How to Estimate Attitude from Vector Observations

AAS Paper 99-427, presented at the
AAS/AIAA Astrodynamics Specialist Conference,
Girdwood, Alaska
August 16–19, 1999

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Wahba's Problem - SIAM Review, July 1965

Find the orthogonal matrix $A$ with determinant $+1$ that minimizes

$$L(A) \equiv \frac{1}{2} \sum_{i} a_i |b_i - Ar_i|^2 .$$

where $\{b_i\}$ are unit vectors in a body frame, $\{r_i\}$ are unit vectors in a reference frame, and $\{a_i\}$ are non-negative weights. Writing

$$L(A) = \lambda_0 - \text{tr}(AB^T), \quad \text{with} \quad \lambda_0 \equiv \sum_i a_i \quad \text{and} \quad B \equiv \sum_i a_i b_i r_i^T,$$

it is clear that we can minimize $L(A)$ by maximizing $\text{tr}(AB^T)$.

This is equivalent to the orthogonal Procrustes problem, which is to find the orthogonal matrix $A$ that is closest to $B$ in the sense of the Frobenius norm,

$$\|M\|_F^2 \equiv \sum_{i,j} M_{ij}^2 = \text{tr}(MM^T), \quad \text{since}$$

$$\|A - B\|_F^2 = \|A\|_F^2 + \|B\|_F^2 - 2\text{tr}(AB^T) = 3 + \|B\|_F^2 - 2\text{tr}(AB^T)$$
First Solutions - *SIAM Review*, July 1966

1: J. L. Farrell and J. C. Stuelpnagel:

\[ B \text{ has the polar decomposition } B = WH \text{ where } W \text{ is orthogonal and } H \text{ is symmetric and positive semidefinite.} \]

If \( \det W \) is positive, then \( A_{opt} = W \).

Else, diagonalize \( H \) by \( H = VDV^T \), where \( V \) is orthogonal and \( D \) is diagonal with elements arranged in decreasing order.

Then \( A_{opt} = WV \text{ diag}[1 \ 1 \ \det W] V^T \).

2: R. H. Wessner:

\[ A_{opt} = (B^T)^{-1}(B^T B)^{1/2}, \text{ which is equivalent to } A_{opt} = B(B^T B)^{-1/2}. \]

This requires 3 vectors (\( \det B \neq 0 \)); only 2 are really needed.

Singular Value Decomposition (SVD) Method - 1987

$B$ has the Singular Value Decomposition:

$$B = U \Sigma V^T = U \text{diag}[\Sigma_{11} \; \Sigma_{22} \; \Sigma_{33}] \; V^T,$$

where $U$ and $V$ are orthogonal and $\Sigma_{11} \geq \Sigma_{22} \geq \Sigma_{33} \geq 0$.

The optimal attitude matrix is $A_{\text{opt}} = U \text{diag}[1 \; 1 \; (\det U)(\det V)] \; V^T$.

The SVD method is completely equivalent to the Farrell and Stueelpnagel solution with $U = WV$. The difference is that SVD algorithms exist now and are among the most robust numerical algorithms. MATLAB computes $A_{\text{opt}}$ from $B$ in two lines of code.
QUaternion ESTimator (QUEST) - 1978

The first three rows of \((\lambda_{\text{max}} I - K)q_{\text{opt}} = 0\) give

\[
q_{\text{opt}} = \frac{1}{\sqrt{\gamma^2 + |x|^2}} \begin{bmatrix} x \\ \gamma \end{bmatrix},
\]

where \(x \equiv \{\text{adj}[(\lambda_{\text{max}} + \text{tr}B)I - B - B^T]\}z\), and \(\gamma \equiv \det[(\lambda_{\text{max}} + \text{tr}B)I - B - B^T]\)

Find \(\lambda_{\text{max}}\) by Newton-Raphson iteration of the characteristic eqn.,

\[
\det(\lambda_{\text{max}} I - K) = (\lambda_{\text{max}} - \text{tr}B)\gamma - z^T x = 0.
\]

Iterate from \(\lambda_0\), since \(\lambda_{\text{max}}\) is very close to \(\lambda_0\) if \(L(A_{\text{opt}}) = \lambda_0 - \lambda_{\text{max}}\) is small. The analytic solution is slower and no more accurate.

QUEST would fail for 180° rotations, but the method of sequential rotations (effectively permuting \(q\) components) handles this case.
Solve the characteristic equation for $\lambda_{\text{max}}$ as in QUEST.

The adjoint of $\lambda_{\text{max}} I - K$ can be shown analytically to obey

$$\text{adj}(\lambda_{\text{max}} I - K) = (\lambda_{\text{max}} - \lambda_2)(\lambda_{\text{max}} - \lambda_3)(\lambda_{\text{max}} - \lambda_4)q_{\text{opt}}q_{\text{opt}}^T,$$

where $\lambda_2$, $\lambda_3$, and $\lambda_4$ are the other three eigenvalues of $K$.

