# A NEW SYSTEM FOR MEASURING EYE POSITION ON A PERSONAL COMPUTER.

K.Matsuda*, T.Nagami, K.Kawano and S.Yamane

Information Science Division, Electrotechnical Laboratory, Tsukuba, Japan

744.2

# Introduction

We have developed a new system based on on-line image processing to measure eye position noninvasively. We use an infrared LED to illuminate the eye of a subject, whose head movement is lightly restricted, and record images of the subject's pupil using a CCD camera with a sampling frequency of 60Hz. The image of the pupil in each video-frame is digitized by a video capture board and transferred to a personal computer. The outline of the pupil and the reflection center of the illumination on the cornea are then detected using image-processing software, and the pupil is approximated by an ellipse. Using the shape, size of the ellipse and reflection center, we estimate the subject's view axis in the camera-coordinate system (the origin is the center of the eye rotation and the x-y plane parallels the plane of the CCD camera) and the diameter of the pupil. To calculate the transformation matrix to transfer a vector from the camera-coordinate system to the target-coordinate system (the origin is the same as above and the x-y plane parallels the plane of the targets), we ask the subject to fixate each of the 9 targets displayed on a screen. We measure the subject's eye positions in the camera-coordinate system and compare them to the respective required eye positions in the target-coordinate system. After this calibration process, we are able to measure the subject's eye position in the targets' plane. The accuracy of the measurement is better than 1 degree. We use Red Hat Linux 6.1 as the operating system, Video for Linux as the device driver for the video capture board, and the X Window system for display. This system can be used for both monkeys and humans. The program is available at http://www.etl.go.jp/~matsuda/eye/.

# Method

## 1.Calibration.

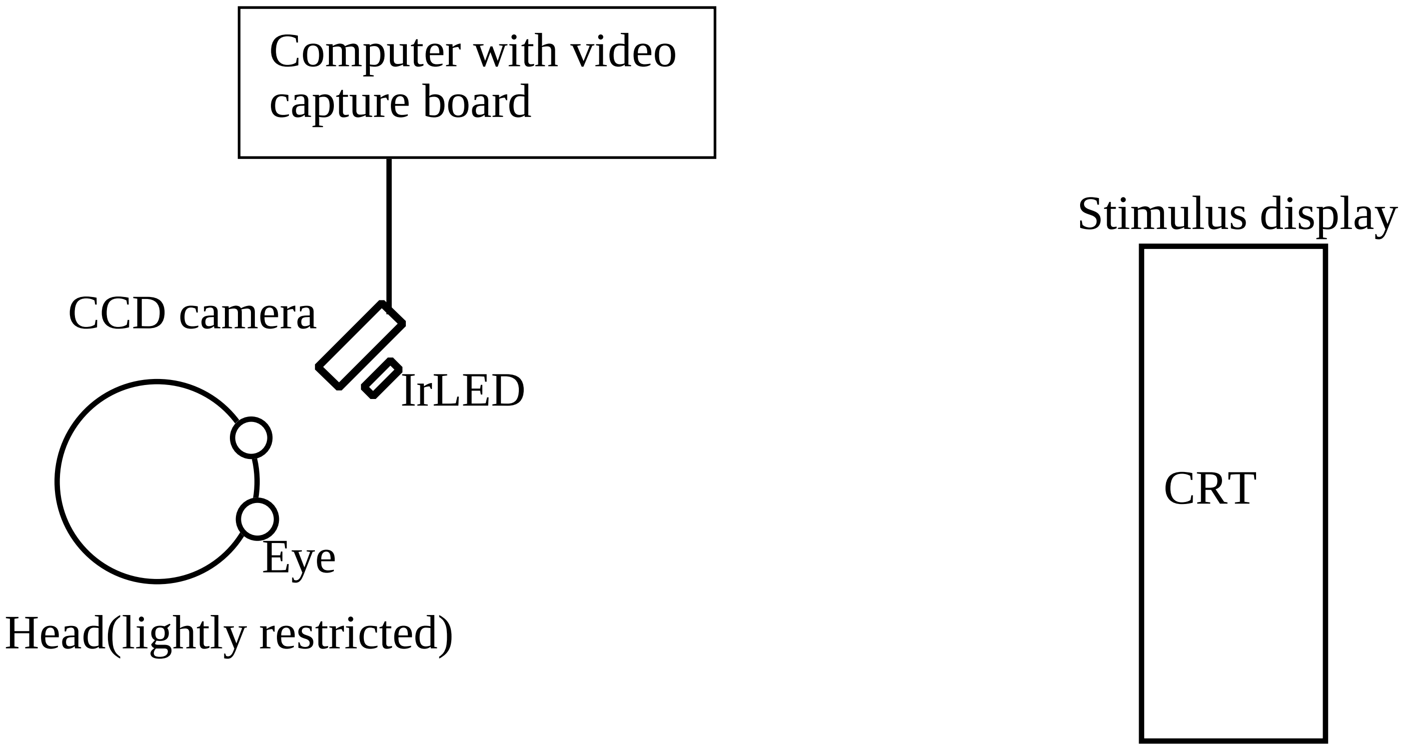
To obtain values listed below which are necessary for the measurement, we ask the subject to fixate each of the 5 (more than 3) targets displayed on a screen and capture images of its eye. The subject's head movement must be restricted.

i) The eye rotation center (Xo, Yo).
ii) The pupil center rotation radius (Rp)
iii) The cornea curvature center rotation radius (Rc).
iv)The length between the reflection on the cornea and the cornea curvature center in each axis ($\alpha$,$\beta$).
v) The coordinate system transformation matrix.

## 2.Measurement.

i) Find the pupil center and the illumination's reflection center using image-processing.
ii) Calculate the subject's view axis vector in the camera-coordinate system.
iii) Transfer the subject's view axis vector from the camera-coordinate system to the target-coordinate system, using the transformation matrix.
iv) Calculate view axis angles in the target-coordinate system.
v) Output angles as voltage by using D/A converter (option).

