{v})$ is a linear transformation, let a be a real–valued scalar and let $\hat{v}$ and $\hat{w}$ be 3D vectors; then

$$
\begin{aligned}
R(a\hat{v} + \hat{w}) &= q(a\hat{v} + \hat{w})q^* \\
&= (qa\hat{v}q^*) + (q\hat{w}q^*) \\
&= a(q\hat{v}q^*) + (q\hat{w}q^*) \\
&= aR(\hat{v}) + R(\hat{w}),
\end{aligned}
$$

thereby showing that the transform of a linear combination of vectors is the linear combination of the transforms.

The previous three properties show that $R(\hat{v})$ is an orthonormal transformation. Such transformations include rotations *and* reflections. Consider R as a function of q for a *fixed vector* $\hat{v}$. That is, $R(q) = q\hat{v}q^*$. This function is a continuous function of q. For each q it is a linear transformation with determinant $D(q)$, so the determinant itself is a continuous function of q. Thus, $\lim_{q \to 0} R(q) = I$, the identity function (the limit is taken along any path of quaternions which approach the zero quaternion) and $\lim_{q \to 0} D(q) = D(0) = 1$. By continuity, $D(q)$ is identically 1 and $R(q)$ does not have a reflection component.

Now we prove that the unit rotation axis is the 3D vector $\hat{u}$ and the rotation angle is 2θ. To see that $\hat{u}$ is a unit rotation axis we need only show that $\hat{u}$ is unchanged by the rotation. Recall that $\hat{u}^2 = \hat{u}\hat{u} = -1$. This

implies that $\hat{u}^3 = -\hat{u}$. Now

$$
\begin{aligned}
R(\hat{u}) &= q\hat{u}q^* \\
&= (\cos\theta + \hat{u}\sin\theta)\hat{u}(\cos\theta - \hat{u}\sin\theta) \\
&= (\cos\theta)^2\hat{u} - (\sin\theta)^2\hat{u}^3 \\
&= (\cos\theta)^2\hat{u} - (\sin\theta)^2(-\hat{u}) \\
&= \hat{u}.
\end{aligned}
$$

To see that the rotation angle is 2θ, let $\hat{u}$, $\hat{v}$, and $\hat{w}$ be a right–handed set of orthonormal vectors. That is, the vectors are all unit length; $\hat{u} \bullet \hat{v} = \hat{u} \bullet \hat{w} = \hat{v} \bullet \hat{w} = 0$; and $\hat{u} \times \hat{v} = \hat{w}$, $\hat{v} \times \hat{w} = \hat{u}$, and $\hat{w} \times \hat{u} = \hat{v}$. The vector $\hat{v}$ is rotated by an angle ϕ to the vector $q\hat{v}q^*$, so $\hat{v} \bullet (q\hat{v}q^*) = \cos(\phi)$. Using equation (8) and $\hat{v}^* = -\hat{v}$, and $\hat{p}^2 = -1$ for unit quaternions with zero real part,

$$
\begin{aligned}
\cos(\phi) &= \hat{v} \bullet (q\hat{v}q^*) \\
&= W(\hat{v}^*q\hat{v}q^*) \\
&= W[-\hat{v}(\cos\theta + \hat{u}\sin\theta)\hat{v}(\cos\theta - \hat{u}\sin\theta)] \\
&= W[(-\hat{v}\cos\theta - \hat{v}\hat{u}\sin\theta)(\hat{v}\cos\theta - \hat{v}\hat{u}\sin\theta)] \\
&= W[-\hat{v}^2(\cos\theta)^2 + \hat{v}^2\hat{u}\sin\theta\cos\theta - \hat{v}\hat{u}\hat{v}\sin\theta\cos\theta + (\hat{v}\hat{u})^2(\sin\theta)^2] \\
&= W[(\cos\theta)^2 - (\sin\theta)^2 - (\hat{u} + \hat{v}\hat{u}\hat{v})\sin\theta\cos\theta]
\end{aligned}
$$

Now $\hat{v}\hat{u} = -\hat{v} \bullet \hat{u} + \hat{v} \times \hat{u} = \hat{v} \times \hat{u} = -\hat{w}$ and $\hat{v}\hat{u}\hat{v} = -\hat{w}\hat{v} = \hat{w} \bullet \hat{v} - \hat{w} \times \hat{v} = \hat{u}$. Consequently,

$$
\begin{aligned}
\cos(\phi) &= W[(\cos\theta)^2 - (\sin\theta)^2 - (\hat{u} + \hat{v}\hat{u}\hat{v})\sin\theta\cos\theta] \\
&= W[(\cos\theta)^2 - (\sin\theta)^2 - \hat{u}(2\sin\theta\cos\theta)] \\
&= (\cos\theta)^2 - (\sin\theta)^2 \\
&= \cos(2\theta)
\end{aligned}
$$

and the rotation angle is $\phi = 2\theta$.

