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Analysis of eye tracking data in 3D virtual environments

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1.Background

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What is eye tracking and what is eye tracker?

- Eye tracking is the process of measuring either the point of gaze or the motion of an eye relative to the head.
- Eye tracker is a device for measuring eye positions and eye movement.

Screen-based eye tracker[1]

Glassed eye tracker[1]

[1] imotions. Eye tracker technology. https://imotions.com/blog/eye-trackingwork/.

1.Background

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Why are they so important?

1. They can help us understanding how does human vision system works.
2. Eye tracking data comparison technique can measure the different between the ground truth and the model predicted, this can tell us if the attention model works well.

1.Background

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What problem do we study with?

1. The virtual reality and augment reality becomes increasingly popular these years.


HTC vive [1]


Microsoft hololens [2]

[1] HTC. Htcvive. https://www.vive.com/cn/.
[2] Microsoft. hololens. https://www.microsoft.com/en-us/hololens.

1.Background

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What problem do we study with?

2. The tools and techniques for comparing eye-tracking data in 2D are numerous.
3. But their equivalents for data acquired in a virtual 3D world are very limited for the moment.
4. Our research study on the concepts and methods for comparing eye tracking data acquired in virtual reality.

2.Related works

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- Researches had done lots of works in 2D environment, and only accountable works in 3D environment.
- Most works in 2D can not be directly used in 3D.
- I will introduce it in this section, this can provide a global view of various methods in 2D.
- We can also learn from it and it can help us proposing a new method.

- There are three reasons that 2D methods can not be directly used in 3D

1. Combination movements of head, body and eyes.
2. Difference of point of view.
3. Distinction between foreground and backplane.

2.Related works

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The 2D methods be categorized into 4 types based on their respective characteristic, they respectively are

1. **Grid-based:**
    - This method will divide the whole image into distinct grids, and each grid is assigned a unique character.
    - But how to defined the number of grids is time-consuming.
2. **Sample-based:**
    - resample scanpath in time uniformly, and then truncated it to the shorter length.
    - It’s also not have a good idea of how to defined the time threshold.

2.Related works

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3. **Direct measure:**
   - This methods does not need to be quantified as Grid-based or Simple-based measures, it provides several methods to directly measure the difference between scanpaths.
   - But it’s difficult to assess which measure is most applicable in a give scenario.
4. **Recurrence-based measures:**
   - This method can provide an overall measure of similarity across two eye movement sequences.
   - But the longer sequence need to be truncated.

2.Related works

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- Here we briefly introduce one of the 3D method
- The idea is collecting a sets of still image in VR.
- There are two methods for temporal analysis: head-based and time-based.
  1. **Head based analysis:** It estimates the movements of head and locate a sequences of still images where head is stable.
  2. **Time based analysis:** It assumes a constant frame rate to locate a ROIs (region of interests).

3.Previous works

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- Our team have proposed a method before, I will introduce this method first and then analysis its ups and downs [1].
- To deal with it's disadvantages we proposed a new method based on their previous works.

- **This method has three steps.**
  1. Data: the data we need to collected.
  2. Measurements: how to measure the distinct data we collected.
  3. Comparison: how to compare the data.

[1] Gazer VR2.0: Comparaison de donnees oculometriques issues du visionnage d'une scene 3D en realite virtuelle. Matthieu LE FLOHIC & Solange DAGUISE

3.Previous works

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Collecting data

- The data set collected is formed as a vector list.
- The vector is consisted of three parts, they respectively are ‘timestep’, ‘helmet position’, and ’gaze point’.
- The head position and gaze position are represented by 3D coordinates, and timestamp is a scalar.


```
"dataset": {
  "0": {
    "timestamp": 1548248188437,
    "pos": {
      "x": 1.3445571000095538,
      "y": 2.0344827504014082,
      "z": 2.043493299448808
    },
    "gaze": {
      "x": 0.9132832374728457,
      "y": 1.0384518128496083,
      "z": 0.6921216235538485
    }
```

Measurement

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- A1, B1 are two datasets.
- P represents the helmet position.
- G is the gaze position.
- V means vector.

1. The time distance is the difference of them divided by the max of them.
2. They take the angle between two observers and the gaze point as the helmet position distance.
3. The angle between two gaze points and the observer as the gaze point distance.
4. Here are three coefficients α,β,γ to control the weight of the three factors.

$$d_t(t_{A1}, t_{B1}) = \frac{abs(t_{A1} - t_{B1})}{max(T_A, T_B)} \quad (1)$$

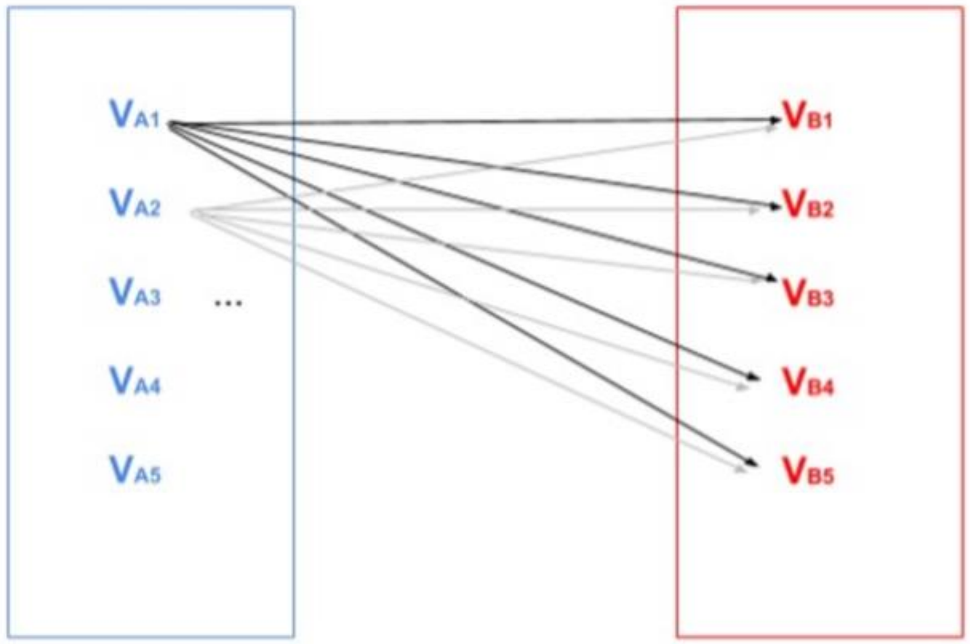
$$d_p(p_{A1}, p_{B1}) = \frac{\widehat{p_{A1} g_{A1} p_{B1}}}{180} \quad (2)$$

$$d_g(g_{A1}, g_{B1}) = \frac{\widehat{g_{A1} p_{A1} g_{B1}}}{180} \quad (3)$$

$$d_v(v_{A1}, v_{B1}) = v_{d_v(v_{A1}, v_{B1})} \times \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix} \quad (4)$$

Comparison

1. There are two data sets and each of them has numbers of vectors.
2. The vectors of the first dataset will be compared with each vectors in the second dataset.
3. And each of these comparisons will return one value, and only the smallest will be kept as a match.
4. The sum of all the values is the difference between the dataset.
5. And there are three new coefficients to control the sum value of head position, gaze position, and timestamp.



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- **Drawbacks of this method.**
  1. They didn't consider the distance information of headset and gaze.
     - The only information they have is the angle between the two vectors.
     - This means if two observers stand at different distance but has the same angle with the gaze object, there will have the same result with the reference target.

  2. All calculation is linear.
     - Based on the human visual system, with the angle between the observer and gaze object increased 180 the influence will be increased sharply. It’s not linear. More details will be presented in the next section.

