

Article

Revisiting the Mathematical Model for Determining Coordinates of Points in a Trimetric Projection

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Abstract

In a recent article in this journal, Nikolić et al. presented a mathematical model for computing the coordinates in the trimetric projection of a 3D object, in terms of the projections of unit areas on the three dihedral planes. We revisit this model and analytically formalize its geometric principles, noting that such projections amount to the direction cosines of the unit normal to the viewplane. Thus, we reinterpret their proposal as providing three direction numbers that define a scaled version of this unit normal. The model also derives formulas relating the trimetric parameters (i.e., trimetric angles and foreshortening ratios). We observe that these relationships, found in classical literature, admit more compact expressions through simpler derivations. Also, we compile and reexamine various methods for selecting the trimetric projection, making them more accessible. In particular, the turn and tilt rotations of interactive user interfaces provide an intuitive way to choose the direction cosines. Ultimately, any method defines the mathematical model through a transformation matrix that maps 3D world coordinates to viewplane coordinates in the viewing pipeline.

Keywords: axonometry; direction cosine; direction number; foreshortening ratio; viewing pipeline; transformation matrix; trimetric angle; trimetric projection

MSC: 68U05

1. Introduction

An orthogonal axonometric projection is simply an orthogonal parallel projection, i.e., one with projection lines perpendicular to the projection plane Π . In the axonometric case, the line of sight (normal to Π) does not align with any of the principal axes of the observed object [1]. While a perspective projection may offer a more realistic representation as perceived by the human eye, Foley et al. [2] warn that optical realism is not always more desirable or useful when the primary goal is to convey information visually. An axonometric view facilitates the visualization of geometric properties [3] as it depicts an object “not as it is seen, but as it should be” [4], which makes it more “technical” compared to the “artistic” perspective [5]. Indeed, it preserves parallelism and distance ratios, thus enjoying the following advantages over perspective projection:

- **Simplicity:** This characteristic applies not only to the mathematical model but also to the user interface for selecting the projection parameters, which will be discussed later.
- **Homogeneity:** There are no vanishing lines or points, so the perspective does not depend on the distance to Π . This property simplifies navigation and scrolling on a wide image compared to the camera-like model of a perspective view [6,7].



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- Size preservation: The perceived size of an object does not depend on its distance to Π . Consistent linear measurements in any direction enable the reconstruction of the object's dimensions—a desirable property for product definition in engineering technical drawings [8]—and automatic generation of 3D models from 2D sketches [9].
- Preservation of polynomial curves: Such curves retain their polynomial (i.e., integral) character under this projection, which facilitates implementation, whereas a perspective converts them to rational curves [10]. Both the PostScript page description language [11] and the SVG (Scalable Vector Graphics) format [12] incorporate polynomial Bézier cubics, but neither of them supports rational curves as a data type.

Axonometric projections can be categorized as isometric, dimetric, or trimetric (Figure 1), depending on whether all, two, or none of the three principal axes appear equally foreshortened. Given an object, the fundamental tenet for selecting the right view is to maximize information, with the aim of minimizing foreshortening across most faces of the object [13]. Equivalently, as Duff and Maxson [14] recommend, place important features on the more exposed faces, where exposure indicates how much of a face can be seen. This has inspired interest in a general trimetric projection, in which placing selective emphasis allows more freedom, whereas the simplest isometric projection gives equal importance to all principal faces [1].

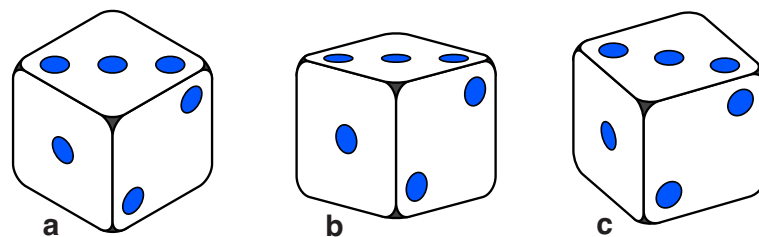


Figure 1. Types of axonometric projection: (a) isometric, (b) dimetric, and (c) trimetric.

