PERSPECTIVE TRANSFORMATION FOR
WIDE-VIEW SKY SCENES

by

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Fixed vantage point simulation requires a wide field of view for the external visual environment. The sky scene, however, is of secondary importance as moving objects in the scene are the areas of interest. It is therefore cost-effective to represent the sky in such cases as a two dimensional spherical surface enclosing the earth. This memorandum derives the perspective transformation necessary to project points from this sphere onto two dimensional viewing screens. Inversion of this transformation is also presented.
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1. INTRODUCTION

Fixed vantage point simulators, such as battlefield or air traffic control tower visual simulators, require wide field of view sky scenes (up to 360° in azimuth) for realistic presentation. Production of a three dimensional sky image using computer generated imagery would be computationally expensive. Since moving objects in the scene delineate the areas of interest, the sky scene itself is of secondary importance, and can be represented as a two dimensional surface around the earth. This can be accomplished by treating the earth as a sphere, with the sky/cloud base as another sphere enclosing the earth.

This memorandum derives the perspective transformation necessary to project points from the cloud base sphere onto two dimensional screens for viewing. However, as elevation decreases towards the horizon, larger regions of the cloud base sphere are represented by the same area measure on the two dimensional screen. It is therefore more appropriate to compute pictures by starting with pixels on the two dimensional screen, and finding the cloud sphere regions to which they correspond. These can then be used to determine the pixels’ colour. This approach requires the inversion of the perspective transformation, and is discussed following the derivation of the perspective transformation.

2. PERSPECTIVE TRANSFORMATION

It is assumed that the field of view is divided among a number of two dimensional viewplanes, so that each viewplane spans an angle of \( \alpha \) in azimuth. Let \( \beta \) be the elevation angle spanned from the horizon upwards. Each viewplane has its own two dimensional coordinate system, \( X,Y_0 \), with origin at the bottom left corner as seen by an observer. \( X_0 \) increases to his right, and \( Y_0 \) increases upwards, so that values near zero represent points on the left, near the horizon. Coordinates in this system are dimensionless, and lie in the range 0 to 1. We also define a three dimensional coordinate system, \( X,Y,Z_0 \), with origin centred at the observer’s eye. \( X_0 \) points out of the centre of one of the viewplanes, \( Z_0 \) points downward, and \( Y_0 \) is such that the resulting system is right handed. Coordinates in this system are expressed in kilometres. Figure 1 illustrates the case for the viewplane containing the \( X_0 \)-axis. \( O \) is the eye of the observer and \( KLMN \) is the viewplane.

To formulate the perspective transformation, consider the line of sight to a point \( P(x_0, y_0, z_0) \) on the cloud layer – the line \( OP \) in Figure 1, which intersects the viewplane at \( I \). Looking in the \( X_0-Z_0 \) plane (see Figure 2), \( P' \) is the projection of \( P \), and \( I' \) the projection of \( I \). \( C \) is the centre of the earth, \( H \) the horizon, \( KL \) the edge of the viewplane and \( \angle LOK = \beta \), the elevation from the horizon upwards. Now, the normalised viewplane coordinate, \( y_0 \), is
FIG. 1 CLOUD SPHERE AND VIEWPLANE CONTAINING $X_1$-AXIS
FIG. 2 EARTH AND CLOUD SPHERES IN THE $X_c-Z_c$ PLANE
the distance \( LP' \), divided by the viewplane height, \( LK \). In terms of distances to the \( Xc \)-axis,

\[
y_s = \frac{LP'}{LK} = \frac{LW + WI'}{LW + WK}
\]  
\( (1) \)

where \( W \) is the point at which \( KL \) intersects the \( Xc-Yc \) plane. Since \( LW = OW \tan \angle LOW \), \( WI' = OW \tan \angle WO1' \) and \( WK = OW \tan \angle WOK \), then

\[
y_s = \frac{OW \tan \angle LOW + OW \tan \angle WO1'}{OW \tan \angle LOW + OW \tan \angle WOK} = \frac{TL + \tan \angle WO1'}{TL + TW}
\]  
\( (2) \)

where \( TL = \tan \angle LOW \) and \( TW = \tan \angle WOK \). Now, \( \angle LOW = \angle OCH \), and in triangle \( OCH \), \( CH = R \), the earth radius, and \( OC = R + h_s \), the height of the observer's eye above the earth centre \( (h_s \) is the height of the observer's eye above the earth's surface.) Thus,

\[
\angle WOK = \beta - \angle LOW, \quad \text{so}
\]

\[
TW = \tan \angle WOK = \frac{\tan \beta - TL}{1 + TL \tan \beta}
\]  
\( (4) \)

The coordinates of \( P \) are used to determine \( \tan \angle WO1' \), which is the same as \( \tan \angle P'Q \) in Figure 2. Thus,

\[
\tan \angle WO1' = -z_s/x_s.
\]  
\( (5) \)

The negative sign arises because \( Zs \) points downward, whereas the distance \( PQ \) is measured in the opposite sense. The viewplane coordinate, \( y_s \), is therefore given by

\[
y_s = \frac{TL - z_s}{TL + TW}
\]  
\( (6) \)

where \( TL \) and \( TW \) are given by (3) and (4).