4.Proposed methods

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- As mentioned above, there still exist some shorts in the previous methods.
- The new methods we proposed hope to deal with the two shorts.
- To make the problem simple we focused on a very simple scenario — only two observers were looking at the same gaze point

4.Proposed methods

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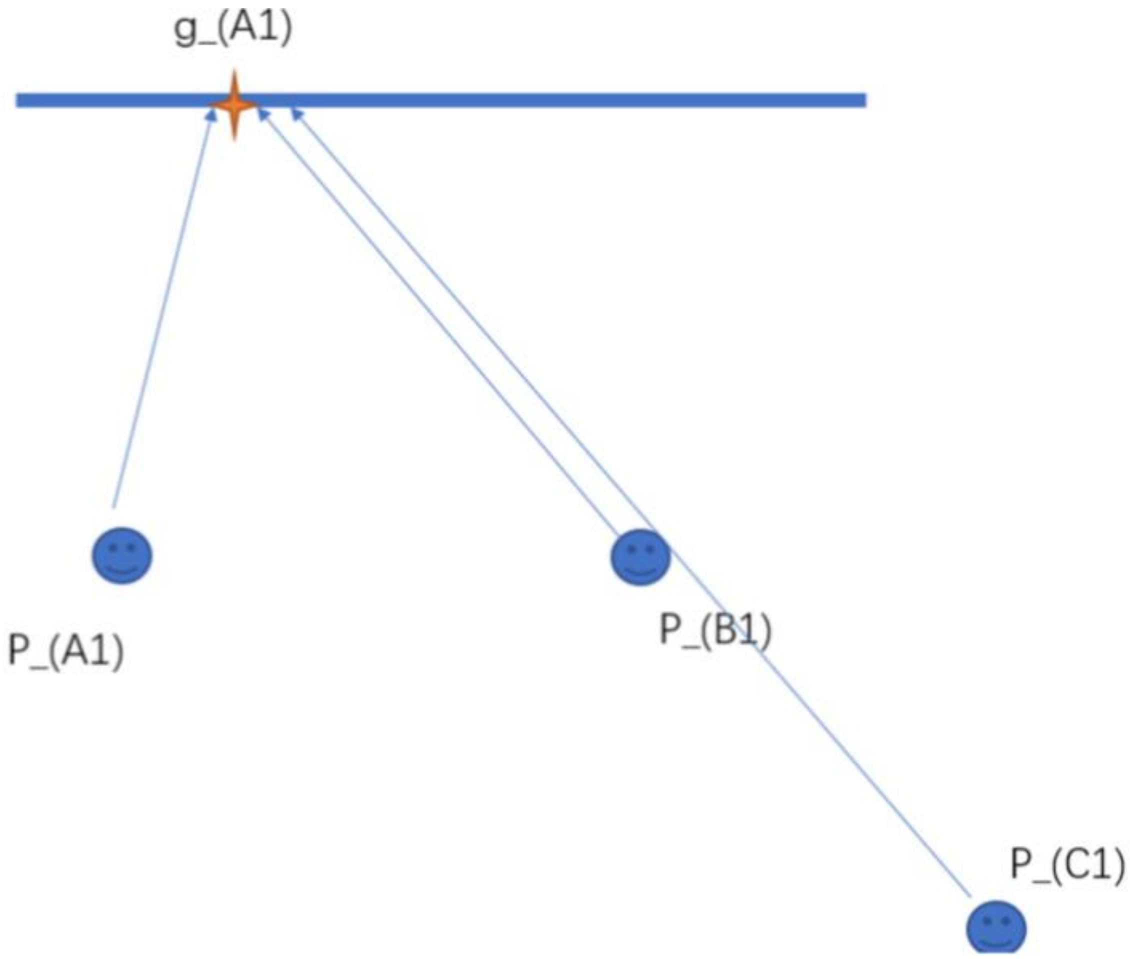
Problem statement

- there are three observers and they all look at the same object g_{A1}.
- B1 and C1 have the same angle with A1, but C1 stands at a further place.

- In this situation, the previous method will give the same result for (A1,B1) and (A1, C1)
- In fact, the difference between (A1,B1) should less than (A1, C1).



4.Proposed methods

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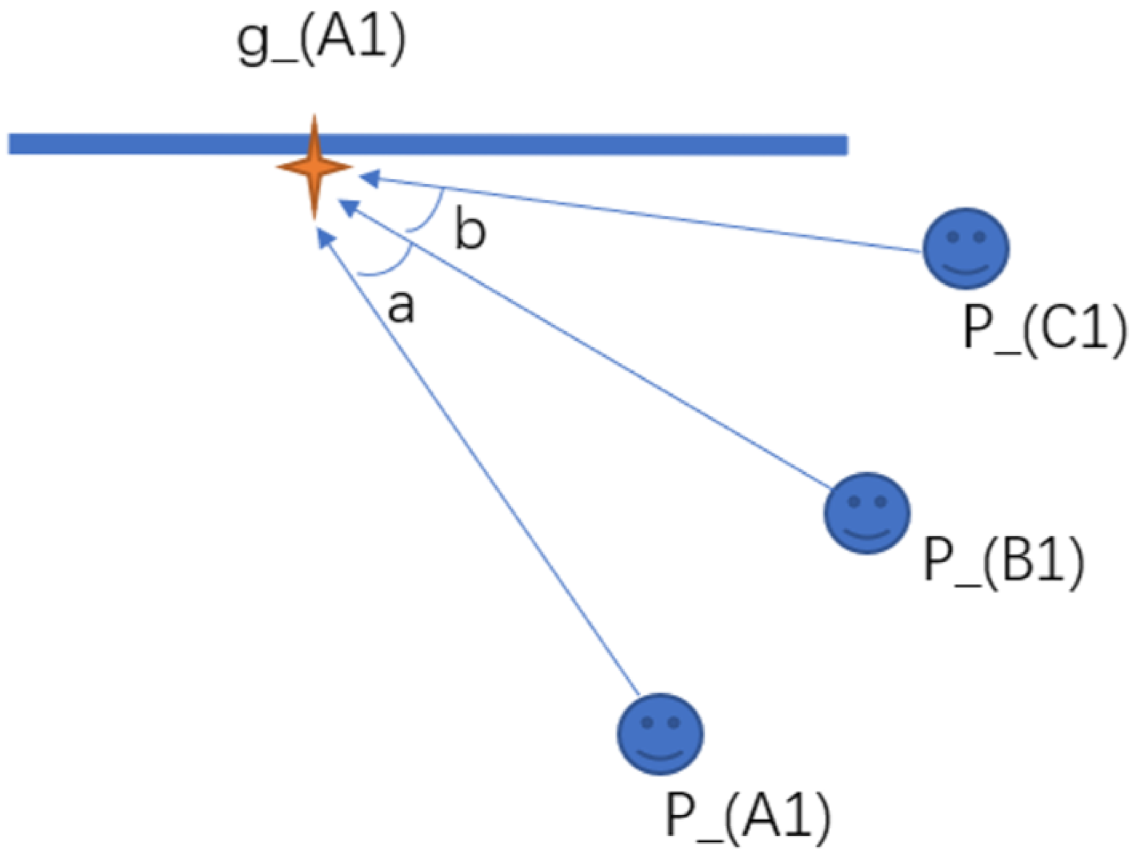
Problem statement

- there are three observers and they all look at the same object.
- a, b represents the angle between observers and gaze point. and a=b.

- Our previous method give the result that the distance between the three observers are the same.
- But we hope distance (B1,C1) bigger than (A1,B1) because observer C1 at a very sharp angle, it means he can see few thing about gaze point.