In a recent article in this journal, Nikolić et al. [15] presented a mathematical model for computing the coordinates of points in a trimetric projection. We reinterpret and simplify this model, giving proper attribution to its findings, some of which date back to the 19th century. Also, we compile existing, yet scattered, results from descriptive geometry and reexamine them through the lens of modern computer graphics, making them more accessible and providing a unifying reference.

The article is structured as follows. Section 2 reviews the parameters involved in trimetric projection (direction cosines of the unit normal to the viewplane, foreshortening ratios, and trimetric angles) as well as the relationships among them. In particular, we note that the projections of unit areas onto the three dihedral planes coincide with such direction cosines, which leads to the result highlighted in [15] that their squares sum to one. Section 3 identifies the available pair of degrees of freedom and lists existing strategies for selecting them. Section 4 recalls that, in a computer graphics environment, a transformation matrix defines the mathematical model of the projection. Finally, Section 5 closes with practical Conclusions.

2. Trimetric Parameters: Definitions and Their Relationships

2.1. Direction Cosines, Foreshortening Ratios, and Trimetric Angles

In a trimetric projection (Figure 2), none of the principal axes $i = 1, 2, 3$ defining the *principal trihedron* are parallel to the projection plane Π , called *viewplane* in computer graphics [2]. The unit normal vector $\mathbf{n}$ to Π , indicating the line of sight, has as components n_i its *direction cosines* [1,16–19]:

$$\mathbf{n} = \{n_1, n_2, n_3\}, \quad n_i = \cos \phi_i, \quad i = 1, 2, 3, \quad (1)$$

where ϕ_i indicates the angle between the i th axis and $\mathbf{n}$. For simplicity's sake, as implicitly done in [15], we assume a normal $\mathbf{n}$ in the positive octant of the trihedron, i.e., the three axes point to the observer so that $n_i > 0, \forall i$.

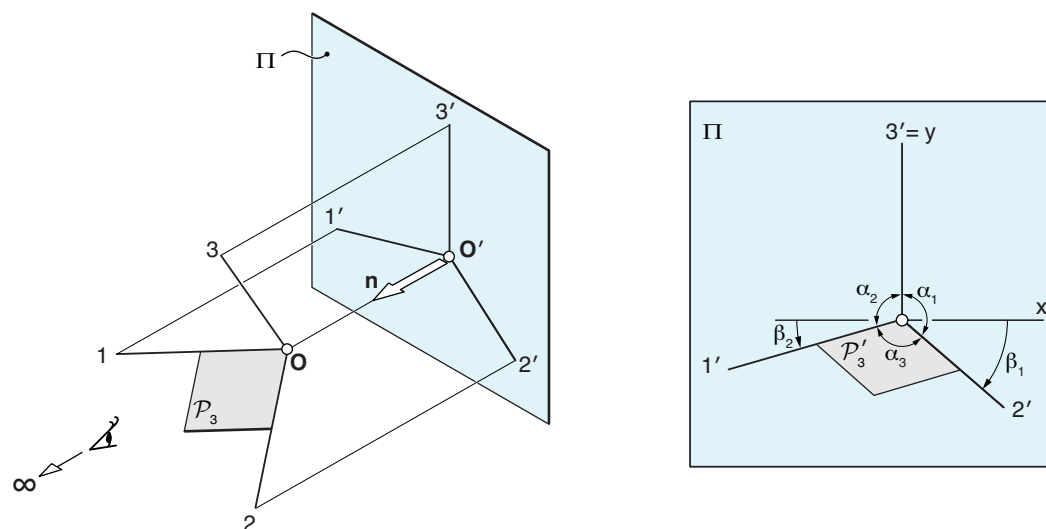


Figure 2. Projecting the principal trihedron of principal axes $i = 1, 2, 3$ to the viewplane Π . The resulting trimetric angles.