To determine the normalised coordinate, \( x_s \), consider the \( Xc-Yc \) plane as shown in Figure 3. \( ML \) is the bottom edge of the viewplane, and intersects the \( Xc-Zc \) plane at \( J \). Coordinate \( x_s \) is the distance \( MJ' \) divided by the viewplane width, \( ML \). That is,

\[
x_s = \frac{MJ'}{ML} = \frac{MJ + JJ''}{2MJ} = \frac{1}{2}(1 + \frac{JJ''}{MJ})
\]  
\( (7) \)

Using the coordinates of \( P \) (triangle \( OJM \)) gives

\[
\frac{JJ''}{OJ} = \frac{y_s}{x_s}
\]  
\( (8) \)
FIG. 3 LOOKING DOWN ON THE VIEWPLANE CONTAINING X*-AXIS
and from triangle $OJM$, 

$$OJ = MJ \cot(a/2).$$  \hspace{1cm} (9)$$

Using (9) and (8) in (7) gives

$$x_\alpha = \frac{1}{2}(1 + \frac{y_c}{x_c} \cot \frac{\alpha}{2}).$$  \hspace{1cm} (10)$$

The perspective transformation for the viewplane containing the $X_\alpha$-axis is thus given by (6) and (10). For the other viewplanes, it is necessary to rotate that screen into the one with the $X_\alpha$-axis before applying the transformation. This rotation is about the $Z_\alpha$-axis thus:

$$x' = x_\alpha \cos \omega - y_\alpha \sin \omega$$
$$y' = x_\alpha \sin \omega + y_\alpha \cos \omega$$
$$z' = z_\alpha$$  \hspace{1cm} (11)$$

where $\omega$ is the angle required to rotate a viewplane into coincidence with the one containing the $X_\alpha$-axis. To determine this angle, $\tan^{-1}(y_c/x_c)$ is examined as a four quadrant angle. If this is between $\pm \alpha/2$, then it is the $X_\alpha$-axis viewplane and $\omega = 0$. If the angle is between $\alpha/2$ and $3\alpha/2$, it is the next viewplane and $\omega = -\alpha$. Similar reasoning applies for the other viewplanes.

Having performed the appropriate rotation, the perspective transformation is applied to $(x_\alpha, y_\alpha, z_\alpha)$ through (6) and (10).

3. INVERTING THE PERSPECTIVE TRANSFORMATION

In producing wide field of view scenes, it may be more appropriate to approach the problem in a manner similar to that used in ray tracing, where tracing starts at the viewpoint and rays are traced backwards through each pixel to their origin (Ref. 1). In this case, a pixel on the two dimensional viewplane would be mapped into a region on the cloud sphere, with that region being used to determine the pixel's colour.

To achieve this, it is necessary to invert the perspective transformation, so that given viewplane coordinates $(x_\alpha, y_\alpha)$, and which viewplane it is, the cloud sphere coordinates $(x_c, y_c, z_c)$ can be found. Generally, this is not possible because the perspective transformation loses information. In this case, however, the required point lies on the cloud sphere, whose equation is

$$x_c^2 + y_c^2 + [z_c - (R + h_c)]^2 = (R + h_c)^2$$  \hspace{1cm} (12)$$

where $h_c$ is the height of the cloud sphere above the surface of the earth. Rearranging (6) and (10) for the viewplane containing the $X_\alpha$-axis give $z_c$ and $y_c$ in terms of $x_\alpha$ thus:

$$z_c = x_\alpha(T_L - y_\alpha(T_L + T_W))$$
$$y_c = x_\alpha \tan \frac{\alpha}{2}(2x_\alpha - 1)$$  \hspace{1cm} (13)$$
Substituting these into (12) gives:

\[
x_e^2 \left(1 + \tan^2 \theta \frac{2x_e - 1}{2} \right) + (T_L - y_L(T_L + T_W)^2) - 2(R + h_e)x_e[T_L - y_L(T_L + T_W)] + (R + h_e)^2 = 0
\]

(14)

Solution of this quadratic gives two values for \(x_e\), representing opposite points on the cloud sphere. For this viewplane, however, the solutions will be of opposite sign, and since \(x_e\) is always positive in this viewplane, the negative solution can be eliminated. We thus have a unique value for \(x_e\), which can be substituted into (13) to obtain the \(y_e\) and \(z_e\) values.

Having determined the coordinates corresponding to \((x_e, y_e)\) for the viewplane containing the \(X_e\)-axis, the cloud sphere coordinates can now be obtained by rotating these coordinates about the \(Z_e\)-axis through \(\omega\), where \(\omega\) is the angle required to rotate a viewplane into coincidence with the one containing the \(X_e\)-axis:

\[
x_e = x'_e \cos \omega + y'_e \sin \omega
\]
\[
y_e = -x'_e \sin \omega + y'_e \cos \omega
\]
\[
z_e = z'_e
\]

(15)

where \((x'_e, y'_e, z'_e)\) are the coordinates in the \(X_e\)-axis viewplane and \((x_e, y_e, z_e)\) are the coordinates in the required viewplane.

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ABSTRACT
Fixed vantage point simulation requires a wide field of view for the external visual environment. The sky scene, however, is of secondary importance as moving objects in the scene are the areas of interest. It is therefore cost-effective to represent the sky in such cases as a two dimensional surface enclosing the earth. This memorandum derives the perspective transformation necessary to project points from this sphere onto two dimensional viewing screens. Inversion of this transformation is also presented.