4.Proposed methods

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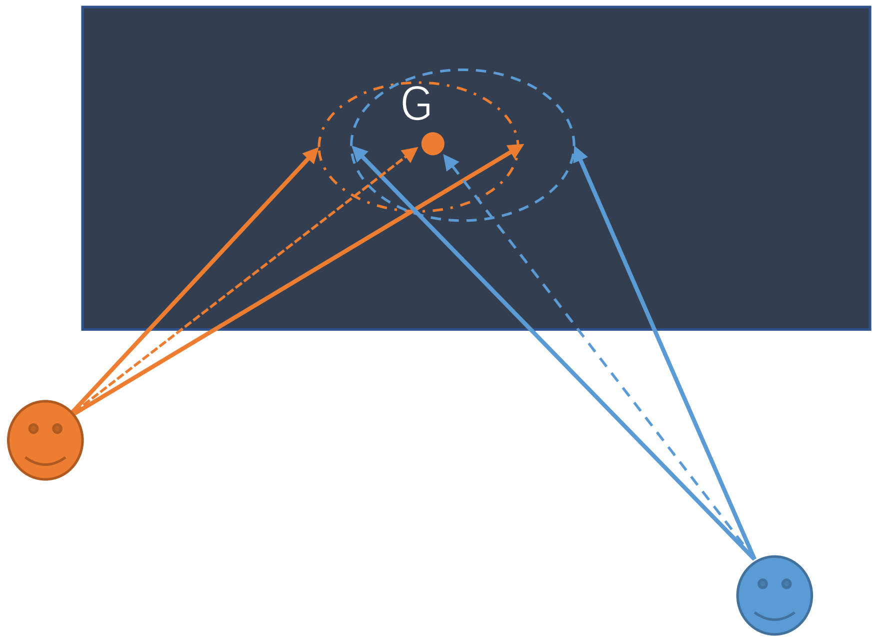
- We think it's more reasonable using the projected area of the eyesight to represent what the observer seeing.
- We only focus on a very simple scenario, the two observers were looking at the same gaze point.
  1. Fovea is the small area on the human eye's retina which has a sharp vision, and we assume the fovea angle is 15.
  2. The eyesight of human is a cone. When this cone projected onto a plane an ellipse is formed.
  3. The area of this ellipse represents what observer was seeing.



4.Proposed methods

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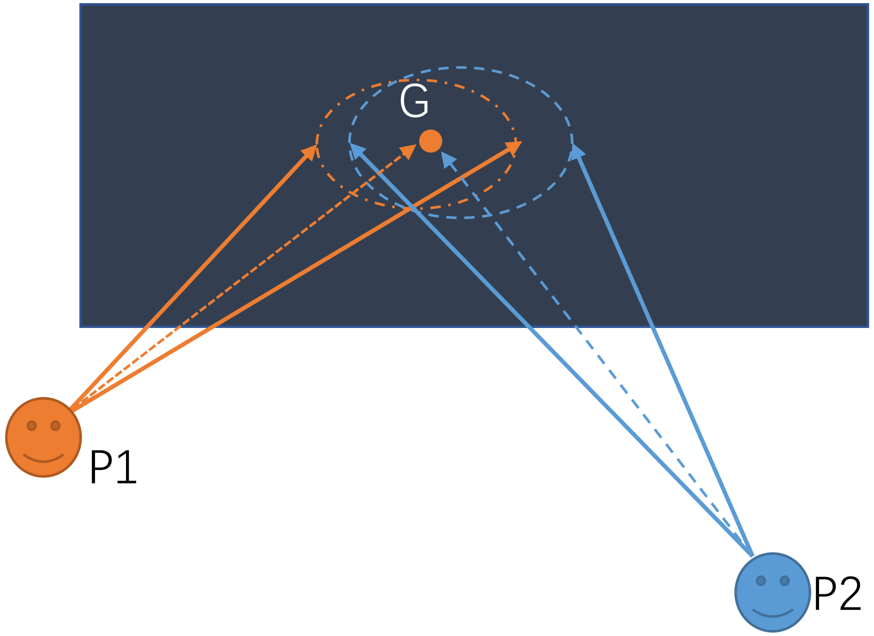
1. Two observers have two ellipse and we assume the common area is S.
2. The orange observer has the S(orange), the blue observer has the S(blue). The similarity is defined as:

$$similarity = ave(\frac{s}{s_{orange}} + \frac{s}{s_{blue}})$$



- So, the question is transferred into how to get the area of the ellipses and the common region.

4.Proposed methods

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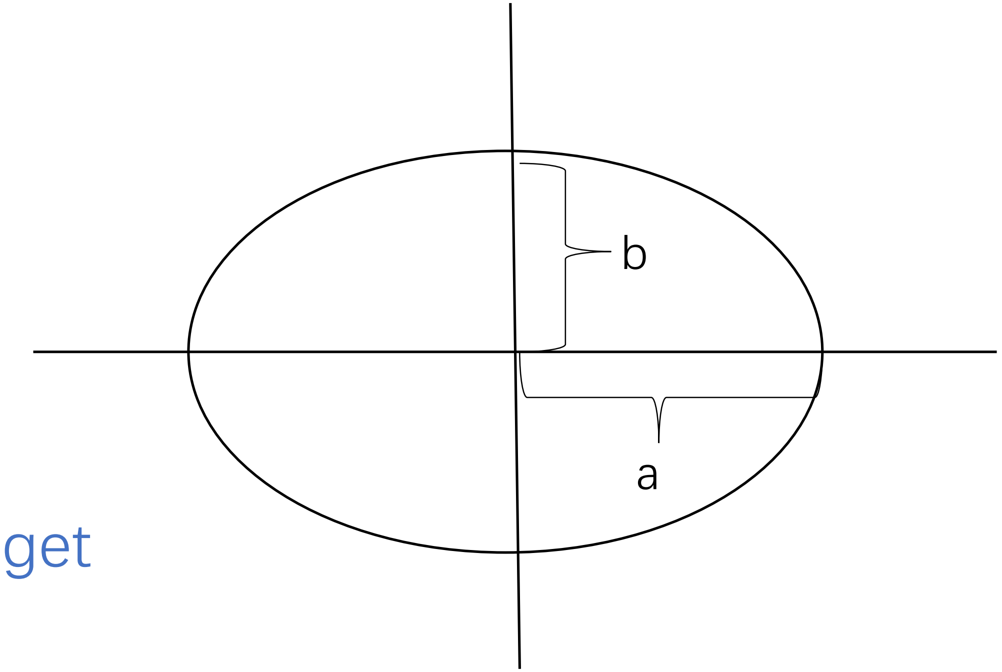
1. We know the equation of the standard ellipse as below.
2. If we know a,b of each ellipse, we can get the area of it.
   - a is the long semimajor axis of ellipsoid and b is the short one.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