# System outline




1. All equipment can be bought on the market.

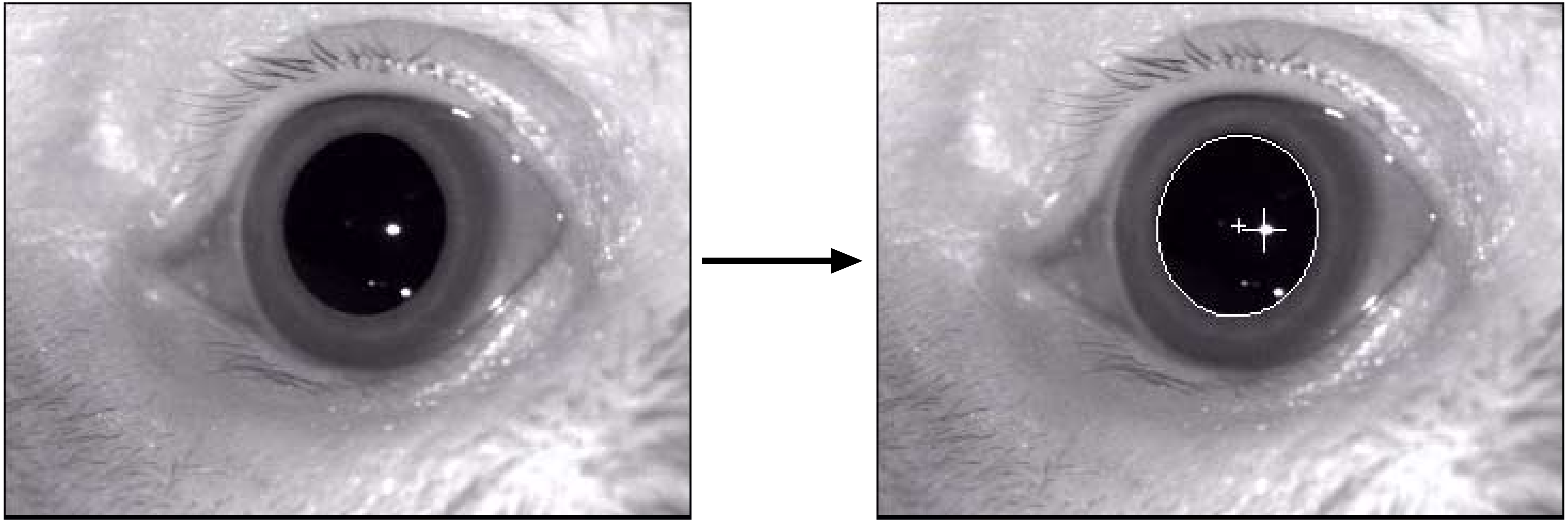
2. The CCD camera can be arranged at any position within the range where a picture of the pupil can be taken.

3. The IrLED can be arranged at any position within the range where a picture of the illumination's reflection on the cornea can be taken.

# System equipment

| | model | memo | price(about) |
|---|---|---|---|
| CCDCamera | XC-EI50 (Sony) | Power supply DC-700<br>Lens 45mm Macro Lens | <$3000 |
| IrLED | SLR931A(Sanyo) | Use 56 LEDs.<br>Power supply. | <$15 |
| Video Capture Card | GV-VCP2/PCI(IO data) | Any board adopt Video for Linux. | <$120 |
| DA converter | DA12-4L(PCI)(Contec) | D/A Converter PCI bus | <$600 |
| IBM PC Compatible | Pentium III 700MHz | RedHat Linux 6.1 | <$2000 |
| | | total | <$6000 |

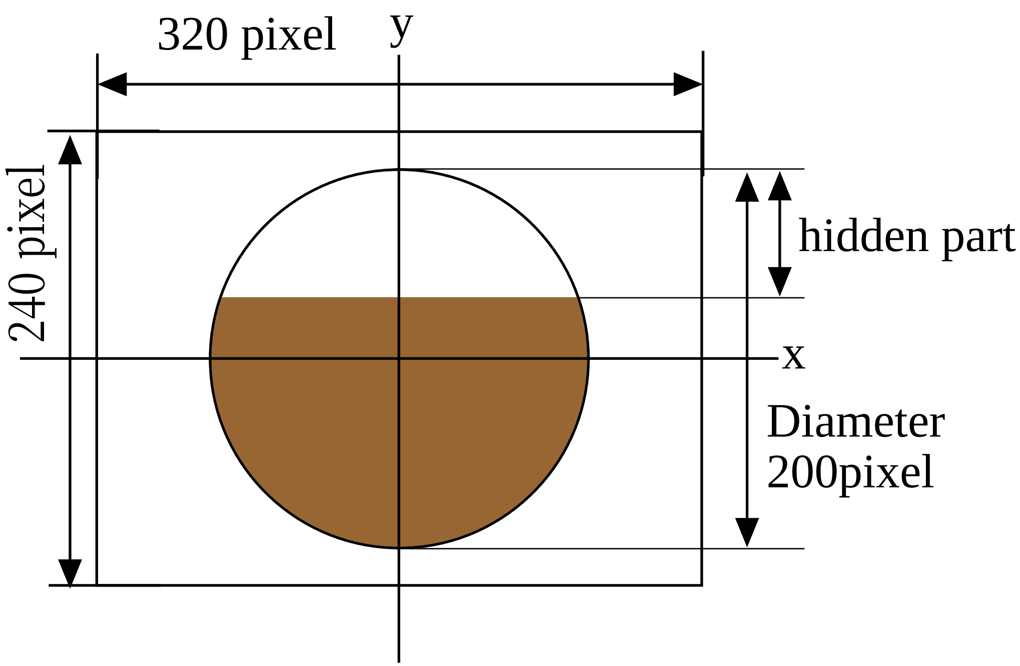
# Image-processing



The outline of the pupil and the reflection center on the cornea are detected using image-processing software. The Pupil is approximated by an ellipse expression. The center of the pupil, the pupil radius, minor-axis major-axis ratio and the minor axis slope are calculated from the expression. The processing time is less than 1ms.

There is an another method to obtain the pupil center, by using the pupil barycenter. But our method surpasses the barycenter method in accuracy when the pupil is hidden by the eyelid. Furthermore our method can obtain the exact diameter of a pupil even when the pupil is hidden by the eyelid.

To compare the accuracy of these methods, we measured the center of a circle in y-axis, which was partly hidden, shown the following figure, by two methods. We also measured the diameter of a circle, which was partly hidden, to reveal our method's performance.