Thus $q_{\text{opt}}$ can be computed by normalizing any non-zero column of $\text{adj}(\lambda_{\text{max}} I - K)$. This is the “4-dimensional cross-product” of the other three columns of $\lambda_{\text{max}} I - K$. 
Substituting \( q_{\text{opt}} = \begin{bmatrix} \mathbf{e} \sin(\phi/2) \\ \cos(\phi/2) \end{bmatrix} \) into \( (\lambda_{\text{max}} I - K)q_{\text{opt}} = 0 \) gives

\[
(\lambda_{\text{max}} - \text{tr} B) \cos(\phi/2) = \mathbf{e}^T \mathbf{z} \sin(\phi/2)
\]

and

\[
[(\lambda_{\text{max}} + \text{tr} B)I - B - B^T] \mathbf{e} \sin(\phi/2) = \mathbf{z} \cos(\phi/2).
\]

Eliminating the rotation angle \( \phi \) gives \( M \mathbf{e} = \mathbf{0} \), where

\[
M \equiv (\lambda_{\text{max}} - \text{tr} B)[(\lambda_{\text{max}} + \text{tr} B)I - B - B^T] - \mathbf{z} \mathbf{z}^T \equiv [\mathbf{m}_1 \ \mathbf{m}_2 \ \mathbf{m}_3].
\]

The rotation axis is \( \mathbf{e} = \mathbf{y}/|\mathbf{y}| \), where \( \mathbf{y} \) is any \( \mathbf{m}_i \times \mathbf{m}_j \). Then

\[
q_{\text{opt}} = \frac{1}{\sqrt{|(\lambda_{\text{max}} - \text{tr} B)\mathbf{y}|^2 + (\mathbf{z} \cdot \mathbf{y})^2}} \begin{bmatrix} (\lambda_{\text{max}} - \text{tr} B)\mathbf{y} \\ \mathbf{z} \cdot \mathbf{y} \end{bmatrix}.
\]
Find $\lambda_{\text{max}}$ by solving the characteristic equation

$$0 = (\lambda^2 - \|B\|_F^2)^2 - 8\lambda \det B - 4\|\text{adj} B\|_F^2.$$  

This becomes an easily solved quadratic in $\lambda^2$ if $\det B = 0$, as in the case of two observations. The attitude matrix is given by

$$A_{\text{opt}} = (\kappa\lambda_{\text{max}} - \det B)^{-1}[(\kappa + \|B\|_F^2)B + \lambda_{\text{max}}\text{adj} B^T - BB^T B],$$  

where $\kappa \equiv \frac{1}{2}(\lambda_{\text{max}}^2 - \|B\|_F^2)$.

For the analysis in this paper, the quaternion representation of the optimal attitude is computed.

ESOQ, ESOQ2, and FOAM avoid QUEST's sequential rotations.
Two-Observation Case

In this case det$B = 0$, the odd terms in $\lambda$ in the characteristic equation vanish, and

$$\lambda_{\text{max}} = \sqrt{a_1^2 + a_2^2 + 2a_1a_2[(b_1 \cdot b_2)(r_1 \cdot r_2) + |b_1 \times b_2||r_1 \times r_2|]}.$$  

This simplifies both QUEST and FOAM; FOAM gives

$$A_{\text{opt}} = b_3 r_3^T + (a_1/\lambda_{\text{max}})[b_1 r_1^T + (b_1 \times b_3)(r_1 \times r_3)^T]$$

$$+ (a_2/\lambda_{\text{max}})[b_2 r_2^T + (b_2 \times b_3)(r_2 \times r_3)^T],$$

where $b_3 \equiv (b_1 \times b_2)/|b_1 \times b_2|$ and $r_3 \equiv (r_1 \times r_2)/|r_1 \times r_2|$.

This goes over to the TRIAD solution for $a_1 = 0$, $a_2 = 0$, or $a_1 = a_2$. 
Sequential Methods

The basic idea is to propagate $B$ or $K$ to time $t$ and then update.