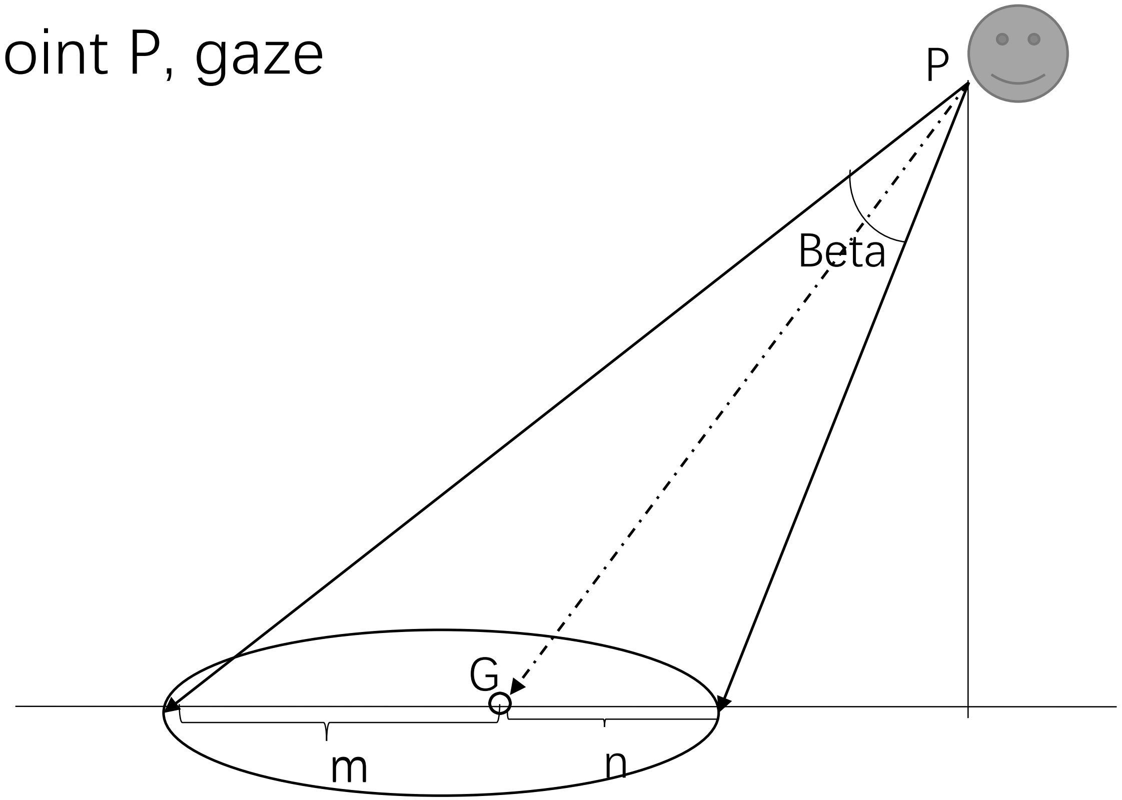
$$s = \pi ab$$



- The question is changed into how to get a,b of the corresponding ellipse.

4.Proposed methods

- **How to get a,b of ellipse?**
  - We only know the coordinates of pos point P, gaze point G, and the angle of fovea Beta.



$$2a = m + n$$

$$a = \frac{m+n}{2}$$

- If we can get m and n , we can get a.

4.Proposed methods

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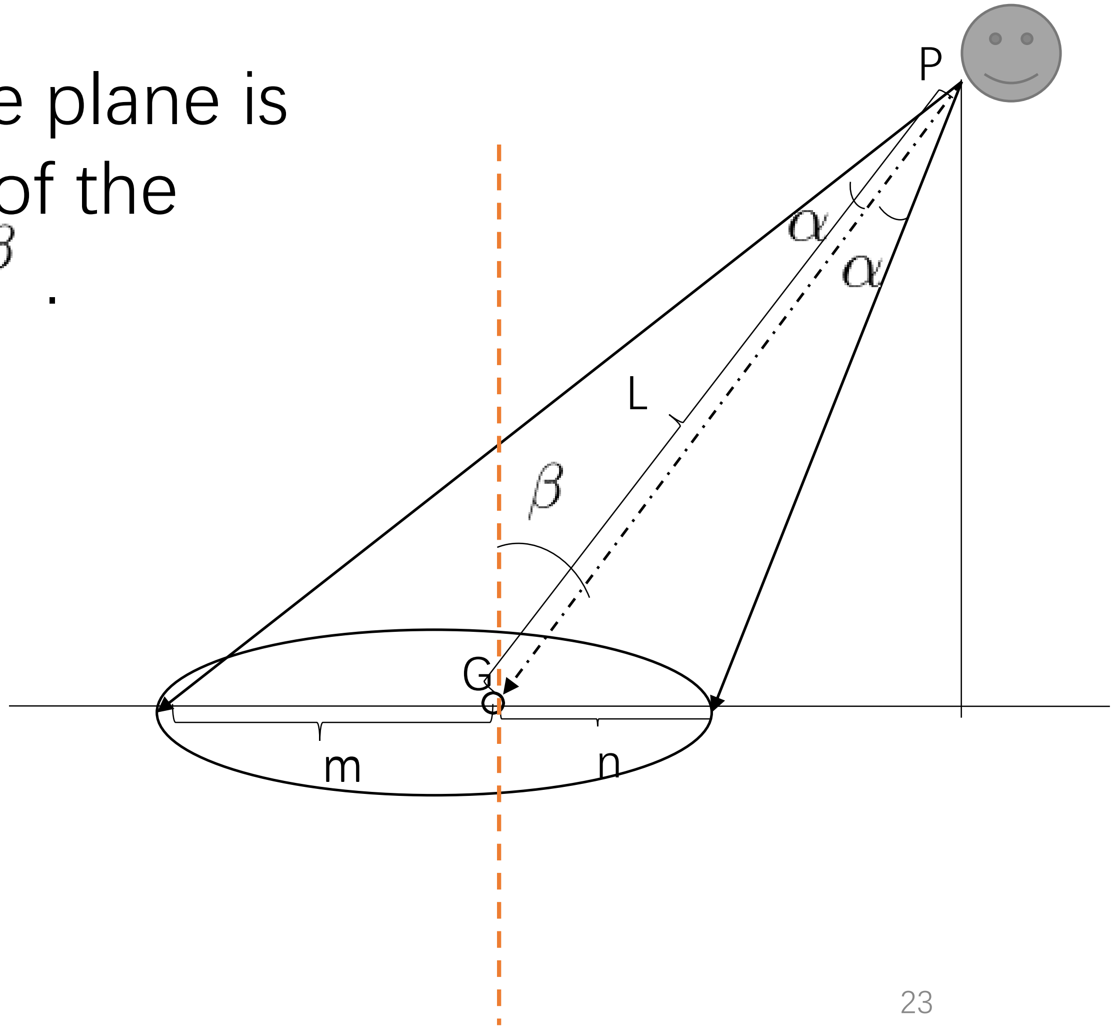
- **How to get the a,b of ellipse?**
  - We assume the norm vector of the plane is Norm, then we can get the angle of the vector PG and Norm. Setting it as β .
  - And we make $\alpha = \dfrac{Beta}{2}$
  - L = length of vector PG