A trimetric projection implies *foreshortening ratios* or *factors* $f_i \in (0, 1)$ [1,17,20] for each axis i , defined as the ratio between projected length and original length of the i th axis. These dimensionless scalars, variously called *axonometric ratios* [5], *shrink factors* [6], *distortion factors* [3,18], or *scales* [19], are given by:

$$f_i = \sin \phi_i, \quad i = 1, 2, 3. \quad (2)$$

We similarly define the foreshortening ratio A'/A between the projected area A' and true area A of a patch on a given plane, which quantifies the concept of exposure by Duff and Maxon [14]. As is well known in descriptive geometry [21,22], stress analysis [23], or photometry and radiometry [24], $A'/A = \cos \phi$, where ϕ denotes the angle between Π and the given plane. Therefore, for each of the three principal planes Π_i (orthogonal to the i th axis and spanned by the remaining pair j, k of axes), this ratio coincides with the direction cosine $n_i = \cos \phi_i$ (1). This correspondence provides a transition from a geometric-intuitive model [15] to a formal vector-based representation.

Since f_i, n_i define a sine–cosine pair (2), (1), they relate as follows:

$$f_i^2 + n_i^2 = 1, \quad i = 1, 2, 3. \quad (3)$$

Thus, as with the ratios f_i , the projection is isometric, dimetric, or trimetric (Figure 1) depending on whether all, two, or none of the n_i are equal [17,25].

As is well-known, the squares of the direction cosines sum to one:

$$\|\mathbf{n}\| = 1 \Rightarrow n_1^2 + n_2^2 + n_3^2 = 1. \quad (4)$$

Contrary to what Nikolić et al. [15] claim, the sum (4) can be found in the treatise on descriptive geometry by Rehbock [22] in this specific context of axonometric projection, as a relationship between area foreshortening ratios for the principal planes. Also, classical

books [18,22,26–32] employ it, combined with (3), to derive the so-called [19] *fundamental law of axonometry*. This relationship among the ratios f_i can be written in a compact form as:

$$\|\mathbf{f}\| = \sqrt{2}, \quad \mathbf{f} = \{f_1, f_2, f_3\}. \quad (5)$$

As Figure 2 (right) shows, we define a generic value α_i indicating the trimetric angle between the projected axes j', k' , for the three cyclic index permutations $\{i, j, k\} = \{1, 2, 3\}, \{3, 1, 2\}, \{2, 3, 1\}$. Typically, the projected axis $3'$ defines the vertical direction y on the viewplane Π . Therefore, an alternative [33] are the angles

$$\beta_i = \alpha_i - \pi/2, \quad i = 1, 2, 3, \quad (6)$$

so that β_1, β_2 denote the oriented angles between the projected axes $2', 1'$, respectively, and the horizontal x -axis on Π . Since $\sum \alpha_i = 2\pi$:

$$\beta_3 = \pi/2 - \beta_1 - \beta_2. \quad (7)$$

Our assumption of $\mathbf{n}$ in the first octant implies well-defined angles with ranges $\alpha_i \in (\pi/2, \pi)$, and hence $\beta_i \in (0, \pi/2)$ in the first quadrant.

Figure 3 visually summarizes the above trimetric parameters by showing the projection of an axis-aligned unit cube $\hat{C}$. The ratios f_i, n_i correspond to the projected lengths/areas of the edges/faces of $\hat{C}$, respectively.

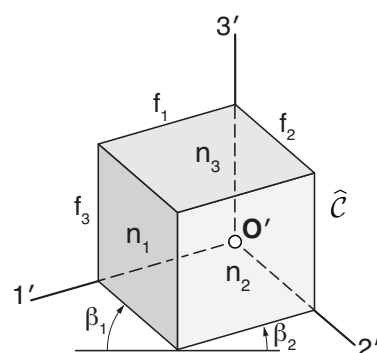


Figure 3. Axis-aligned unit cube $\hat{C}$: projected lengths f_i of edges and areas n_i of faces.