It is important to note that the quaternions q and $-q$ represent the same rotation since $(-q)\hat{v}(-q)^* = q\hat{v}q^*$. While either quaternion will do, the interpolation methods require choosing one over the other.

3   Quaternion Calculus

The only support we need for quaternion interpolation is to differentiate unit quaternion functions raised to a real–valued power. These formulas are identical to those derived in a standard calculus course, but the order of multiplication must be observed.

The derivative of the function q^t where q is a constant unit quaternion is

$$
\frac{d}{dt}q^t = q^t \log(q) \tag{13}
$$

where log is the function defined earlier by $\log(\cos\theta + \hat{u}\sin\theta) = \hat{u}\theta$. The power can be a function itself,

$$\frac{d}{dt}q^{f(t)} = f'(t)q^{f(t)}\log(q) \tag{14}$$

4 Spherical Linear Interpolation

Given two distinct points on a unit hypersphere in n–dimensional space, it is possible to interpolate between them by sampling along a great arc containing the two points. In particular, the idea may be applied to quaternions as points on the unit hypersphere in 4–dimensional space.

To construct the formula, let q_0 and q_1 be distinct unit vectors on the hypersphere. We seek an interpolation

$$q(t) = c_0(t)q_0 + c_1(t)q_1, \;\; 0 \le t \le 1,$$

where $c_0(t)$ and $c_1(t)$ are real–valued functions and where $q(t)$ is always a unit vector. Moreover, $c_0(0) = 1$, $c_1(0) = 0$, $c_0(1) = 0$, and $c_1(1) = 1$. Thus,

$$1 = q(t) \bullet q(t) = c_0(t)^2 + 2c_0(t)c_1(t)(q_0 \bullet q_1) + c_1(t)^2 = \begin{bmatrix} c_0 & c_1 \end{bmatrix}^T \begin{bmatrix} 1 & d \\ d & 1 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \end{bmatrix} = c^t M c$$

where $d = q_0 \bullet q_1 = \cos\theta$ and θ is the angle between the two unit quaternions. The matrix M is positive definite since $|d| < 1$. It can be factored as $M = R^t D R$ where $D = \text{diag}(1 + d, 1 - d)$ and R is orthogonal with first column $(1, -1)/\sqrt{2}$ and second column $(1, 1)/\sqrt{2}$. Defining $u = \sqrt{D}Rc$, the displayed equation becomes $u^T u = 1$. Therefore u is a unit length vector and can be written as $u = (\cos(\omega t)), \sin(\omega t))$. Solving for c_0 yields

$$c_0 = \frac{\cos(\omega t)}{\sqrt{2(1 + d)}} - \frac{\sin(\omega t)}{\sqrt{2(1 - d)}} = \frac{\sin(\omega t + \psi_0)}{\sqrt{1 - d^2}} = \frac{\sin(\omega t + \psi_0)}{\sin\theta}$$

for some phase angle ψ_0. Similarly

$$c_1 = \frac{\sin(\omega t + \psi_1)}{\sin\theta}$$

for some phase angle ψ_1. Using the boundary conditions for c_0 we obtain $1 = \sin(\psi_0)/\sin\theta$ and $0 = \sin(\omega + \psi_0)/\sin\theta$ which are satisfied when $\psi_0 = \theta$ and $\omega = -\theta$. Thus,

$$c_0(t) = \frac{\sin((1 - t)\theta)}{\sin\theta}.$$

Using the boundary conditions for c_1 we obtain $0 = \sin(\psi_1)/\sin\theta$ and $1 = \sin(\omega + \psi_1)/\sin\theta$ which are satisfied when $\psi_1 = 0$ and $\omega = \theta$. Thus,

$$c_1(t) = \frac{\sin(t\theta)}{\sin\theta}.$$

The spherical linear interpolation, abbreviated as *slerp*, is defined by

$$\text{Slerp}(t; q_0, q_1) = \frac{q_0 \sin((1 - t)\theta) + q_1 \sin(t\theta)}{\sin\theta} \tag{15}$$

for $0 \le t \le 1$.