Filter QUEST - 1989

$$B(\text{new}) = \mu \Phi_{3\times3} B(\text{old}) + \sum_{i=k+1}^{k+n_t} a_i b_i r_i^T, \text{ sum over } n_t \text{ observations at } t.$$  

Recursive QUEST (REQUEST) - 1996

$$K(\text{new}) = \mu \Phi_{4\times4} K(\text{old}) \Phi^T_{4\times4} + \sum_{i=k+1}^{k+n_t} a_i \tilde{K}_i, \text{ where}$$

$$\tilde{K}_i \equiv \begin{bmatrix} b_i r_i^T + r_i b_i^T - (b_i \cdot r_i)I & (b_i \times r_i) \\ (b_i \times r_i)^T & b_i \cdot r_i \end{bmatrix}.$$  

These are mathematically equivalent. Filter QUEST requires fewer computations, but neither has been successful in practice.
Reynolds's Sequential Algorithm - 1997

There are two orthogonal quaternions that map a vector $r_i$ into $b_i$:

$$q_1 = \frac{1}{\sqrt{2(1 + b_i \cdot r_i)}} \left[ b_i \times r_i \right]$$
$$q_2 = \frac{1}{\sqrt{2}(1 + b_i \cdot r_i)} \left[ b_i + r_i \right].$$

These span the subspace of 4D quaternion space consistent with this measurement. The projection matrix onto this 2D subspace is

$$q_1q_1^T + q_2q_2^T = \frac{1}{2}(I + \tilde{K}_i).$$

We update the quaternion by

$$q(+) = (I + \eta\tilde{K}_i)q(-)/|(I + \eta\tilde{K}_i)q(-)|,$$

where $\eta = 1$ for perfect measurements, and $0 < \eta < 1$ for filtering.
Star Camera Attitude Determination (SCAD) - 1998

Write \( \mathbf{r}_i = \overline{\mathbf{r}} + (\mathbf{r}_i - \overline{\mathbf{r}}) \) with \( \overline{\mathbf{r}} = (\sum_i a_i \mathbf{r}_i) / (\sum_i a_i) \), and similarly for \( \mathbf{b}_i \).

Then

\[
L(A) \equiv (\frac{1}{2} \sum_i a_i) |\overline{\mathbf{b}} - A\overline{\mathbf{r}}|^2 + \frac{1}{2} \sum_i a_i |(\mathbf{b}_i - \overline{\mathbf{b}}) - A(\mathbf{r}_i - \overline{\mathbf{r}})|^2.
\]

For small-field-of-view sensors, the second term is much smaller than the first. The general quaternion minimizing the first term is

\[
q(\psi) = q_1 \cos(\psi/2) + q_2 \sin(\psi/2)
\]

where \( q_1 \) and \( q_2 \) are the two quaternions that map \( \overline{\mathbf{r}} / |\overline{\mathbf{r}}| \) into \( \overline{\mathbf{b}} / |\overline{\mathbf{b}}| \).

Then an arctangent gives the \( \psi \) that minimizes the second term.

Computation of \( \overline{\mathbf{r}} \) and \( \overline{\mathbf{b}} \) makes SCAD fairly slow.
Testing

MATLAB versions of the $q$ method, the SVD method, QUEST, ESOQ, ESOQ2 and FOAM were tested. The $q$ method used \texttt{eig} and the SVD method used \texttt{svd}. The other methods used 0, 1, or 2 iterations of the characteristic equation to compute $\lambda_{\max}$.

Three test scenarios were simulated:

Star tracker scenario: 5 stars in narrow field-of-view star tracker, 6 arcsecond per star per axis measurement errors

Unequal weights: one measurement with 1 arcsecond measurement noise, two with 1° measurement noise

Mismodeled weights: two measurements with 0.1° measurement noise and one with 1°, all weighted equally.

Each scenario was tested with 1000 random attitude matrices.
Accuracy Results

All algorithms performed equally well in the star tracker scenario.

The $q$ method, the SVD method, and FOAM performed well in the unequal weight scenario. The iterative refinement of $\lambda_{\text{max}}$ failed in QUEST, ESOQ, and ESOQ2 in this scenario.

A single update of $\lambda_{\text{max}}$ is required for best performance in the mismodeled weight scenario (except in the $q$ and SVD methods).

A second update of $\lambda_{\text{max}}$ may improve the agreement of the estimate with the optimal ($q$ and SVD method) attitude, but it never improves the agreement with the (simulated) true attitude.

Special first-order variants of ESOQ (ESOQF1) and ESOQ2 (ESOQ2.1) were developed to take advantage of this observation.
Timing of Slower Methods

Floating point operations vs. number of observed vectors.
Timing of Faster Methods

- ESOQ(1)
- ESOQ2(1)
- QUEST(1)
- ESOQ2.1
- ESOQF1
- QUEST(0)
- ESOQ2(0)
- ESOQ(0)

Floating point operations vs. number of observed vectors.
Summary

The most robust estimators minimizing Wahba’s loss function are Davenport’s $q$ method and the SVD method. The $q$ method is faster than the SVD method with three or more measurements.

The other algorithms are less robust since they solve the characteristic polynomial equation to find the maximum eigenvalue of Davenport’s $K$ matrix. They are only preferable when speed or processor power is an important consideration.

Of these, FOAM is the most robust and faster than the $q$ method.

Robustness is only an issue for measurements with widely differing accuracies, so the fastest algorithms, QUEST, ESOQ, and ESOQ2, are well suited to star sensor applications.