CSC418 Computer Graphics Assignment 1

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1. Curves

1.1 Convert Parametric to Implicit

$$
\begin{aligned}
x(t)^2 &= 4\sin^2(t) \\
y(t)^2 &= 25\sin^2(t)\cos^2(t) \\
y(t)^2 &= \frac{25}{16}x^2(4-x^2) \\
0 &= y^2 + \frac{25}{16}x^4 - \frac{25}{4}x^2
\end{aligned}
$$

1.2 Tangent Vector

$$
\begin{aligned}
\vec{T}(t) &= \frac{\langle \frac{dx}{dt}, \frac{dy}{dt} \rangle}{||\langle \frac{dx}{dt}, \frac{dy}{dt} \rangle||} \\
\frac{dx}{dt} &= 2\cos(t) \\
\frac{dy}{dt} &= 5\cos(2t) \\
\langle \frac{dx}{dt}, \frac{dy}{dt} \rangle &= \langle 2\cos(t), 5\cos(2t) \rangle \\
\vec{T}(t) &= \frac{\langle 2\cos(t), 5\cos(2t) \rangle}{\sqrt{4\cos^2(t) + 25\cos^2(2t)}}
\end{aligned}
$$

1.3 Normal Vector

$$
\begin{aligned}
\vec{N}(t) &= \frac{\frac{d\vec{T}}{dt}}{||\frac{d\vec{T}}{dt}||} \\
\vec{N}(t) &= \frac{\langle -\sin(t), -10\sin(2t) \rangle}{||\frac{d\vec{T}}{dt}||} \\
&= \frac{\langle -\sin(t), -10\sin(2t) \rangle}{\sqrt{\sin^2(t) + 100\sin^2(2t)}}
\end{aligned}
$$

1.4 Symmetry

1.4.1 X-axis Symmetry

If the function is symmetrical about the X-axis, then $f(x, y) = f(x, -y)$.

$$
\begin{gathered}
f(x, y) = f(x, -y) \\
y^2 + \frac{25}{16}x^4 - \frac{25}{4}x^2 = (-y)^2 + \frac{25}{16}x^4 - \frac{25}{4}x^2 \\
y^2 = (-y)^2 \\
\text{left side} = \text{right side}
\end{gathered}
$$

Therefore the function is symmetric about the X-axis.

1.4.2 Y-axis Symmetry

If the function is symmetrical about the Y-axis, then $f(x, y) = f(-x, y)$.

$$
\begin{gathered}
f(x, y) = f(-x, y) \\
y^2 + \frac{25}{16}x^4 - \frac{25}{4}x^2 = y^2 + \frac{25}{16}(-x)^2 - \frac{25}{4}(-x)^2 \\
\frac{25}{16}x^4 - \frac{25}{4}x^2 = \frac{25}{16}(-x)^4 - \frac{25}{4}(-x)^2 \\
\text{left side} = \text{right side}
\end{gathered}
$$

Therefore the function is symmetric about the Y-axis.

1.5 Area

Since the function is symmetric about the X and Y axis, it is sufficient to find the area of the function in one quadrant and multiply by 4.

$$
\begin{aligned}
f(x) &= \sqrt{\frac{25}{4}x^2 - \frac{25}{16}x^4} = \frac{5}{4}x\sqrt{4 - x^2} \\
\frac{1}{4}A &= \frac{5}{4}\int_0^2 x\sqrt{4 - x^2}\,dx \\
\text{let } j &= 4 - x^2 \\
dx &= \frac{1}{-2x}dj \\
A &= \frac{5}{2}\int_0^4 \sqrt{j}\,dj \\
A &= \frac{5}{2} \cdot \frac{16}{3} = \frac{40}{3}
\end{aligned}
$$

Therefore the area under the bowtie is $\frac{40}{3}$.

1.6 Perimeter

The perimeter of the curve can be algorithmically approximated by dividing the curve into a reasonable number of segments and taking the linear euclidean distance between the endpoints of each segment.

```
function X(t):
    return 2 * sin(t)

function Y(t):
    return 5 * sin(t) * cos(t)

// N is the number of segments to break the curve into
function ApproximatePerimeter(N):
    distance = 0
    lastX = X(0)
    lastY = Y(0)
    dt = 2 * pi / N
    for t = dt; t <= 2 * pi; t = t + dt:
        currentX = X(t)
        currentY = Y(t)

        // Increment by euclidean distance between current point and last
        distance = distance + sqrt(pow(currentX - lastX, 2) + pow(currentY - lastY, 2))

        lastX = currentX
        lastY = currentY

    return distance
```

Running this code with $N = 20$ results in a distance of 22.1.