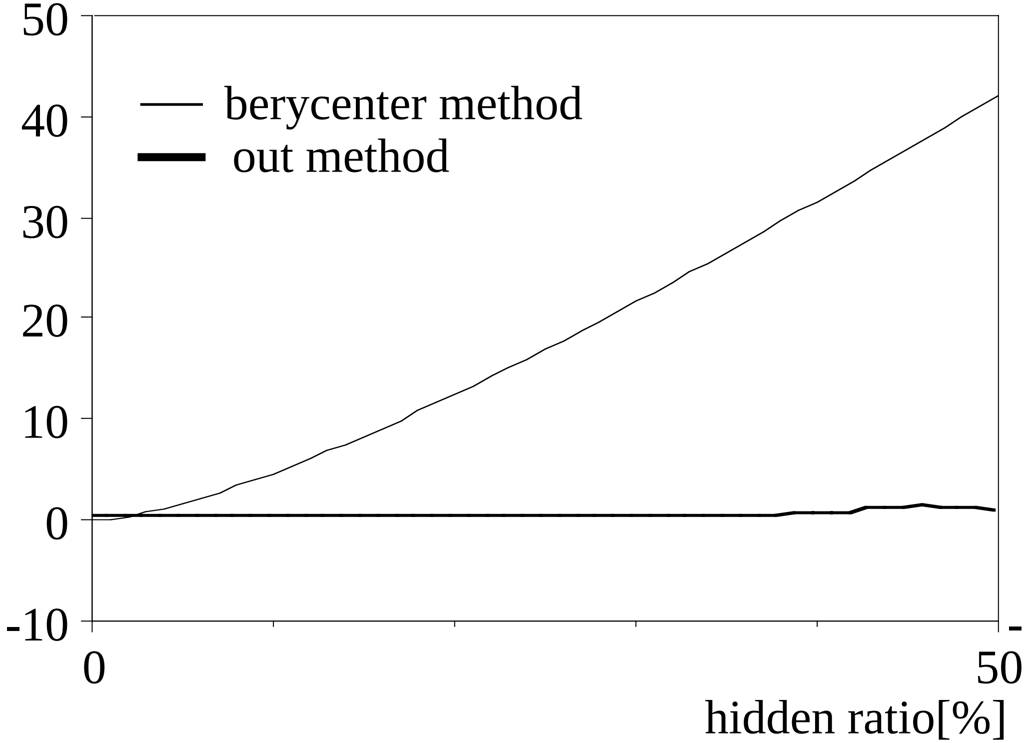

$$\text{hidden ratio}[\%] = \frac{\text{hidden part}}{\text{diameter}} \times 100$$

1. In our method, the gap ratio is less than 0.1% when the hidden ratio is 30 %.

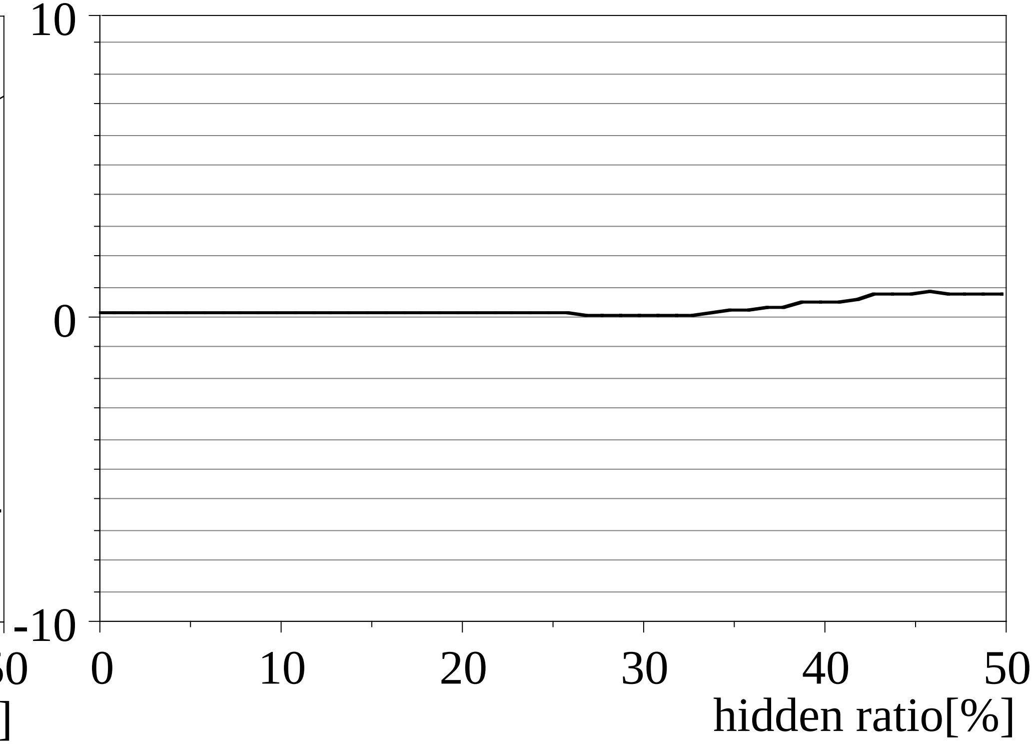
2. In our method, the diameter ratio is less than 0.1% when the hidden ratio is 30%.

$$\text{gap ratio[\%]} = \frac{\text{gap of center}}{\text{diameter}} \times 100$$

$$\text{diameter ratio[\%]} = \frac{\text{diameter-measured diameter}}{\text{diameter}} \times 100$$



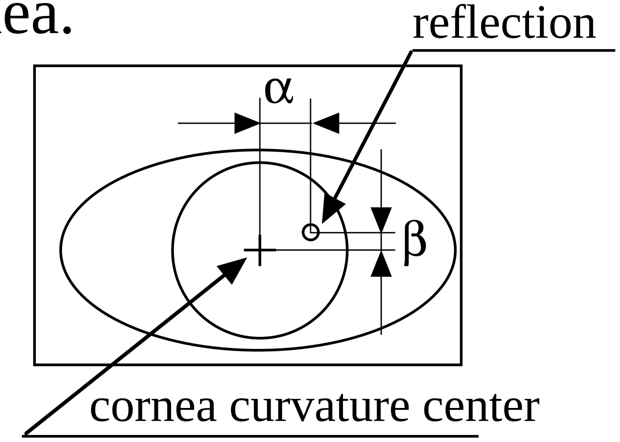

Measured center in y-axis of partly hidden circle.