4.Proposed methods

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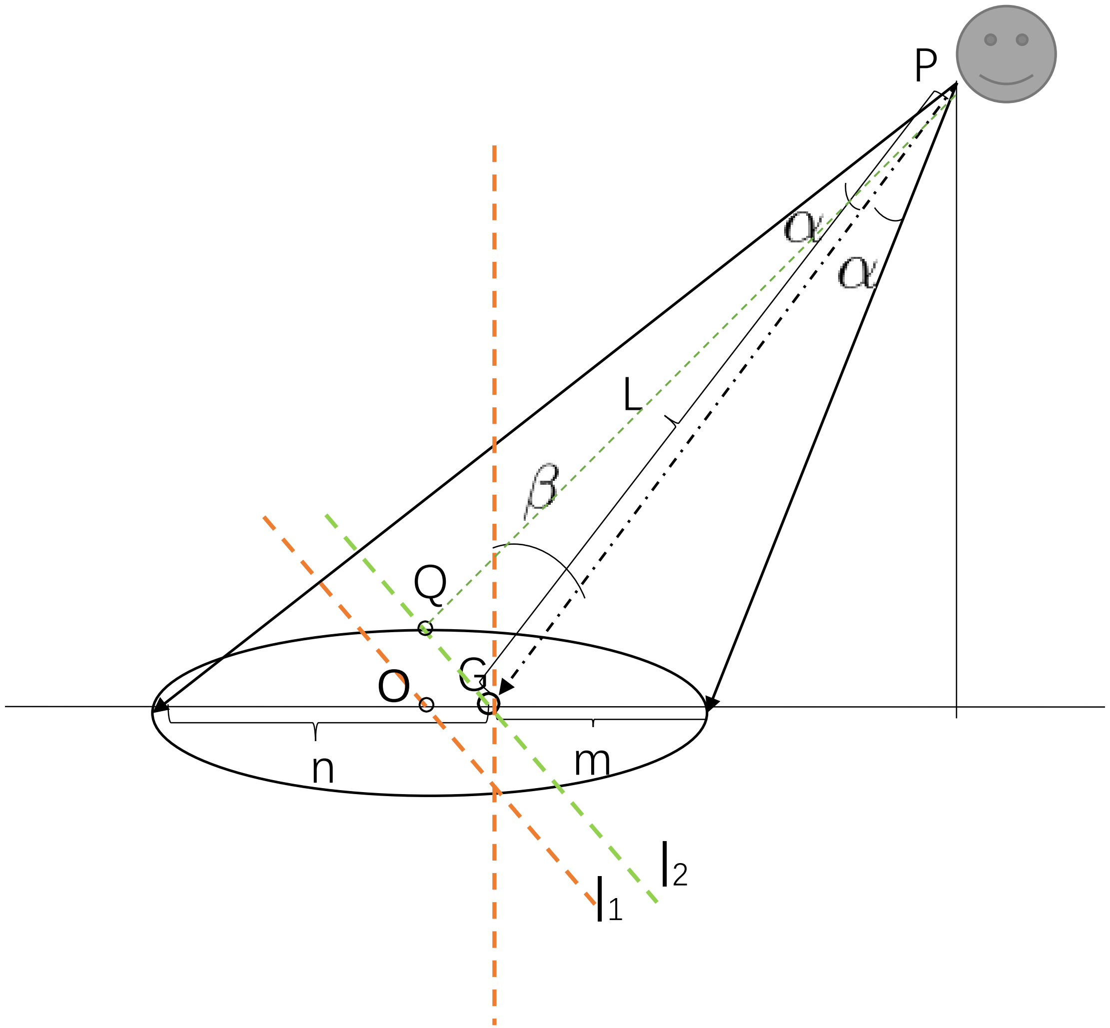
- **How to get the a,b of ellipse?**
  - Then we can get m and n

$$m = L * \sin\beta - L * \tan(\beta - \alpha) * \cos\beta$$

$$n = \frac{L * \cos\beta}{\tan(\pi/2 - \beta - \alpha)} - L * \sin\beta$$

$$a = \frac{m + n}{2}$$

- Finally, we can get a:



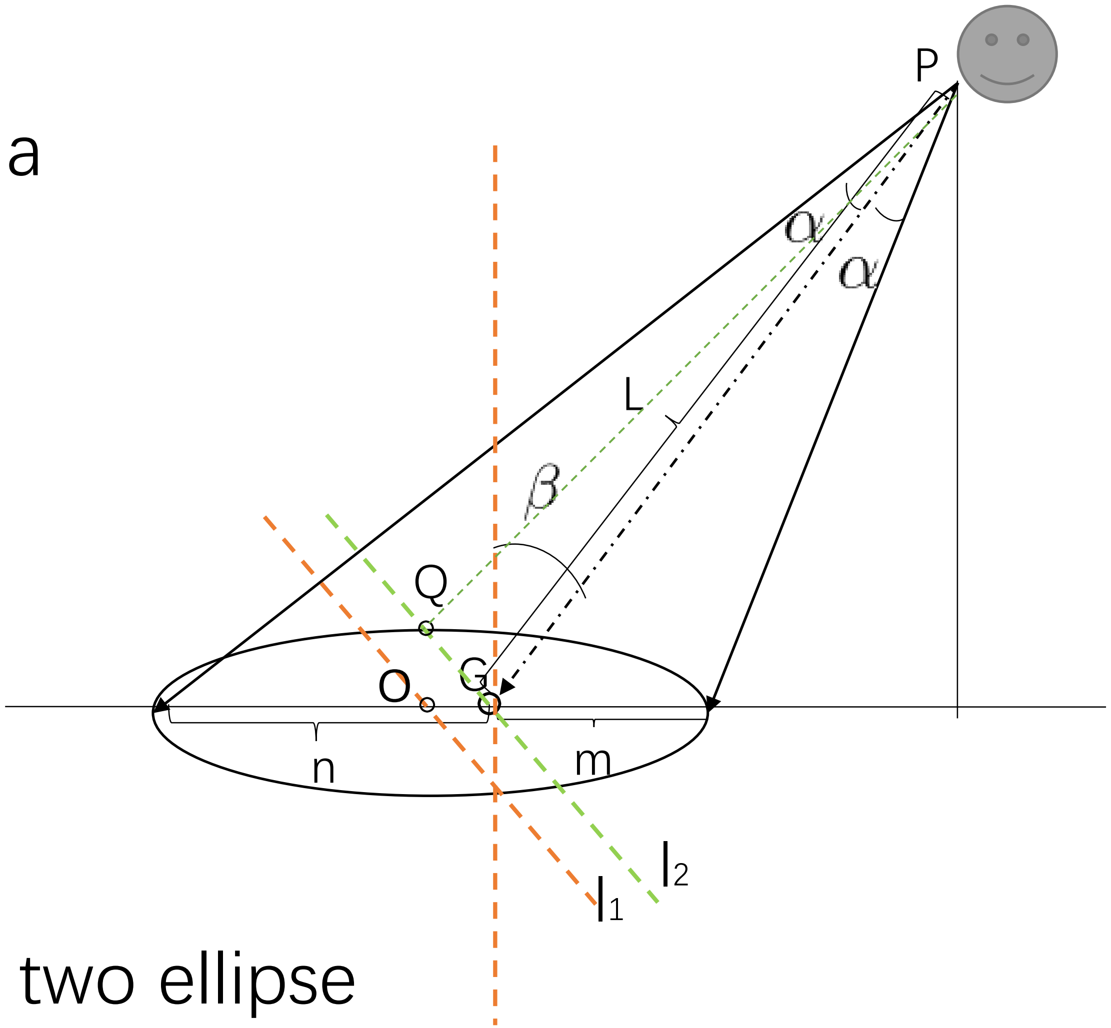
4.Proposed methods

- **How to get the a,b of ellipse?**
  - We also can get b as the formula below:

$$\begin{cases} X_Q = a - m, \\ Y_Q = L * \tan\alpha \end{cases}$$

$$\begin{cases} \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1, \\ (X_Q, Y_Q), \\ b = ay\sqrt{\frac{1}{a^2-b^2}} \end{cases}$$

$$s = \pi * a * b$$



- Eventually, we can get area of the two ellipse

4.Proposed methods

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- **Next question is how to get the area of the common region.**
  - If we can put the two ellipses at the same coordinate system, then we can solve area with calculus.
  - We can assume one ellipse as main ellipse and another as inferior ellipse.
  - For the main ellipse its equation is: $$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$
  - And for the inferior one is:
    - (x_0 y_0) is the coordinates of the center point.

$$A(x - x_0)^2 - B(x - x_0)(y - y_0) + C(y - y_0))^2 + f = 0$$

- And for the inferior ellipse we also know:

$$\begin{cases} A = a^2(\sin\theta)^2 + b^2(\cos\theta), \\ B = 2(a^2 - b^2)\sin\theta\cos\theta, \\ C = a^2(\cos\theta)^2 + b^2(\sin\theta), \\ f = -a^2b^2 \end{cases}$$