2. Transformations

2.a Translation and Translation

Two sequential $N \times N$ translations have the form

$$T_1 = \begin{bmatrix} 1 & 0 & \dots & t_{x1} \\ 0 & 1 & \dots & t_{y1} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}$$

$$T_2 = \begin{bmatrix} 1 & 0 & \dots & t_{x2} \\ 0 & 1 & \dots & t_{y2} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}$$

$$T_1 T_2 = \begin{bmatrix} 1 & 0 & \dots & t_{x1} \\ 0 & 1 & \dots & t_{y1} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & \dots & t_{x2} \\ 0 & 1 & \dots & t_{y2} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & \dots & t_{x1} + t_{x2} \\ 0 & 1 & \dots & t_{y1} + t_{y2} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}$$

By inspection, the summation in the rightmost column does not change value based on the order of t_{i1} and t_{i2}. Changing the order of $T1$ and $T2$ does not affect the resulting transformation matrix, therefore **translation and translation is commutative**.

2.b Translation and Rotation

Assume that translations and rotations are commutative. The form of an $\mathbb{R}^2$ rotation in homogenous form is

$$T = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

It follows that a translation followed by a rotation has the form

$$T_1 = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & t_x\cos\theta - t_y\sin\theta \\ \sin\theta & \cos\theta & t_x\sin\theta + t_y\cos\theta \\ 0 & 0 & 1 \end{bmatrix}$$

Conversely, a rotation followed by a rotation has the form

$$T_2 = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & t_x \\ \sin\theta & \cos\theta & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

$T_1 \neq T_2$ which is a contradiction, therefore **translation and rotation are not commutative**.

2.c Scaling and Rotation, with different fixed points

Assume towards a contradiction that scaling and rotation with differing fixed points is commutative.

Consider the following transformations:

$$T_{scale} = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & -1 \\ 0 & 0 & 1 \end{bmatrix} \text{(fixed point at (0,1))}$$
$$T_{rotate} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{(90 degrees, fixed point at (0,0))}$$

If scaling and rotation are commutative, then in this example:

$$T_{scale}T_{rotate} = T_{rotate}T_{scale}$$
$$\begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & -1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & -1 \\ 0 & 0 & 1 \end{bmatrix}$$
$$\begin{bmatrix} 0 & -2 & 0 \\ 2 & 0 & -1 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -2 & 1 \\ 2 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Which is a contradiction, therefore **scaling and rotation around different fixed points is not commutative**.

2.d Scaling and Scaling, with the same fixed point.

A scaling transformation about a fixed point p can be expressed as a series of transformations:

1. Translate such that p is at the new origin
2. Scale (denoted S) about the origin
3. Translate the inverse of 1.

Let Two scaling transformations (denoted T_a, T_b) about the same fixed point has the form

$$\begin{aligned} T_aT_b &= (T_1S_aT_3)(T_1S_bT_3) \\ &= T_1S_aT_3T_3^{-1}S_bT_3 \\ &= T_1(S_aS_b)T_3 \end{aligned}$$

And reversing the order of a, b will yield a similar result

$$\begin{aligned} T_bT_a &= (T_1S_bT_3)(T_1S_aT_3) \\ &= T_1S_bT_3T_3^{-1}S_aT_3 \\ &= T_1(S_bS_a)T_3 \end{aligned}$$

We then observe that

$$T_aT_b = T_bT_a \iff S_aS_b = S_bS_a$$

The implication here is that since both T_a and T_b share the same T_1 and T_3, the overall transformation will be commutative if arbitrary origin-centred scale transformations S_a and S_b are also commutative.