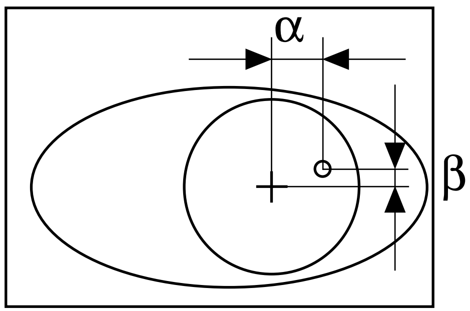


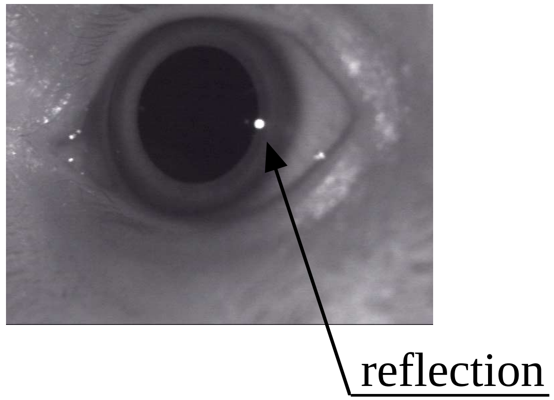

Measured diameter of partly hidden circle.