5

Although q_1 and $-q_1$ represent the same rotation, the values of $\mathrm{Slerp}(t; q_0, q_1)$ and $\mathrm{Slerp}(t; q_0, -q_1)$ are not the same. It is customary to choose the sign σ on q_1 so that $q_0 \bullet (\sigma q_1) \geq 0$ (the angle between q_0 and σq_1 is acute). This choice avoids extra spinning caused by the interpolated rotations.

For unit quaternions, slerp can be written as

$$\mathrm{Slerp}(t; q_0, q_1) = q_0 \left(q_0^{-1} q_1 \right)^t . \tag{16}$$

The idea is that $q_1 = q_0(q_0^{-1}q_1)$. The term $q_0^{-1}q_1 = \cos\theta + \hat{u}\sin\theta$ where θ is the angle between q_0 and q_1. The time parameter can be introduced into the angle so that the adjustment of q_0 varies uniformly with over the great arc between q_0 and q_1. That is, $q(t) = q_0[\cos(t\theta) + \hat{u}\sin(t\theta)] = q_0[\cos\theta + \hat{u}\sin\theta]^t = q_0(q_0^{-1}q_1)^t$.

The derivative of slerp in the form of equation (16) is a simple application of equation (13),

$$\mathrm{Slerp}'(t; q_0, q_1) = q_0(q_0^{-1}q_1)^t \log(q_0^{-1}q_1). \tag{17}$$

Note that $\mathrm{Slerp}'(0; q_0, q_1) = q_0 \log(q_0^{-1}q_1)$ and $\mathrm{Slerp}(1; q_0, q_1) = q_1 \log(q_0^{-1}q_1)$.

5 Spherical Cubic Interpolation

Cubic interpolation of quaternions can be achieved using a method described in [2] which has the flavor of bilinear interpolation on a quadrilateral. The evaluation uses an iteration of three slerps and is simliar to the de Casteljau algorithm (see [3]). Imagine four quaternions p, a, b, and q as the ordered vertices of a quadrilateral. Interpolate c along the "edge" from p to q using slerp. Interpolate d along the "edge" from a to b. Now interpolate the edge interpolations c and d to get the final result e. The end result is denoted *squad* and is given by

$$\mathrm{Squad}(t; p, a, b, q) = \mathrm{Slerp}(2t(1-t); \mathrm{Slerp}(t; p, q), \mathrm{Slerp}(t; a, b)) \tag{18}$$

For unit quaternions we can use equation (16) to obtain a similar formula for squad,

$$\mathrm{Squad}(t; p, a, b, q) = \mathrm{Slerp}(t; p, q)(\mathrm{Slerp}(t; p, q)^{-1}\mathrm{Slerp}(t; a, b))^{2t(1-t)} \tag{19}$$

The derivative of squad in equation (19) is computed as follows. Let $u(t) = c_0(t)p + c_1(t)q$, $v(t) = c_0(t)a + c_1(t)b$, and $S(t) = \mathrm{Squad}(t; p, a, b, q) = c_0(2t(1-t))u(t) + c_1(2t(1-t))v(t)$. The derivative is

$$
\begin{aligned}
S'(t) \quad = \quad & c_0(2t(1-t))u'(t) + c_0'(2t(1-t))(2-4t)u(t) + \\
& c_1(2t(1-t))v'(t) + c_1'(2t(1-t))(2-4t)v(t).
\end{aligned}
$$

Evaluating at $t = 0$ yields

$$
\begin{aligned}
S'(0) \quad = \quad & c_0(0)u'(0) + 2c_0'(0)u(0) + c_1(0)v'(0) + 2c_1'(0)v(0) \\
= \quad & u'(0) + 2[c_0'(0)u(0) + c_1'(0)v(0)] \\
= \quad & p\log(p^{-1}q) + 2p\log(p^{-1}a).
\end{aligned}
$$

Similarly,

$$
\begin{aligned}
S'(1) &= c_0(0)u'(1) - 2c_0'(0)u(1) + c_1(0)v'(1) - 2c_1'(0)v(1) \\
&= u'(1) - 2[c_0'(0)u(1) + c_1'(0)v(1)] \\
&= q\log(p^{-1}q) - 2q\log(q^{-1}b).
\end{aligned}
$$