2.2. Relationship Between the Foreshortening Ratios and Trimetric Angles

Now, we turn our attention to the relationship between the foreshortening ratios and trimetric angles. The expression of β_i (6) in terms of f_i, n_i (2), (1) directly stems from the definition of these foreshortening ratios. As illustrated in Figure 2 for $i = 3$, consider a unit square $\mathcal{P}_i$ on Π_i with edges of unit length along the axes j, k , which projects as a parallelogram $\mathcal{P}'_i$ with inner angle α_i and edges shrunk by ratios f_j, f_k . Therefore, $\mathcal{P}'_i$ has an area $n_i = f_j f_k \sin \alpha_i = f_j f_k \cos \beta_i$, and isolating:

$$\cos \beta_i = \frac{n_i}{f_j f_k}. \quad (8)$$

Since $\sin \beta_i = \sqrt{1 - \cos^2 \beta_i}$ for β_i in the first quadrant, after rewriting f_j, f_k in terms of n_j, n_k (3) in (8) and simplifying using relationship (4), we get the equivalent expressions:

$$\sin \beta_i = \frac{n_j n_k}{f_j f_k}, \quad \tan \beta_i = \frac{n_j n_k}{n_i}. \quad (9)$$

On the other hand, the product of two quotients (9) (right) for angles β_j, β_k yields n_i^2 and hence f_i in terms β_j, β_k :

$$f_i = \sqrt{1 - n_i^2}, \quad n_i^2 = \tan \beta_j \tan \beta_k. \quad (10)$$

Our notation provides concise, generic expressions which otherwise are well-known:

- In 1887, Beyel [34] derived (8) similarly, using a triangle instead of a square. The book by Boehm and Prautzsch [35] provides an equivalent expression.
- Formula (9) (left) can be traced back at least to the 1850s in the treatises on axonometry by Meyer and Meyer [36] and Weisbach [37], and is also found in [1]. In these references it is expressed in terms of $\tan \phi_i = f_i/n_i$ (or using the complementary angle).
- The variant (9) (right), corresponding to the formulas by Nikolić et al. [15], can be found (in terms of ratios f_i) on Barber's [33] webpage.
- Similarly, the simplified generic formula (10) encompasses the three expressions in [15], corresponding to those in [33]. Utilizing geometric reasoning and angles α_i , Wunderlich [32] derives equivalent formulas, also found in [35,38] (though without derivation).

Unfortunately, some of the literature on computer graphics overlooks Formula (10) for the ratios f_i , which leads to the misleading claim [20] that “the wide variety of trimetric projections precludes a general equation for these ratios”.

3. Choosing the Trimetric Projection

In a trimetric projection, only two of the three ratios f_i (or n_i), or axonometric angles β_i , are independent, as the corresponding sums (5), (4), (7) indicate. We could just choose $\beta_1, \beta_2 \in (0, \pi/2)$ as input and then set β_3 (7), taking into account that $\beta_3 > 0$ implies the restriction:

$$\beta_1 + \beta_2 < \pi/2. \quad (11)$$

3.1. Triplets of Foreshortening Ratios

Managing the nonlinear relationships among the ratios f_i or n_i requires a more elaborate strategy. Classical books [22,26,31,36,37,39,40] choose as degrees of freedom two consecutive ratios $f_1:f_2:f_3$, defined by setting three scalars $F_i > 0$ such that $F_1:F_2:F_3 = f_1:f_2:f_3$. Geometrically, they correspond to projected lengths F_i of the edges of a general (non-unit) axis-aligned cube $\mathcal{C}$. In algebraic terms, we define a triplet $\mathbf{F} = \{F_1, F_2, F_3\}$ proportional to $\mathbf{f}$ (5). To guarantee the length $\|\mathbf{f}\| = \sqrt{2}$, just set:

$$\mathbf{f} = \sqrt{2} \frac{\mathbf{F}}{\|\mathbf{F}\|}. \quad (12)$$

Additionally, we must consider the three restrictions $f_i^2 < 1$. Combined with relationship (5), they furnish the corresponding homogeneous triplet of inequalities $f_i^2 < f_j^2 + f_k^2$ which, in geometric terms [41], constrain $\mathbf{f}$ to the interior of a circular triangle on a sphere of radius $\sqrt{2}$. These restrictions carry over to the scalars F_i as:

$$F_i^2 < F_j^2 + F_k^2. \quad (13)$$

Barber [33] implemented this strategy in a handy web-based axonometric calculator that calculates β_1, β_2 by inputting a triplet $\mathbf{F}$ verifying conditions (13). This calculator also outputs the values f_i by entering angles β_1, β_2 verifying constraint (11). The proposal by Nikolić et al. [15] extends the above classical procedure based on ratios, moving from ratios f_i to n_i . Similarly, this is done by choosing three scalars $N_i > 0$ such that $N_1:N_2:N_3 = n_1:n_2:n_3$, corresponding to the projected areas of the three visible faces of a general axis-aligned cube

$\mathcal{C}$. The proposal amounts to providing a triplet $\mathbf{N} = \{N_1, N_2, N_3\}$ of *direction numbers* [16], also called *direction ratios*, i.e., a vector $\mathbf{N}$ proportional to the unit normal $\mathbf{n}$. Consequently:

$$\mathbf{n} = \frac{\mathbf{N}}{\|\mathbf{N}\|}. \quad (14)$$

3.2. Choosing the View Direction with Two Angles

Instead of choosing $\mathbf{n}$ (14) with a triplet $\mathbf{N}$ of direction numbers, a pair of spherical angles (*polar* θ and *azimuthal* ϕ) provides a more straightforward and convenient alternative [25]. Indeed, using direction 3 as the polar axis (Figure 4a):

$$\mathbf{n} = \{\sin \phi \cos \theta, \sin \phi \sin \theta, \cos \phi\}, \quad (15)$$

where $\theta, \phi \in (0, \pi/2)$ implies that $\mathbf{n}$ lies in the first octant ($n_i > 0$). Therefore, the azimuth $\phi = \phi_3$ directly yields the direction cosine n_3 (1), whereas θ determines the ratio n_2/n_1 :