4.Proposed methods

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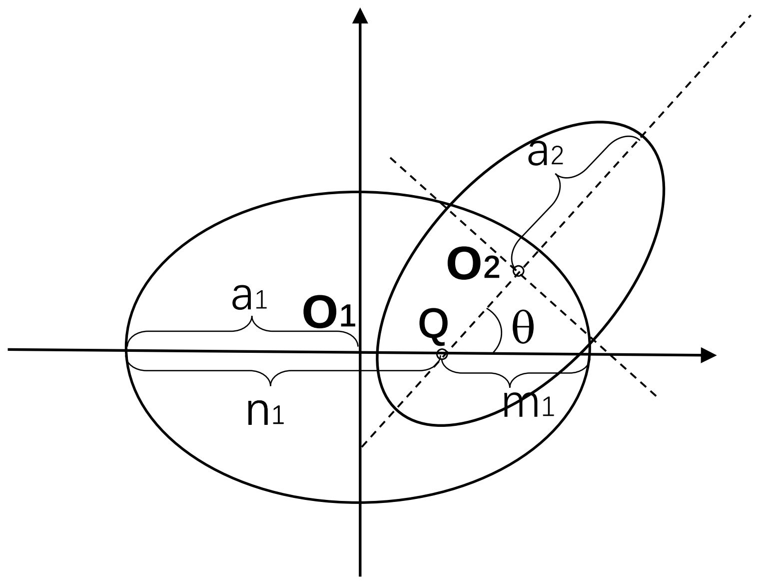
- **How to get the area of the common region?**
  - θ is the angle between long semimajor of the ellipse and the X axis.

$$\begin{cases} A = a^2(\sin\theta)^2 + b^2(\cos\theta), \\ B = 2(a^2 - b^2)\sin\theta\cos\theta, \\ C = a^2(\cos\theta)^2 + b^2(\sin\theta), \\ f = -a^2b^2 \end{cases}$$



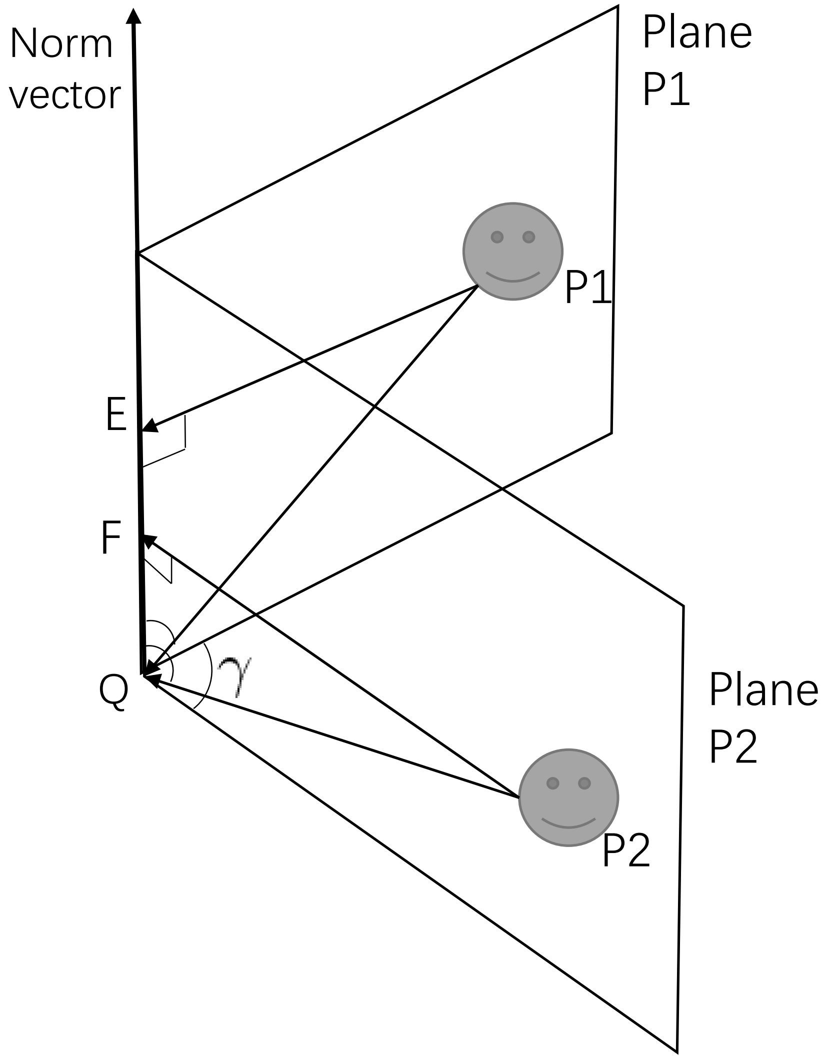
The question transfer to how to get the angle **θ** between two ellipse and how to get the center point coordinates of the inferior ellipse.

4.Proposed methods

- **How to get the area of the common region?**
  - here we represent θ as γ, we know how to get angle between to vectors.
  - We also know the norm vector of the plane.

$$Angel = \arccos \frac{\vec{A}\vec{B}}{|A||B|}$$

$$\begin{cases} \vec{P_1E} = \vec{P_1Q} + \vec{QE}, \\ \vec{QE} = (0, 0, |P_1| \cos Angle_{P_1QE}) \ (and\ the\ same\ for\ \vec{P_2F}), \\ \gamma = \arccos \frac{\vec{P_2F}\vec{P_1E}}{|P_2F||P_1E|}, \end{cases}$$



- So, we can get γ (θ) based on the two formula above, it's the angle between two ellipses.

4.Proposed methods

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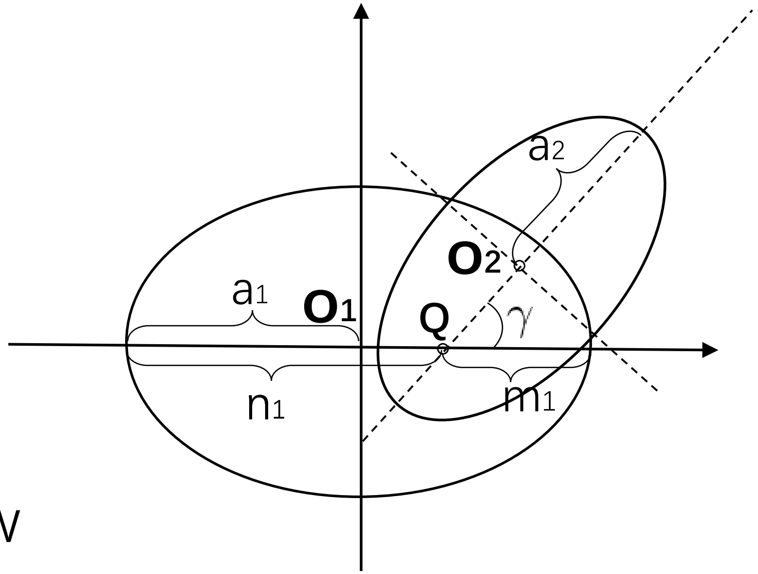
- **How to get the area of the common region?**
  - We already get γ, and we also can obtain center point coordinates based on the formula below.

$$\begin{cases} X_{O_2} = a_1 - m_1 + (a_2 - m_2)\cos\gamma, \\ Y_{O_2} = (a_2 - m_2)\sin\gamma, \end{cases}$$



- Eventually, we can combine the two equations below to get the coordinates of the intersecting points.