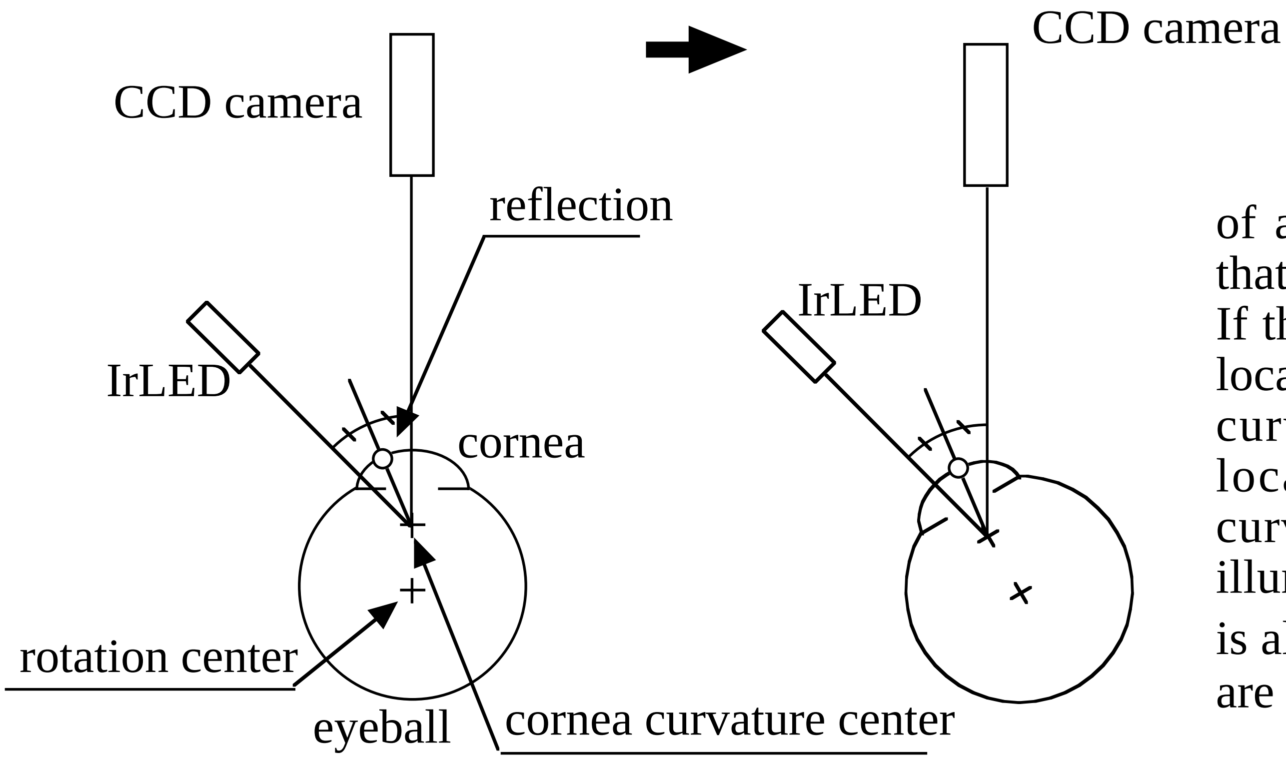
3

# Cornea curvature center is obtained from the illumination's reflection on the cornea.



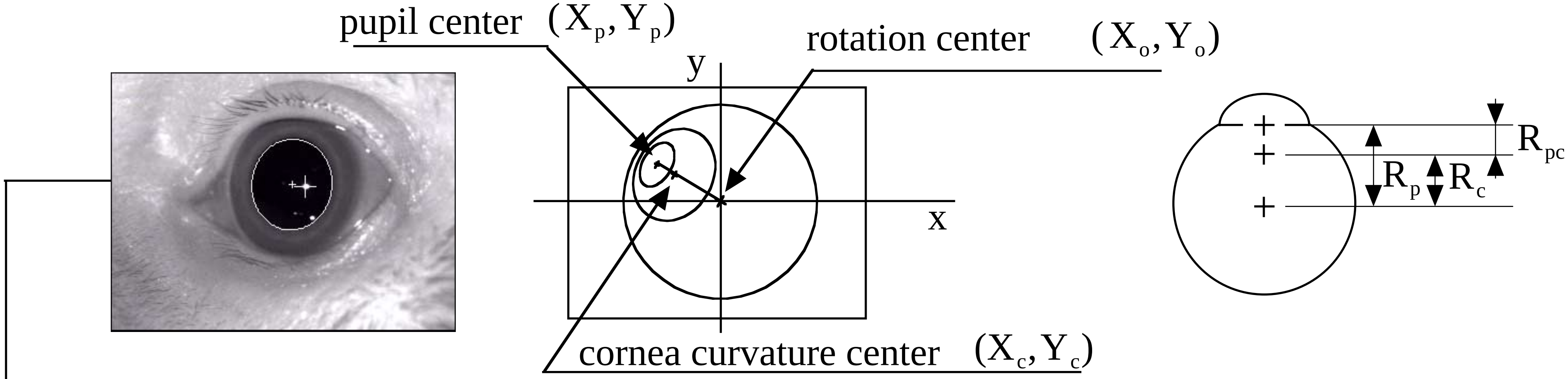



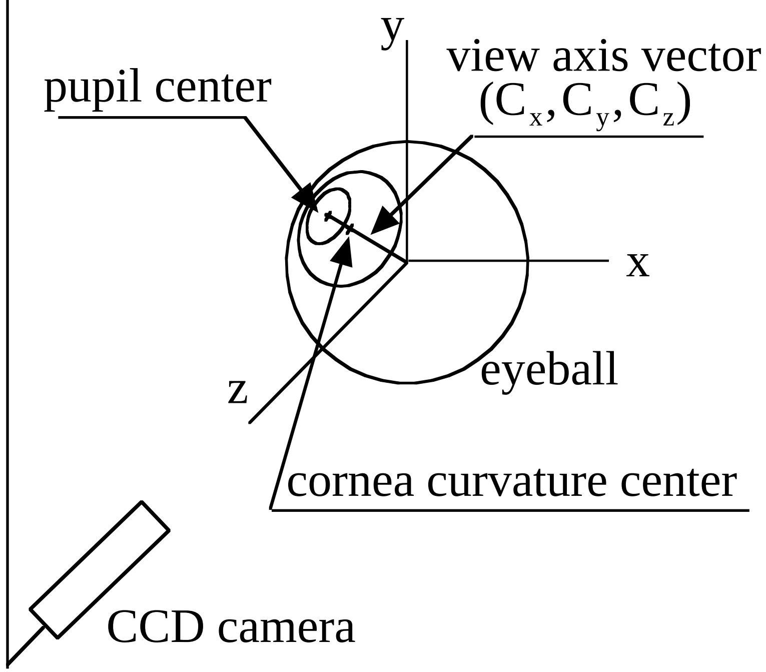




Suppose that the cornea is a part of a sphere, we refer to the center of that sphere as cornea curvature center. If the illumination and CCD camera is located farther enough than the cornea curvature center movements, the location relation of the cornea curvature center and the center of illumination's reflection on the cornea is always same. In this figure, α and β are fixed.

# Measurement

Find the view axis vector and the rotation center in the camera-coordinate system from the pupil center and the cornea curvature center.



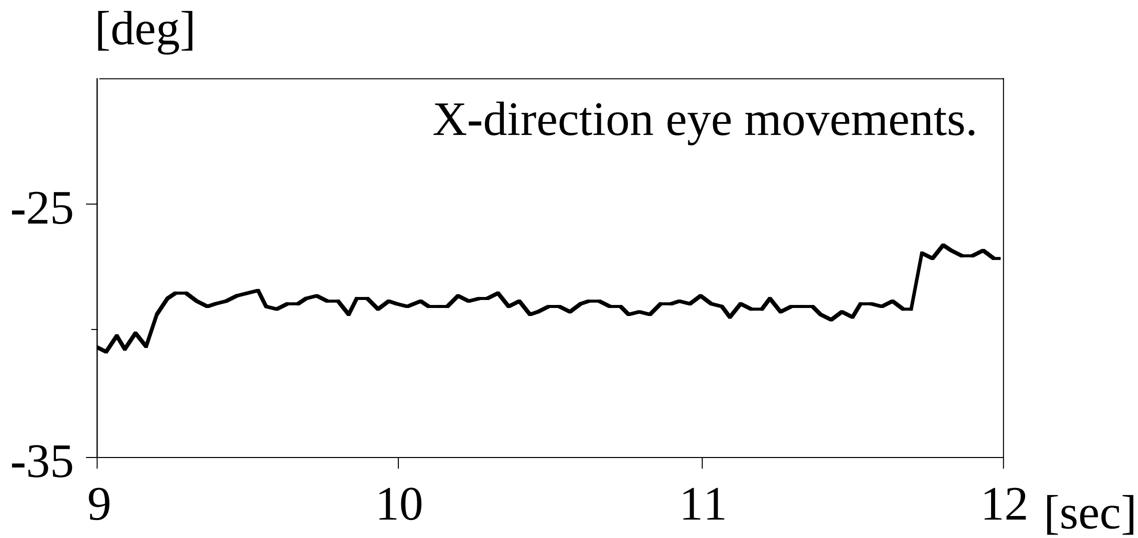

The view axis in the camera-coordinate system.

$$(C_x,C_y,C_z)=\left(\frac{X_p-X_c}{R_{pc}},\frac{Y_p-Y_c}{R_{pc}},\frac{\sqrt{R_{pc}^2-(X_p-X_c)^2-(Y_p-Y_c)^2}}{R_{pc}}\right)$$

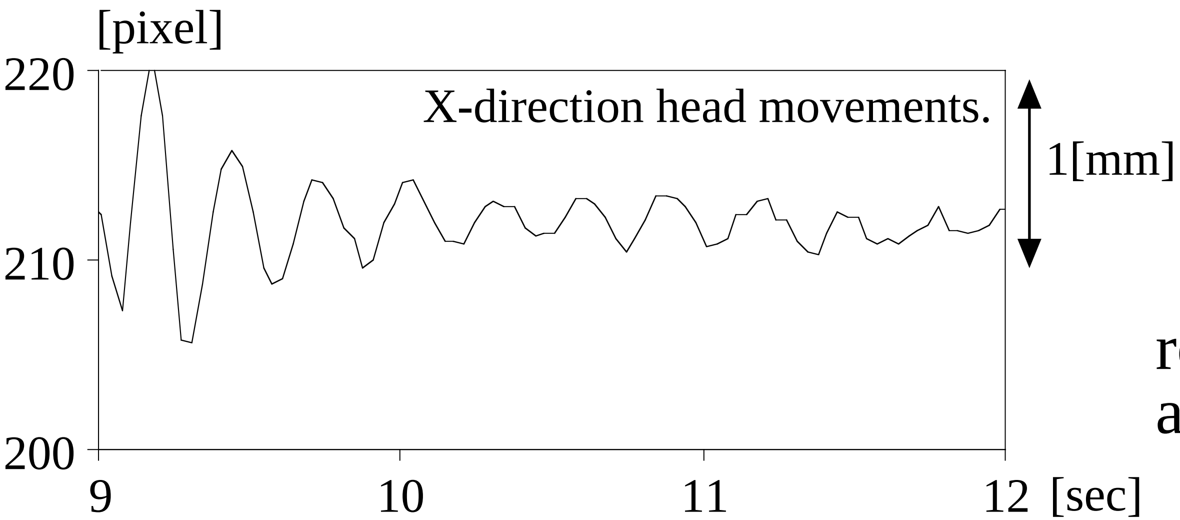
The rotation center.