$$\cos \phi = n_3, \quad \tan \theta = \frac{n_2}{n_1}. \quad (16)$$

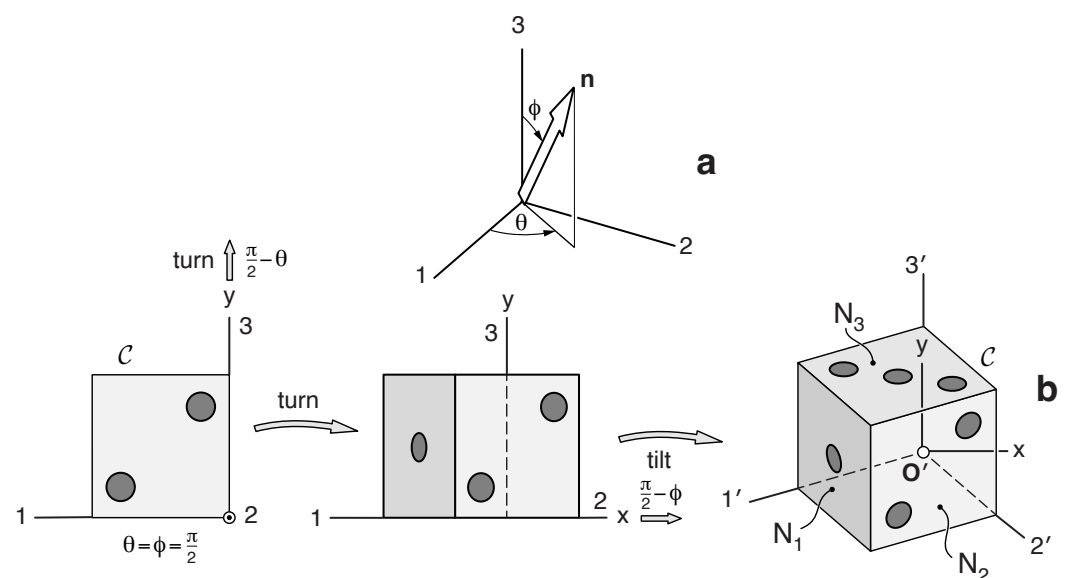


Figure 4. Equivalent pairs defining the view direction: (a) Spherical angles θ, ϕ orienting the normal $\mathbf{n}$. (b) Concatenated rotations orienting the principal trihedron: turn and tilt around respective axes y, x fixed to the viewplane.

Since the observer considers the axes $\{x, y\}$ on the viewplane Π as the fixed frame of reference, we can reinterpret θ, ϕ as angles orienting the principal trihedron with respect to this frame. Consider the initial orientation $\theta = \phi = \pi/2$ (Figure 4b), such that $\mathbf{n}$ (15) points along axis 2, and axis 3 coincides with the vertical direction y on Π . The view orientation (15) results from concatenating two rotations of the trihedron (around fixed axes) of angles complementary to θ, ϕ :

- (1) Turn of $\pi/2 - \theta$ around the vertical y -axis.
- (2) Tilt of $\pi/2 - \phi$ around the horizontal x -axis.

This pair of rotations constitutes the method proposed in the literature on computer graphics [6,17,20,25] to select the view. Some books on descriptive geometry [40] employ an equivalent pair [42] of Euler (body frame) rotations, applied in reverse order (around axes $-1, 3$).

Commercial software often features a graphical interface with an interactive widget whereby the user turns and tilts a general axis-oriented cube $\mathcal{C}$. These rotations enable

independent control over n_3 and n_2/n_1 (16), allowing users to intuitively and interactively adjust the emphasis placed on each plane Π_i . Therefore, these rotations directly correlate to the trimetric parameters n_i and suitably define the projection, whereas the approach in [15] offers a complementary, result-oriented parameterization based on visual exposure. Unsurprisingly, a pair of rotations is implemented in commercial axonometric plug-ins, such as AxoTools [43] or HotDoor CADtools 2026 [44] for Adobe Illustrator v30, where users can also numerically enter the turn and tilt values, or the angles β_1, β_2 in [43], to set the view (Figure 5). Both plug-ins incorporate numerous tools that facilitate axonometric drawing.