Two $N \times N$ origin-scale transformations will take the following form

$$T = \begin{bmatrix} S_{x1} & 0 & \dots & 0 \\ 0 & S_{y1} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} S_{x2} & 0 & \dots & 0 \\ 0 & S_{y2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} = \begin{bmatrix} S_{x1}S_{x2} & 0 & \dots & 0 \\ 0 & S_{y1}S_{y2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}$$

which is clearly commutative. Therefore, since scaling about the origin is commutative, **scaling transformations with the same fixed point are commutative**.

3. Homography

3.1 Affine Transform Derivation

$$\begin{bmatrix} (1,0) \\ (0,1) \\ (1,1) \\ (0,0) \end{bmatrix} \Rightarrow \begin{bmatrix} (6,2) \\ (7,3) \\ (6,3) \\ (7,2) \end{bmatrix}$$

A trace of the transformation reveals that it is a x-scaling by a factor of -1 about the origin, and a translation by $\langle 7, 2 \rangle$. The combined transformation matrix is

$$T = \begin{bmatrix} 1 & 0 & 7 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 7 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{bmatrix}$$

3.2 Map (2,5) Under the Transformation

$$\vec{p} = \begin{bmatrix} -1 & 0 & 7 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 \\ 5 \\ 1 \end{bmatrix} = \begin{bmatrix} 5 \\ 7 \\ 1 \end{bmatrix} \rightarrow (5, 7)$$

The point $(2, 5)$ maps to $(5, 7)$ under this transformation.

4. Polygons

4.1 Point inside triangle

Let $\vec{p}$ represent a test point, and

$$\overrightarrow{l_{ij}} = \overrightarrow{v_j} - \overrightarrow{v_k}, \overrightarrow{l_{ik}} = \overrightarrow{v_k} - \overrightarrow{v_i}$$

are line segments formed from $v_i \rightarrow v_j, v_i \rightarrow v_k$, respectively (i.e. two vectors originating from one triangle vertex to the other two vertices).

If $\textbf{sign}(\overrightarrow{l_{ij}} \times \overrightarrow{l_{ik}}) = \textbf{sign}(\overrightarrow{l_{ij}} \times (\vec{p} - \overrightarrow{v_i}))$, then the point p lies on the "inside" region of the triangle [*fig 4.1*].

Checking this equality for all three points of the triangle creates an intersection which determines if the point lies within the triangle [*fig 4.2*]. That is,

$$\textbf{if} \sum_{i=0}^{2} 1\{\textbf{sign}(\overrightarrow{l_{ij}} \times \overrightarrow{l_{ik}}) = \textbf{sign}(\overrightarrow{l_{ij}} \times (\vec{p} - \overrightarrow{v_i}))\} = \mathbf{3}, \textbf{then the point is in the traingle.}$$

Where $1\{\ldots\}$ is the indicator function and j, k are the other points of the triangle.