$$(X_o,Y_o)=\left(\frac{R_cX_p-R_pX_c}{R_c-R_p},\frac{R_cY_p-R_pY_c}{R_c-R_p}\right)$$

The view axis vector can be measured by using the pupil center and the cornea curvature center without fixing the head. The head movements can be measured at the same time as well.



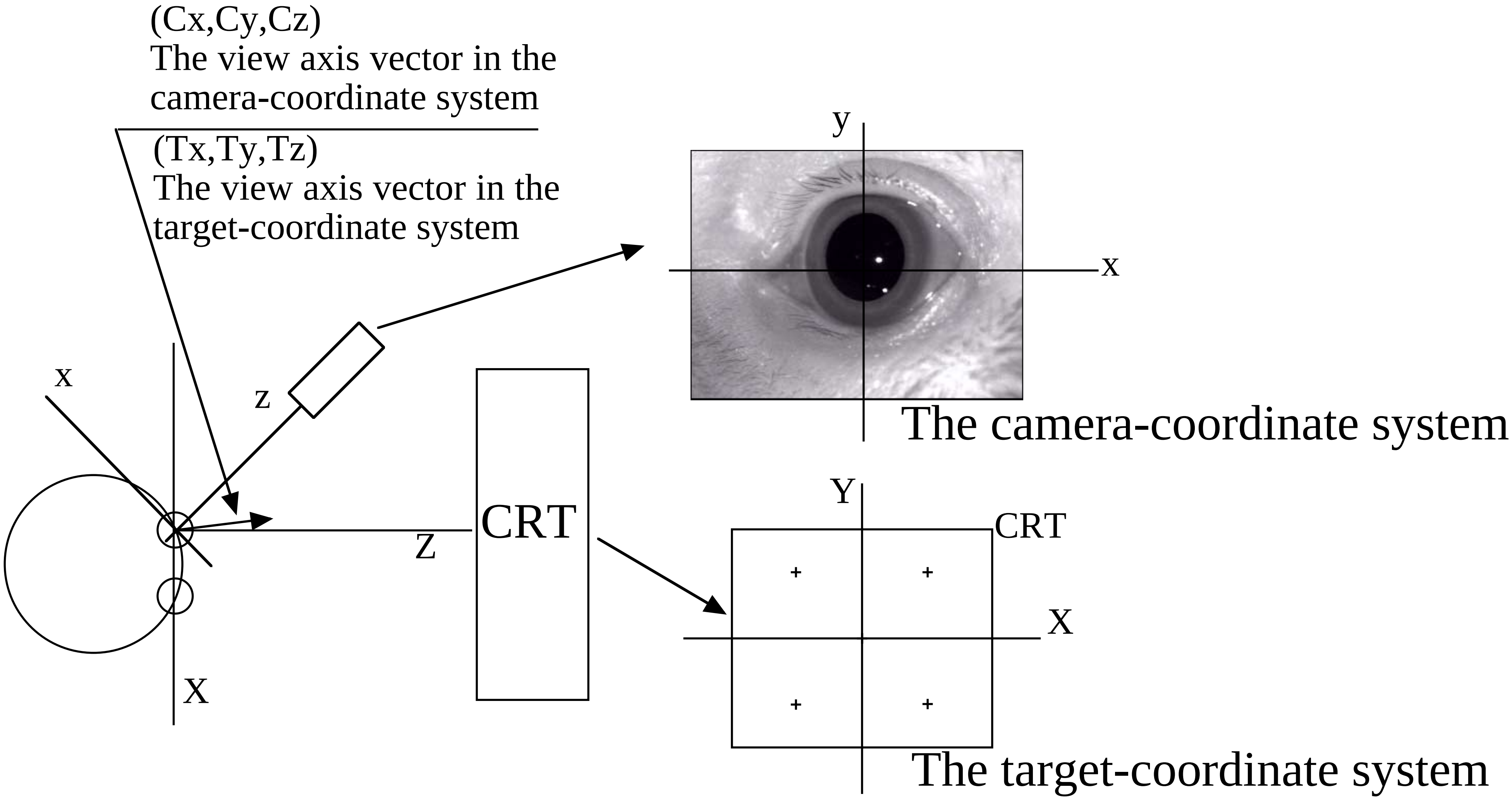

Measured eye movements are not influenced by head movements.




Movements of the eye rotation center is considered as head movements.

Find the view axis vector in the target-coordinate system by using the transformation matrix.

