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The feet of the altitudes of a simplex

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1 Introduction

The construction of the feet of the altitudes of a triangle or a tetrahedron is a standard task in elementary geometry or solid geometry. The planar case is of particular interest: The feet $F_0, F_1, F_2 \in \mathbb{R}^2$ of the altitudes of a triangle with vertices $A_0, A_1, A_2 \in \mathbb{R}^2$ form the so-called orthic triangle. This triangle is the solution of Fagnano's problem (1775), see, e.g., [1]: Among all triangles P_0, P_1, P_2 with P_k on the side opposite to A_k ($k = 0, 1, 2$) or on its extension, find the triangle with minimal perimeter.

In $n \geq 2$ dimensions the computation of all feet $F_0, F_1, \dots, F_n \in \mathbb{R}^n$ of a simplex in \mathbb{R}^n from the coordinates of its vertices $A_0, A_1, \dots, A_n \in \mathbb{R}^n$ is therefore of interest. In this note we describe a surprisingly compact algorithm for this task that is valid in every

Im Unterricht in Elementargeometrie gehören die Höhen im Dreieck zum Standardstoff. Die Verallgemeinerung auf das Tetraeder im Raum liefert gelegentlich Material für Maturitätsaufgaben, etwa *Berechne den der Ecke A gegenüberliegenden Höhenfusspunkt F_A im Tetraeder ABCD aus den Koordinaten der Eckpunkte*. Es zeigt sich, dass es ein erstaunlich einfaches und kompaktes Verfahren für die simultane Berechnung *aller* Höhenfusspunkte eines n -dimensionalen Simplex gibt. Dieses funktioniert für alle Dimensionen $n \geq 1$ und beruht auf der Verwendung homogener Koordinaten und projektiver Räume. Nach einer kurzen Einführung dieser Begriffe werden zunächst alle Seitenflächen eines Simplex mit einer einzigen Matrixinversion berechnet.

dimension $n \geq 1$. The basis of our approach is the use of homogeneous coordinates that will be reviewed in the next section. Then, the faces of the simplex will be represented by means of an inverse matrix. Finally, the feet are obtained by intersecting the altitudes with the faces. An elegant code in MATLAB [4] will be given at the end.

2 Homogeneous coordinates

In homogeneous coordinates the point $X = (X_1, X_2, \dots, X_n)^T \in \mathbb{R}^n$ is represented by the $(n + 1)$ -tuple $\mathbf{x} = (x_0, x_1, \dots, x_n)^T \in \mathbb{R}^{n+1} \setminus \{(0, 0, \dots, 0)^T\}$, where the superscript T denotes transposition and

$$X_k = \frac{x_k}{x_0}, \quad k = 1, \dots, n, \quad (1)$$

for any $x_0 \neq 0$. Any multiple $c \mathbf{x}$ of \mathbf{x} with $c \neq 0$ represents the same point. A projective space is obtained by allowing $x_0 = 0$: $(0, x_1, \dots, x_n)^T$ represents the infinitely remote point, or *absolute point*, in the direction of $(x_1, x_2, \dots, x_n)^T \in \mathbb{R}^n$.

All points $X = (X_1, X_2, \dots, X_n)^T \in \mathbb{R}^n$ satisfying the linear relation

$$e_0 + e_1 X_1 + \dots + e_n X_n = 0 \quad (2)$$

form an $(n - 1)$ -dimensional hyperplane $E \subset \mathbb{R}^n$. The elements e_k of the $(n + 1)$ -tuple $\mathbf{e} = (e_0, e_1, \dots, e_n)^T \in \mathbb{R}^{n+1} \setminus \{(0, 0, \dots, 0)^T\}$ are called the hyperplane coordinates, or *Plücker coordinates*, of E ; again, any multiple $c \mathbf{e}$ of \mathbf{e} with $c \neq 0$ represents the same hyperplane. Equation (2) with (1) yields the condition of incidence,

$$\sum_{k=0}^n e_k x_k = 0 \quad \text{or} \quad \mathbf{e}^T \mathbf{x} = 0; \quad (3)$$

i.e. the hyperplane E contains the point X if and only if the dot product of the homogeneous vectors \mathbf{e} and \mathbf{x} vanishes.