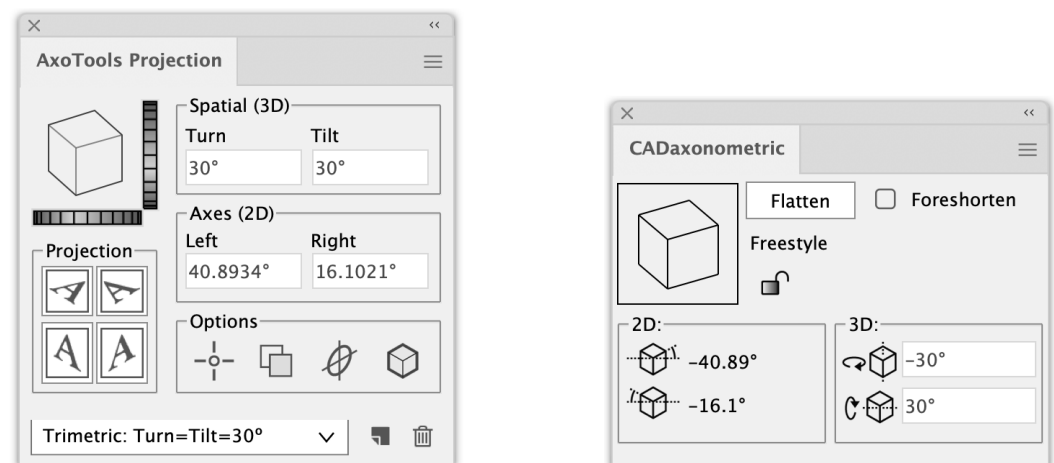


Figure 5. Control panels for setting a trimetric projection in commercial plug-ins for Adobe Illustrator: Graffix AxoTools [43] (left) and HotDoor CADtools 2026 [44] (right).

4. The Projection Matrix Defining the Mathematical Model

The sought mathematical model for determining coordinates boils down to the affine transformation mapping points $\mathbf{p} = \{x_1, x_2, x_3\}^T$ in 3D world coordinates to their projections $\mathbf{p}' = \{x, y\}^T$ on the viewplane Π . For simplicity, we assume that the 3D origin $\mathbf{O}$ (Figure 2) projects as the origin $\mathbf{O}'$ of the 2D viewplane coordinates (Figure 4). Computing the 2×3 transformation matrix $\mathbf{T}$ mapping $\mathbf{p}$ to $\mathbf{p}'$ is a straightforward exercise as the i th column of $\mathbf{T}$ is the projection $\mathbf{u}'_i$ of the unit vector $\mathbf{u}_i$ along the i th axis:

$$\mathbf{p}' = \mathbf{T}\mathbf{p}, \quad \mathbf{T} = [\mathbf{u}'_0, \mathbf{u}'_1, \mathbf{u}'_2]. \quad (17)$$

For completeness, we provide $\mathbf{T}$ in terms of f_i, β_i [38], or spherical angles θ, ϕ :

$$\mathbf{T} = \begin{bmatrix} -f_1 \cos \beta_2 & f_2 \cos \beta_1 & 0 \\ -f_1 \sin \beta_2 & -f_2 \sin \beta_1 & f_3 \end{bmatrix} = \begin{bmatrix} -\sin \theta & \cos \theta & 0 \\ -\cos \theta \cos \phi & -\sin \theta \cos \phi & \sin \phi \end{bmatrix}. \quad (18)$$

If we set the view by choosing the angles $\beta_1, \beta_2 \in (0, \pi/2)$, formula (10) provides the values f_i required in $\mathbf{T}$ (18). If we choose $\mathbf{f}$ (12) or $\mathbf{n}$ (14) with triplets $\mathbf{F}$ or $\mathbf{N}$, then either (8) or (9) furnishes the angles. Alternatively, from $\mathbf{n}$ we could compute θ, ϕ (16) and their corresponding expression of $\mathbf{T}$.

In a real-world computing environment, the viewing pipeline requires this compact matrix form, rather than the expanded explicit expressions in [15]. Also, it usually employs homogeneous coordinates [2,17,20,25] and hence 3×4 transformation matrices that integrate both axonometric and perspective projections (along with translations) in a unified form. The transformation is then passed to an API (Application Programming Interface) that leverages acceleration hardware, such as a GPU (Graphics Processing Unit).

The matrix form (17) yields the projections of points and, hence, the vertices of polylines and polygons. Vector-based design programs, such as Adobe Illustrator or Inkscape, represent free-form art using cubic (or quadratic) Bézier curves. Computing their axonometric projection is straightforward because there is no need to project them pointwise. Indeed, by their affine invariance [10], projecting a curve $\mathbf{p}(u)$ with control points $\mathbf{p}_i$ results in another Bézier curve $\mathbf{p}'(u)$ (of the same degree), with control points $\mathbf{p}'_i$. Figure 6 illustrates three examples: a font and an approximated sinusoid defined with piecewise cubics, and a parabolic segment (i.e., a quadratic Bézier curve). In these cases, the transformation simplifies to a 2D affine map between the plane containing the artwork and Π .