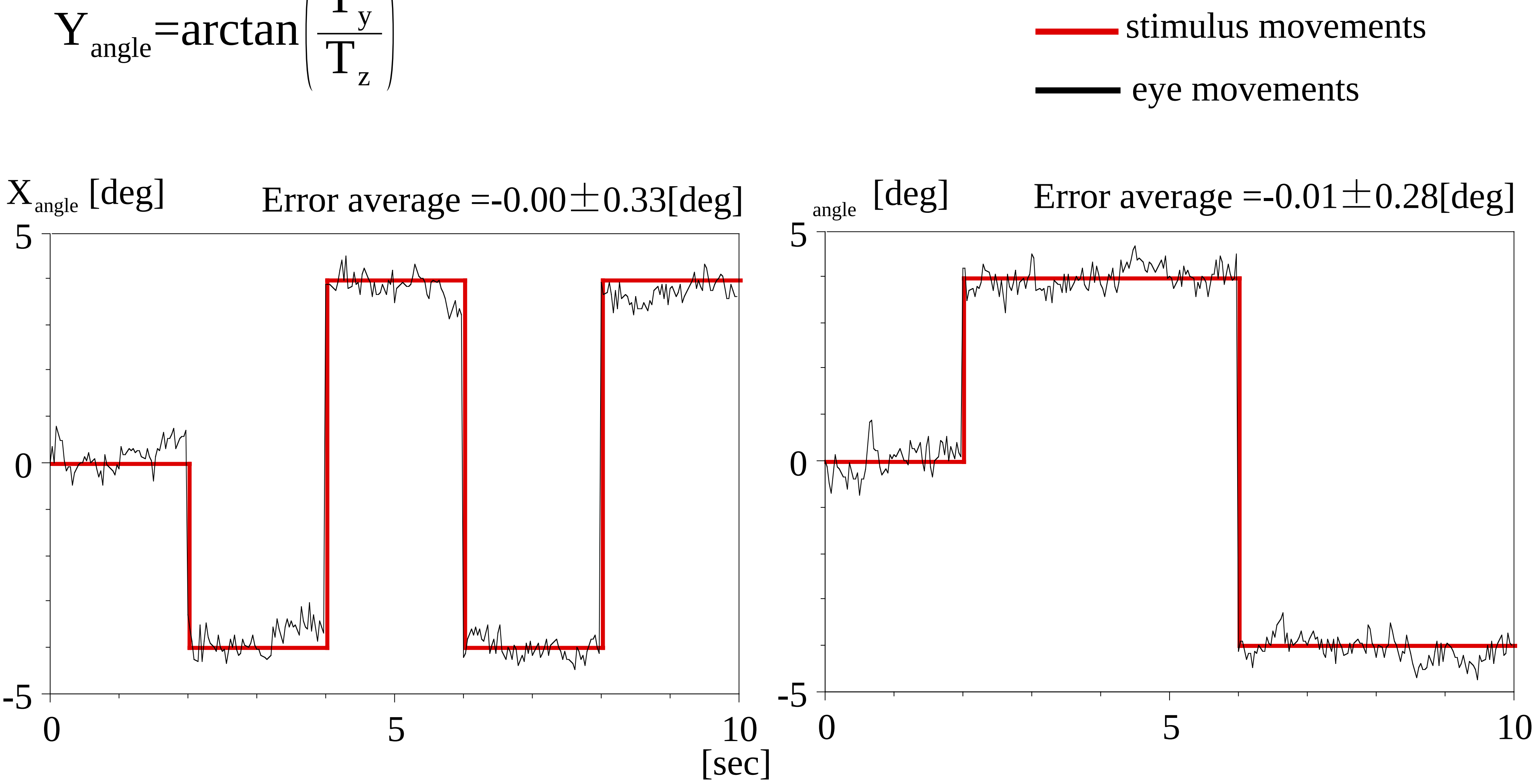
$$\begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix}$$



# Measurement example

$$X_{angle} = \arctan\left(\frac{T_x}{T_z}\right)$$

$$Y_{angle} = \arctan\left(\frac{T_y}{T_z}\right)$$



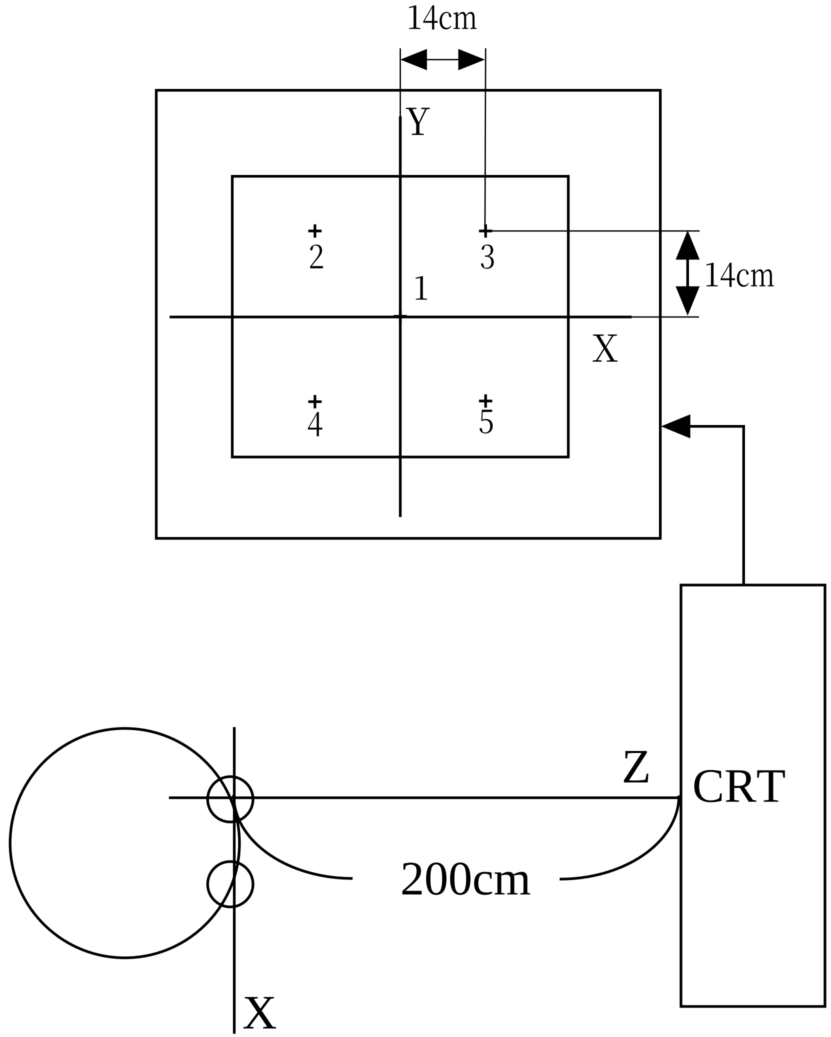
# Example

## Step 1) Input targets information

Input targets information in display order to the program. In this example, we use 5 targets.