From (2) it is seen that the vector $(e_1, e_2, \dots, e_n)^T \in \mathbb{R}^n$ is orthogonal to every vector in the hyperplane E . Therefore, the direction of $(e_1, e_2, \dots, e_n)^T$, i.e. its absolute point

$$\mathbf{e}^0 := (0, e_1, e_2, \dots, e_n)^T \in \mathbb{R}^{n+1}, \quad (4)$$

corresponds to the direction orthogonal to E . For a more detailed introduction to projective spaces and homogeneous coordinates see, e.g., [1] or [3].

3 The faces of a simplex

Let the $n + 1$ vertices A_k ($k = 0, \dots, n$) of a nondegenerate simplex in \mathbb{R}^n be given by their homogeneous coordinates, e.g.

$$\mathbf{a}_k = (1, A_{k1}, A_{k2}, \dots, A_{kn})^T, \quad k = 0, \dots, n, \quad (5)$$

where A_{kj} is the j -th Cartesian component of the position vector of the k -th vertex. Consider now the matrix

$$A = (\mathbf{a}_0, \mathbf{a}_1, \dots, \mathbf{a}_n) \in \mathbb{R}^{(n+1) \times (n+1)} \quad (6)$$

whose columns are the homogeneous coordinates of the vertices of the simplex. Assuming that A is invertible, we denote its inverse by S^T ; hence

$$S^T \cdot A = I \quad \text{or} \quad S := (A^{-1})^T, \quad (7)$$

where I is the unit matrix of order $n + 1$. By partitioning S^T into its rows $\mathbf{s}_k^T = (s_{k0}, s_{k1}, \dots, s_{kn})$ we have

$$S^T = \begin{pmatrix} \mathbf{s}_0^T \\ \vdots \\ \mathbf{s}_n^T \end{pmatrix} \quad \text{or} \quad S = (\mathbf{s}_0, \mathbf{s}_1, \dots, \mathbf{s}_n), \quad (8)$$

and (7) may be written as

$$\mathbf{s}_k^T \mathbf{a}_l = \begin{cases} 0, & k \neq l, \\ 1, & k = l. \end{cases} \quad (9)$$

Therefore, as a consequence of (3), the hyperplane defined by the homogeneous vector \mathbf{s}_k contains every vertex of the simplex except A_k ; it is therefore the face opposite to A_k . Hence, we have the following

Theorem 1. *Let $A \in \mathbb{R}^{(n+1) \times (n+1)}$ be the matrix containing in its k -th column the homogeneous coordinates of the vertex A_k ($k = 0, \dots, n$) of a nondegenerate simplex in \mathbb{R}^n , $n \geq 1$. Then, the transpose of the inverse of A , $S := (A^{-1})^T$, contains the homogeneous coordinates of the face opposite to A_k in its k -th column. \square*

The matrix A in the above theorem is guaranteed to be invertible: Assume that A is singular; then we can express one of the columns of A , say the k -th column, as a linear combination of the remaining columns. Hence, the vertex A_k lies in the subspace spanned by the rest of the vertices, and the simplex is degenerate, in contradiction with the hypotheses of the theorem.

4 The feet of the altitudes

In the following, we restrict ourselves to proper simplices, i.e. no vertices are at infinity. Therefore, the matrix A defined in (6) contains no zeros in its first row. The k -th altitude of the simplex may be defined as the line connecting the vertex A_k with the absolute point $\mathbf{s}_k^0 := (0, s_{k1}, s_{k2}, \dots, s_{kn})^T$ of the normal of the face opposite to A_k . In general, the line connecting two points A, B (given by their homogeneous coordinates \mathbf{a}, \mathbf{b} , respectively) is the set of points $\mathbf{c} = \lambda \mathbf{a} + \mu \mathbf{b}$ with $\lambda, \mu \in \mathbb{R}$, $(\lambda, \mu) \neq (0, 0)$. For the k -th altitude we may choose $\mathbf{c} = \mathbf{f}_k := \mathbf{a}_k - \mu_k \mathbf{s}_k^0$, $\mu_k \in \mathbb{R}$, for simplicity. Its foot satisfies $\mathbf{s}_k^T \mathbf{f}_k = 0$ which implies

$$\mu_k = \frac{\mathbf{s}_k^T \mathbf{a}_k}{\mathbf{s}_k^T \mathbf{s}_k^0}. \quad (10)$$

