

IS71021E Assignment 2

An Interactive Exploration of Camera Projection

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Abstract

This is a technical report detailing and analysing the development of a computer graphics program created in Unity which explains camera projection. The techniques used to create the application, and the underlying mathematical concepts will be cross referenced from academic sources and informational books. Additionally, the effectiveness of the interactive applications ability to intuitively educate users on the topic will be examined and constructively critiqued. Consequently, further improvements which to improve the experience are explored.

1 Objective

The aim of this project was to explain the principle of perspective through showcasing different types of cameras used in computer graphics. The variables of the camera's projection type and transformations can be adjusted, such that the relationship between the camera and the finished rasterized image result can be understood. The purpose of this is to visually demonstrate the relationship between the two visualisations, as to nurture long-term memorisation of the conceptual model so that it can be recalled in the future (Benyon, p.469-71, 2014). This report will elaborate on the methodology for how it was be executed.

2 Introduction

2.1 History

The earliest perspective projection cameras in history are known as pinhole cameras, which take advantage of the *camera obscura* (or pinhole image) phenomenon - an innovation which the rest of perspective geometry builds on. Despite the phenomenon being recorded across many civilizations dating back to antiquity, the 11th century Arabic mathematician Ibn al-Haytham is credited with being the first to provide a clear scientific and geometric description of the effect and of the practical applications of the pinhole camera – leading to him being widely considered its ‘inventor’ (Camera Obscura & World Illusions, 2026). Importantly, al-Haytham showed that the inverted the image of the viewing screen proved that light travelled in straight lines, as well as noting the relationship between the focal point and the size of the pinhole (Camera Obscura & World of Illusions Edinburgh, 2026).

During the European renaissance, pinhole images were used to sketch views of natural landscapes and cities. It is suggestible that the accuracy of the pinhole image allowed for accurate drawing of nature, not directly, but by observations. Artists like Samuel van Hoogstraeten to Leonardo DaVinci used the pinhole camera to understand perspective projection (Delsaute, p.113, 1998).

By approximately the end of the 16th Century, a portable camera obscura was built equipped with converging lenses. It could correct the inverted image to produce a direct representation of the perspective from the view of the user. Mathematician Johannes



Figure 1: Visualisation of Ibn al-Haytham’s camera obscura, comprising of a small hole in a dark room with a screen. (Camera Obscura & World of Illusions Edinburgh, 2026)

Kepler(1571-1630) insisted he only used it ”as a mathematician, not as a painter.” Similarly, through this style of visual communication, this project plans to teach users how to understand the principles of perspective with computer graphics.

2.2 Computer Graphics

The foundation of 3D computer graphics began with wireframe CAD simulations, Boeing flight simulations, and the construction of the perspective -generating algorithm by Larry G. Roberts (Manovich, L, 1993). Roberts introduced a 4x4 matrix, known as the perspective projection matrix, which serves to map points in 3D eye space to the 2D surface of the computer monitor. To do this, the viewing volume of the camera (in eye space) is transformed into the canonical view volume - a normalised 3D cube ranging from -1 to 1. For a given point in eye space $(x_{eye}, y_{eye}, z_{eye})$ and projection matrix P , this can be calculated as:

$$\begin{bmatrix} x_c \\ y_c \\ z_c \\ w_c \end{bmatrix} = P \begin{bmatrix} x_{eye} \\ y_{eye} \\ z_{eye} \\ w_{eye} = 1 \end{bmatrix} \quad (1)$$

Where (x_c, y_c, z_c, w_c) is the representation of the point in the homogenous ‘clip’ coordinate system. It is worth noting that the eye space point is implicitly converted into a homogenous point by assigning the w component to 1. In clip coordinates, it is efficient to determine whether a point is within the viewing volume - as a point is visible if $-w_c \leq x_c, y_c, z_c \leq w_c$. This point can then be transformed into normalised canonical



Figure 2: Samuel van Hoogstraten (Dordrecht, 1627-1678), Perspective of an Open Gallery ('The Tuscan Gallery').)

view volume coordinates through a process known as perspective division:

$$\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} = \begin{bmatrix} \frac{x_c}{w_c} \\ \frac{y_c}{w_c} \\ \frac{z_c}{w_c} \end{bmatrix} \quad (2)$$