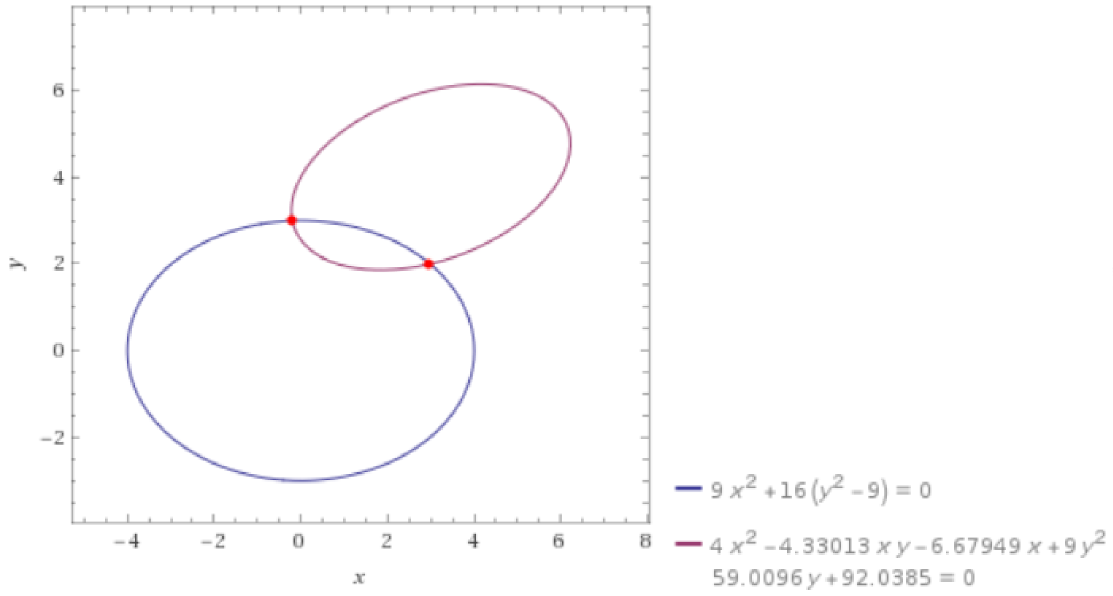
$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

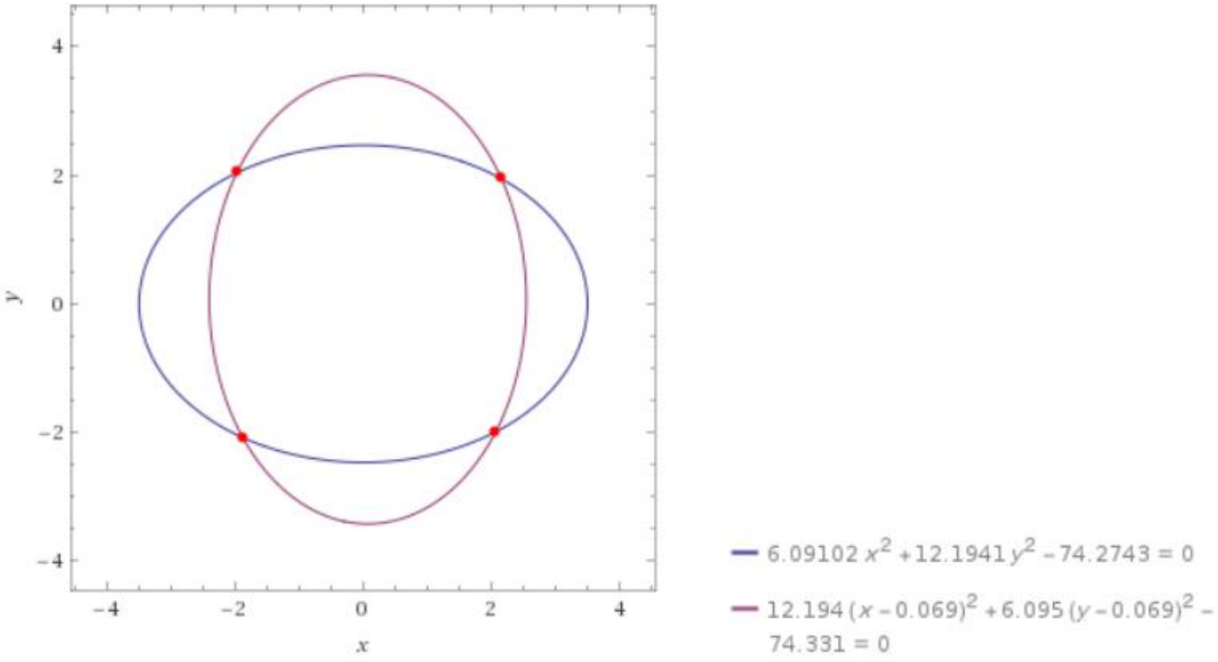
$$A(x - x_0)^2 - B(x - x_0)(y - y_0) + C(y - y_0))^2 + f = 0$$

$$\begin{cases} A = a^2(\sin\theta)^2 + b^2(\cos\theta), \\ B = 2(a^2 - b^2)\sin\theta\cos\theta, \\ C = a^2(\cos\theta)^2 + b^2(\sin\theta), \\ f = -a^2 b^2 \end{cases}$$

4.Proposed methods

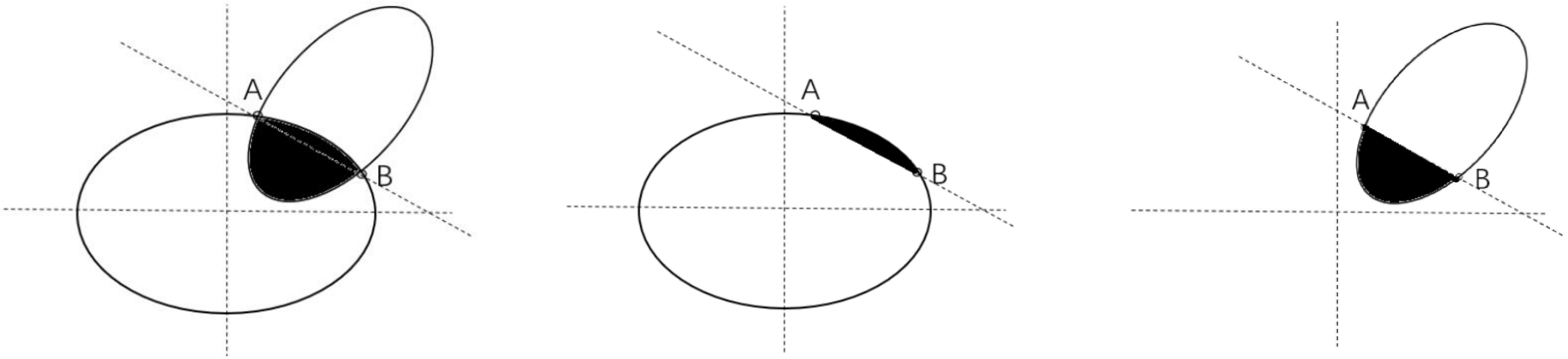
- **There are 4 different case for the solutions of the two equations.**





- 0 and 1 solution means no intersecting area.
- 2 and 3 solutions just like the figure right.
- 4 solutions case will like the figure right.
- Figure above is two examples of intersecting case.

4.Proposed methods



1. Here we discuss 2 intersecting points first.
2. Liking figure above, we can divide the colored area into two parts. If we can calculate the area of the distinct two parts, we can sum them up as the whole area.
3. Next I will show how to calculate the arc area, here we only show example of the middle image.