Evaluating the numerator by means of (9) and using the explicit expression for the denominator yields

$$\mathbf{f}_k = \mathbf{a}_k - \mu_k \mathbf{s}_k^0 \quad \text{with} \quad \mu_k = \frac{1}{\sum_{j=1}^n s_{kj}^2}, \quad k = 0, 1, \dots, n \quad (11)$$

for the foot of the k -th altitude. In order to obtain all feet at once we consider the $n + 1$ first equations of (11) as the columns of a single matrix equation,

$$F = A - S^0 \cdot \text{diag}(\mu_0, \mu_1, \dots, \mu_n), \quad (12)$$

where F is the matrix with the homogeneous coordinates of the feet as its columns. Furthermore, $\text{diag}(\mu_0, \dots, \mu_n)$ is the diagonal matrix with μ_0, \dots, μ_n as its diagonal elements. Finally, $S^0 = (\mathbf{s}_0^0, \mathbf{s}_1^0, \dots, \mathbf{s}_n^0)$, the matrix of the absolute points of the vectors orthogonal to the faces, is obtained from S by zeroing out the first row and may be written as

$$S^0 = \text{diag}(0, 1, \dots, 1) \cdot (A^{-1})^T \quad (13)$$

as a consequence of (7). We therefore have established

Theorem 2. *Let $A \in \mathbb{R}^{(n+1) \times (n+1)}$ be the matrix containing in its k -th column the homogeneous coordinates of the vertex A_k ($k = 0, \dots, n$) of a nondegenerate proper simplex in \mathbb{R}^n , $n \geq 1$. Then S^0 defined in (13) is the matrix of the absolute points of the vectors orthogonal to the faces, and F defined in (12), with μ_k from (11), has the homogeneous coordinates of the feet of the altitudes of the simplex as its columns. \square*

In the case of dimension $n = 1$, when the simplex is a line segment, the algorithm simply exchanges the boundary points.

Remark. The use of projective spaces and homogeneous coordinates is widespread when it comes to deal with simplices. E.g., in [2] it can be seen how proofs of theorems get shortened and how the duality principle of projective geometry can enter the calculations.

5 An elegant implementation in MATLAB

The concise algorithm (13), (12) may be coded in the language of MATLAB [4] as follows below. MATLAB is particularly well suited owing to its powerful instructions for the operations of matrix algebra.

```
% Given data: columns of A are the homogeneous coordinates
% of the vertices of the simplex. Example in 2 dimensions:
```

$$A = \begin{bmatrix} 1 & 1 & 1 \\ -3 & 3 & 1 \\ 0 & 1 & 4 \end{bmatrix};$$

```
% Algorithm
```

```
    S = inv(A)'; S(1,:) = 0*S(1,:);
    F = A - S * diag(1./sum(S.^2)),
```

```
% Columns of F are the homogeneous coordinates of the feet.
% The top row of A (preferably ones) is inherited by F.
```

```
% Result for the above example of A:
```

```
% F = [1.0000000000000  1.0000000000000  1.0000000000000
%       1.615384615385   0.5000000000000  1.540540540541
%       3.076923076923   3.5000000000000  0.756756756757];
```

Comments on the code of the algorithm. We use the symbol S for the matrix S^0 . The prime causes transposition of a real matrix. The second statement replaces the top row of the current S by a row of zeros. The operator `diag` fills its argument vector into a diagonal matrix. The sequence `1./sum(S.^2)` computes all values μ_k for $k = 0, 1, \dots, n$ of equation (11) by summation over the columns of the matrix of the squared elements of S^0 .

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