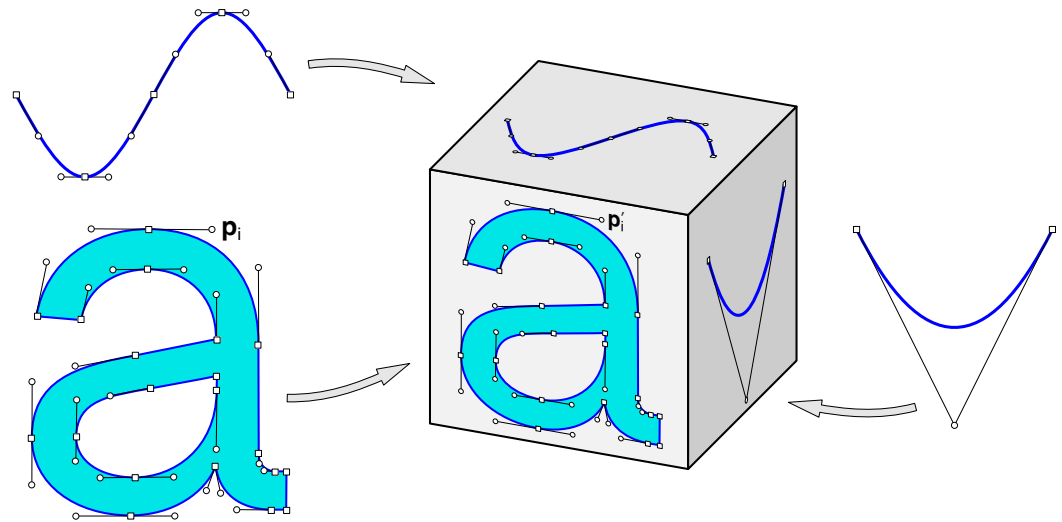


Figure 6. Projecting free-form art defined with Bézier curves by projecting their control points $\mathbf{p}_i$.

5. Conclusions

A trimetric projection involves foreshortening ratios f_i, n_i for the principal axes and areas on principal planes, respectively. The scalars n_i , quantifying the relative exposure of principal planes, are nothing but the direction cosines of the unit normal $\mathbf{n}$ to the viewplane, so their squares obviously sum to one. A pair of compact generic Formulas (8) and (10), adapted from those available in the classical literature, suffice to describe the relationships among these ratios and the trimetric angles β_i .

A designer can choose the view by selecting any of the following parameter sets:

- (i) A pair β_1, β_2 of trimetric angles verifying constraint (11).
- (ii) A pair of spherical angles (polar θ and azimuthal ϕ) orienting the normal $\mathbf{n}$. Equivalently, a pair of rotations (turn $= \pi/2 - \theta$, tilt $= \pi/2 - \phi$) of the principal trihedron.
- (iii) A triplet $\mathbf{F} = \{F_1, F_2, F_3\}$ proportional to $\mathbf{f} = \{f_1, f_2, f_3\}$ verifying constraints (13).
- (iv) A triplet $\mathbf{N} = \{N_1, N_2, N_3\}$ of direction numbers, i.e., a vector $\mathbf{N}$ proportional to $\mathbf{n}$.

User interfaces usually opt for (i), (ii) because they involve only two independent parameters instead of three interrelated scalars. The rotations provide a convenient method, as they independently control the direction cosine n_3 and the ratio n_2/n_1 (16), thus enabling the user to select the relative exposure n_i of each dihedral plane. Any of the above sets defines the mathematical model for projecting points via a transformation matrix that maps 3D world to viewplane coordinates.

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Abbreviations

The following abbreviations are used in this manuscript:

API Application Programming Interface.
GPU Graphics Processing Unit.
SVG Scalable Vector Graphics.

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