4.Proposed methods

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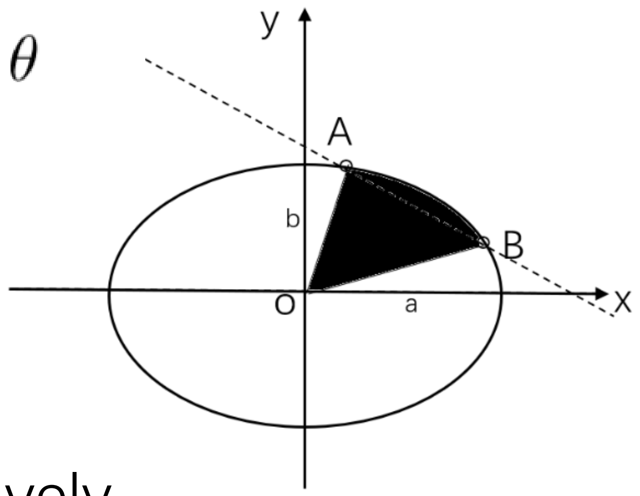
- We can use polar-coordinate to represent the x: $x = r\cos\theta$
- And then we can replace it into equation: $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$
- We can get a new equation below:

$$r^2 = \frac{a^2b^2}{b^2(\cos\theta)^2 + a^2(\sin\theta)^2}$$



- α, β is the angle between point A, B with the X-axis respectively.

$$A(\beta,\alpha) = \int_\beta^\alpha \frac{1}{2}r^2 d\theta = \int_\beta^\alpha \frac{(a^2b^2/2)d\theta}{b^2(\cos\theta)^2 + a^2(\cos\theta)^2}$$

- An anti-derivative of the integrand is

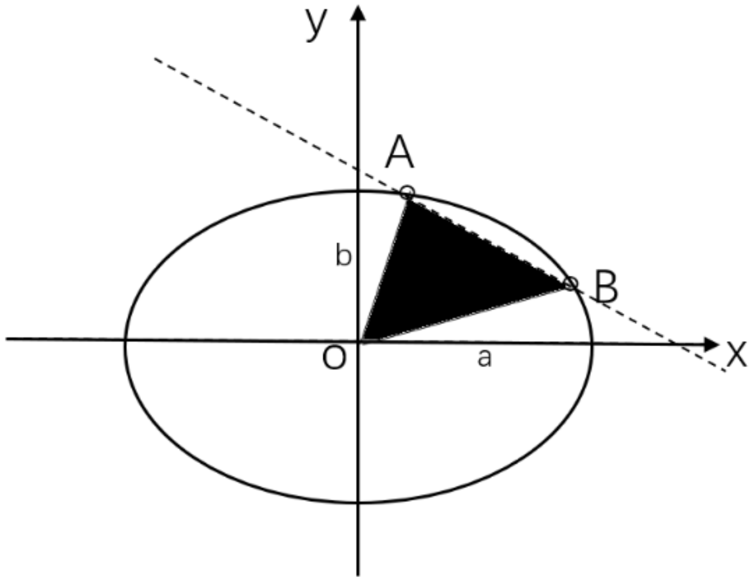
$$F(\theta) = \frac{ab}{2}\left[\theta - \tan^{-1}\left(\frac{(b-a)\sin 2\theta}{(b+a)+(b-a)\cos 2\theta}\right)\right]$$

- So, we can get the area of the ellipse sector

$$A(\beta,\alpha) = F(\alpha) - F(\beta)$$

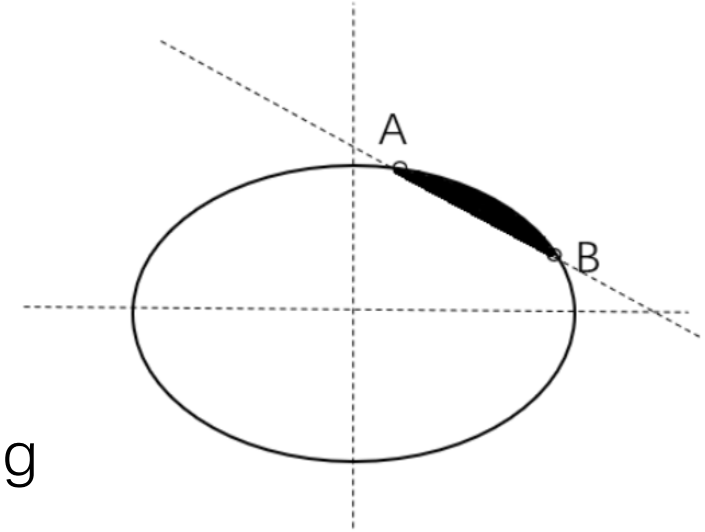
4.Proposed methods

- Then we can divide the ellipse sector into two section, like the figure right.
- And for the triangle section, we can calculate its area based on the formula below.



$$A_{triangle} = \frac{1}{2}|x_1 y_0 - x_0 y_1|$$

- Finally, we can get the area of the arc part.

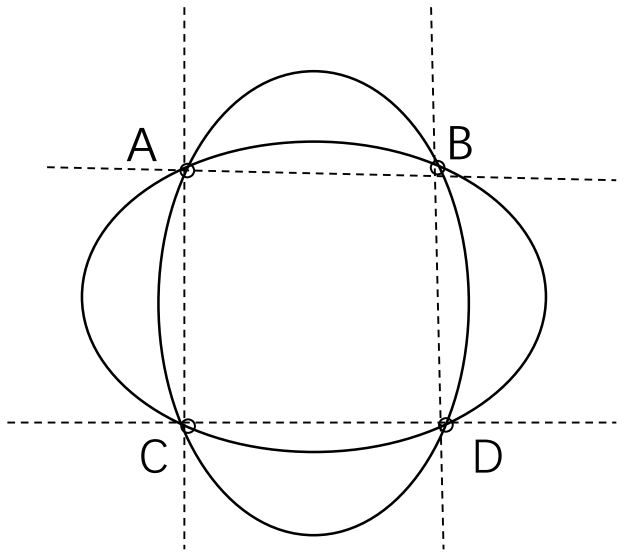


$$A_{arc} = A(\beta, \alpha) - A_{triangle}$$

- And then we can switch the main ellipse and the inferior ellipse to get the arc area of another part.
Summing them up to get the whole area of the intersecting region.

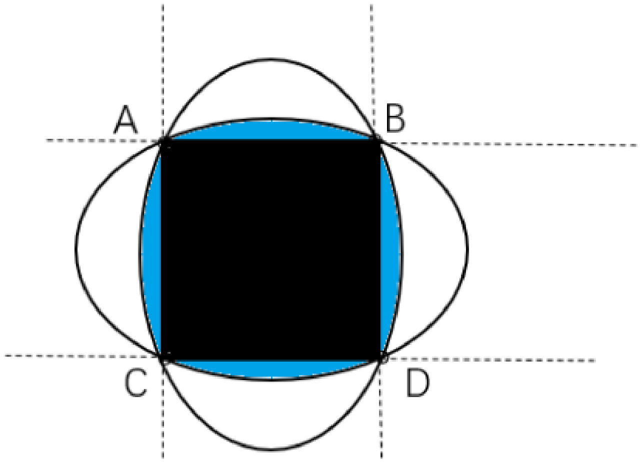
4.Proposed methods

- Here is for the 4 intersecting points case, we can view the intersecting region as black region and blue region.
- Obviously, for the black region it is a polygon, and we can use the polygon area equation to get its area.
- For the 4 arc section, we can just use the methods in previous slide to get its area.
- Eventually, we can obtain the area of the whole colored region by summing up all different parts.



$$A_{polygon} = \frac{1}{2}(x_1y_2 - x_2y_1 + x_2y_3 - x_3y_4 + \ldots + x_{n-1}y_n - x_ny_{n-1} + x_ny_1 - x_1y_n)$$

$$A_{4points} = A_{arc_{AB}} + A_{arc_{BD}} + A_{arc_{DC}} + A_{arc_{CA}} + A_{polygon}$$



5.Conclusion and perspectives

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1. We analyzed the previous works and get 2 drawbacks of it.
2. To deal with these drawbacks we proposed a new method based on projected area of human vision system.
3. Compared with the previous method, our new method is more reasonable in the discussed scenario.

- But the computational complexity is higher than the previous one.
- It’s hard to obtain the norm vector of all planes in some complex scenario.

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Thanks for your listening
Q&A