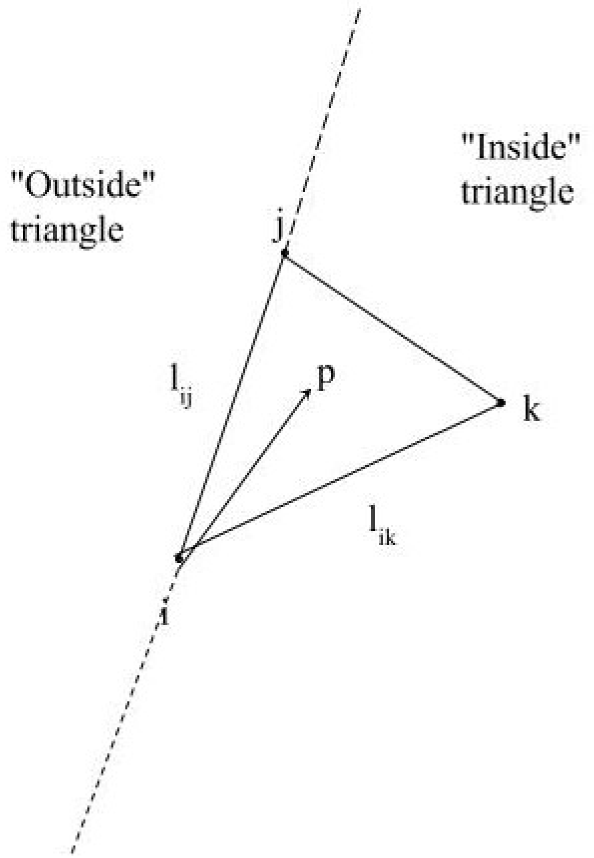

Fig 4.1

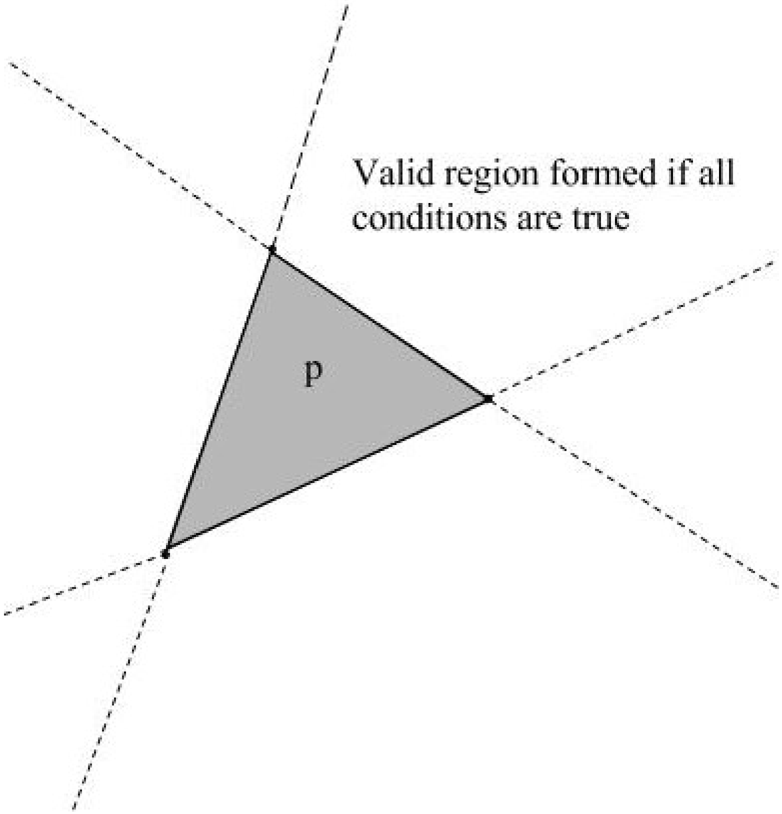

Fig 4.2

4.2 Point on Perimeter

Background

$$\text{point on line segment} \iff \vec{p} \times \vec{l} = 0 \text{ and } l_{1x} \le \vec{p}_x \le l_{2x} \text{ and } l_{1y} \le \vec{p}_y \le l_{2y}$$
$$\text{where } l_1, l_2 \text{ are sorted properly by ascending value for each comparison}$$

Algorithm

```
// Sorts a pair of values by ascending value
function Sort(a, b):
    if a > b:
        return b, a
    else
        return a, b

// Determines if a point lies on a line between start, end
function IsPointOnLine(p, start, end)
    relative_point = p - start // Vector for the point relative to one of the start point

    if CrossProduct(p, end - start) != 0:
        return False

    // Check if the point lies within the bounds of the line
    xStart, xEnd = Sort(start.x, end.x)
    yStart, yEnd = Sort(start.y, end.y)
    if xStart <= p.x and p.x <= xEnd and yStart <= p.y and p.y <= yEnd:
        return True
    else
        return False

// Master function
function IsPointOnTriangle(p, v0, v1, v2):
    return IsPointOnLine(p, v0, v1) or IsPointOnLine(p, v1, v2) or IsPointOnLine(p, v2, v0)
```

4.3 Area

The area of a triangle is solvable exactly and computationally using `Heron';s Formula`, that is:

$$S = \frac{||a|| + ||b|| + ||c||}{2}$$
$$A = \sqrt{S(S - ||a||)(S - ||b||)(S - ||c||)}$$

Where a, b, c are the sides of the triangle.

4.4 Centroid

Geometrically, the centroid of a triangle is the mean of the vertex coordinates. The computation would be:

$$\vec{C} = \frac{\overrightarrow{v_0} + \overrightarrow{v_1} + \overrightarrow{v_2}}{3} = \frac{1}{3}\begin{bmatrix} v_{0x} + v_{1x} + v_{2x} \\ v_{0y} + v_{1y} + v_{2y} \end{bmatrix}$$