Where (x_n, y_n, z_n) is the point in the normalised canonical view volume. x_n and y_n are the normalised screen coordinates, and can be converted to pixel coordinates by remapping them from the range $(-1, 1)$ to the pixel resolution of the target screen (with width W and height H):

$$\begin{aligned} x_{screen} &= (x_n + 1) \cdot \frac{W}{2} \\ y_{screen} &= (y_n + 1) \cdot \frac{H}{2} \end{aligned} \quad (3)$$

2.2.1 Perspective Projection

Perspective projection aims to mimic human vision by making distant objects appear smaller and converge towards a vanishing point - much like we see in photography, where parallel lines converge towards the origin and disappear (Fig. 3). To achieve this, the



Figure 3: Single Perspective Photography by Diane Wehr.

camera view volume is defined as a truncated pyramid frustum as shown in figure 4. The near and far clipping planes of the frustum are defined as $-n$ and $-f$, respectively, and the projection plane (the near plane) of the frustum is rectangular, with a width ranging from l to r in the x direction and from b to t in the y direction. The projection matrix for perspective projection can then be derived as:

$$P_p = \begin{bmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & \frac{-(f+n)}{f-n} & \frac{-2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{bmatrix} \quad (4)$$

The use of homogenous coordinates is crucial for obtaining the perspective effect as after a point has been transformed into clip coordinates, the w component is equivalent to the z coordinate in eye coordinates. Therefore, when this point is transformed into canonical view volume coordinates (equation 2), the x and y values are divided by their distance from the camera in world space - leading to points further away converging towards $(0, 0)$, the centre of the camera's view (Susta, 2024).

2.2.2 Orthographic Projection

Orthographic projection is a form of projection which preserves parallel lines and relative distances by keeping all the projection lines orthogonal to the projection plane. This makes orthographic projection particularly useful for technical applications, such

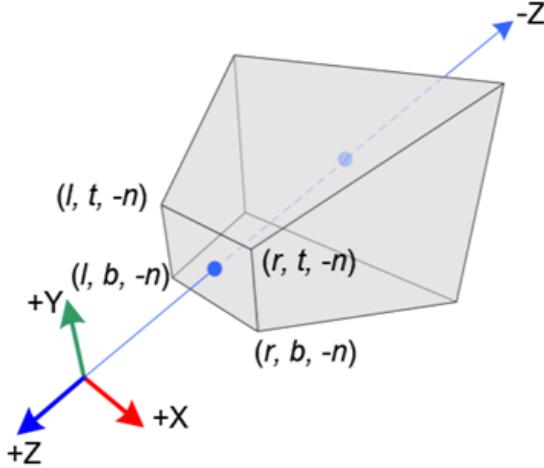


Figure 4: The camera frustum used for perspective projection in the OpenGL rendering pipeline.

as CAD software.

In contrast to the frustum used as the view volume for perspective projection, orthographic projection instead remaps a cuboidal bounding box to the canonical view volume (Figure 5)- which allows for a simpler linear transformation of contained points.

The projection matrix for orthographic projection can then be defined as:

$$P_o = \begin{bmatrix} \frac{2}{r-l} & 0 & 0 & -\frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & \frac{t+b}{t-b} \\ 0 & 0 & \frac{-2}{f-n} & \frac{-(f+n)}{f-n} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

The fourth row of the projection matrix remaining as $(0,0,0,1)$ ensures that the w component has no effect on the projected positions, as it will remain as 1 after transformation.

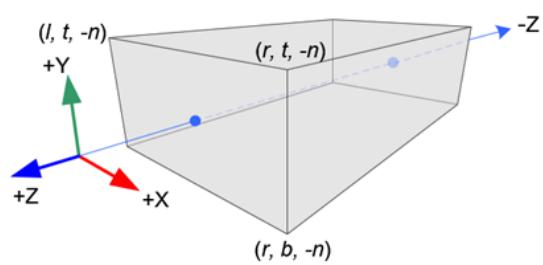


Figure 5: The cuboidal view volume used for orthographic projection in the OpenGL rendering pipeline.