The derivatives of squad at the endpoints are

$$
\begin{aligned}
\text{Squad}'(0; p, a, b, q) &= p[\log(p^{-1}q) + 2\log(p^{-1}a)] \\
\text{Squad}'(1; p, a, b, q) &= q[\log(p^{-1}q) - 2\log(q^{-1}b)]
\end{aligned}
\tag{20}
$$

6 Spline Interpolation of Quaternions

Given a sequence of N unit quaternions $\{q_n\}_{n=0}^{N-1}$, we want to build a spline which interpolates those quaternions subject to the conditions that the spline pass through the control points and that the derivatives are continuous. The idea is to choose intermediate quaternions a_n and b_n to allow control of the derivatives at the endpoints of the spline segments. More precisely, let $S_n(t) = \text{Squad}(t; q_n, a_n, b_{n+1}, q_{n+1})$ be the spline segments. By definition of squad it is easily shown that

$$
S_{n-1}(1) = q_n = S_n(0).
$$

To obtain continuous derivatives at the endpoints we need to match the derivatives of two consecutive spline segments,

$$
S'_{n-1}(1) = S'_n(0).
$$

It can be shown from equation (20) that

$$
S'_{n-1}(1) = q_n[\log(q_{n-1}^{-1}q_n) - 2\log(q_n^{-1}b_n)]
$$

and

$$
S'_n(0) = q_n[\log(q_n^{-1}q_{n+1}) + 2\log(q_n^{-1}a_n)].
$$

The derivative continuity equation provides one equation in the two unknowns a_n and b_n, so we have one degree of freedom. As suggested in [1], a good choice for the derivative at the control point uses an average T_n of "tangents", so $S'_{n-1}(1) = q_nT_n = S'_n(0)$ where

$$
T_n = \frac{\log(q_n^{-1}q_{n+1}) + \log(q_{n-1}^{-1}q_n)}{2}.
\tag{21}
$$

We now have two equations to determine a_n and b_n. Some algebra will show that

$$
a_n = b_n = q_n \exp\left(-\frac{\log(q_n^{-1}q_{n+1}) + \log(q_n^{-1}q_{n-1})}{4}\right).
\tag{22}
$$

Thus, $S_n(t) = \text{Squad}(t; q_n, a_n, a_{n+1}, q_{n+1})$.

EXAMPLE. To illustrate the cubic nature of the interpolation, consider a sequence of quaternions whose general term is $q_n = \exp(i\theta_n)$. This is a sequence of complex numbers whose products do commute and for which the usual properties of exponents and logarithms do apply. The intermediate terms are

$$
a_n = \exp(-i(\theta_{n+1} - 6\theta_n + \theta_{n-1})/4).
$$

7

Also,
$$\text{Slerp}(t, q_n, q_{n+1}) = \exp(i((1-t)\theta_n + t\theta_{n+1}))$$

and
$$\text{Slerp}(t, a_n, a_{n+1}) = \exp(-i((1-t)(\theta_{n+1} - 6\theta_n + \theta_{n-1}) + t(\theta_{n+2} - 6\theta_{n+1} + \theta_n))/4).$$

Finally,

$$
\begin{aligned}
\text{Squad}(t, q_n, a_n, a_{n+1}, q_{n+1}) \quad = \quad & \exp([1 - 2t(1-t)][(1-t)\theta_n + t\theta_{n+1}] \\
& - [2t(1-t)/4][(1-t)(\theta_{n+1} - 6\theta_n + \theta_{n-1}) + t(\theta_{n+2} - 6\theta_{n+1} + \theta_n)]).
\end{aligned}
$$

The angular cubic interpolation is

$$\phi(t) = -\frac{1}{2}t^2(1-t)\theta_{n+2} + \frac{1}{2}t(2 + 2(1-t) - 3(1-t)^2)\theta_{n+1} + \frac{1}{2}(1-t)(2 + 2t - 3t^2)\theta_n - \frac{1}{2}t(1-t)^2\theta_{n-1}.$$

It can be shown that $\phi(0) = \theta_n$, $\phi(1) = \theta_{n+1}$, $\phi'(0) = (\theta_{n+1} - \theta_{n-1})/2$, and $\phi'(1) = (\theta_{n+2} - \theta_n)/2$. The derivatives at the end points are centralized differences, the average of left and right derivatives as expected.

References

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