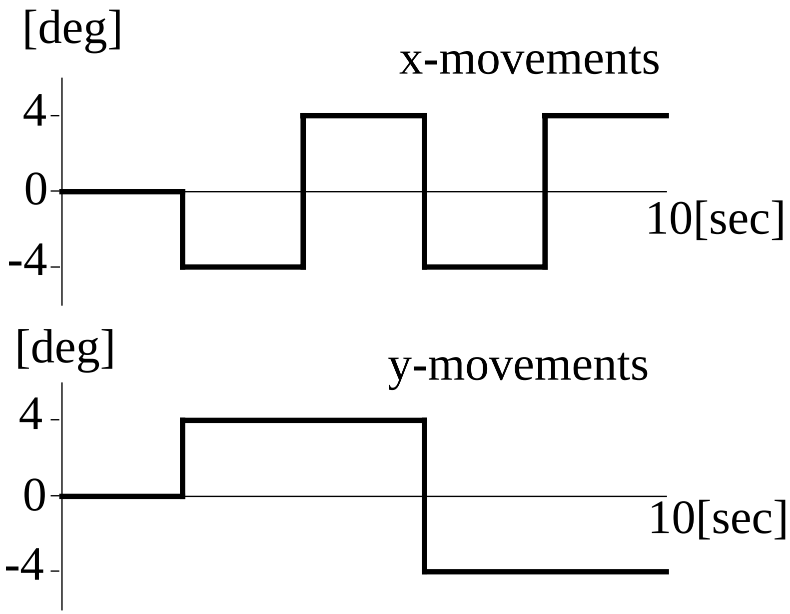
| No | X Position | Y Position | Z Position |
|---|---|---|---|
| 1 | 0.000000 | 0.000000 | 200.000000 |
| 2 | -14.000000 | 14.000000 | 200.000000 |
| 3 | 14.000000 | 14.000000 | 200.000000 |
| 4 | -14.000000 | -14.000000 | 200.000000 |
| 5 | 14.000000 | -14.000000 | 200.000000 |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | | | |

OK Cancel

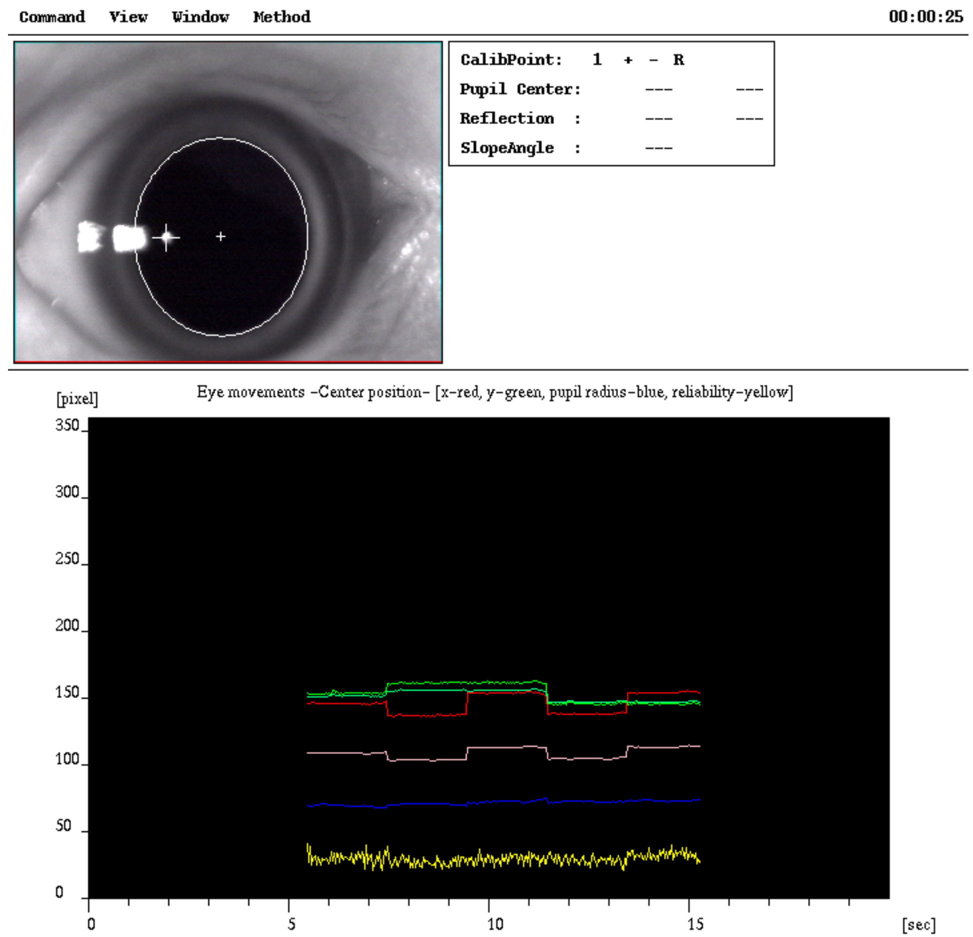


# Step 2) Calibration

We ask the subject to fixate each of the 5 targets displayed on a screen, and store values obtained from image-processing.



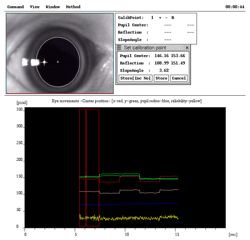
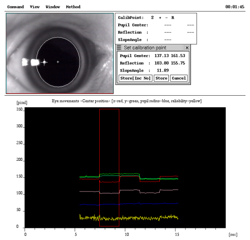
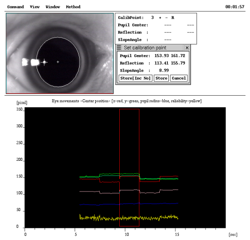
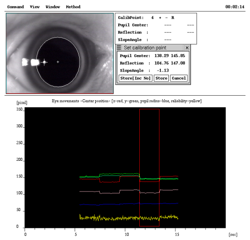
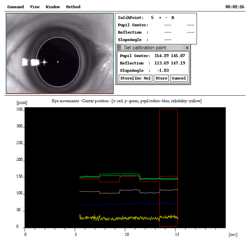

Stimulus movements




Captured computer image.

# Step 3) Calculate parameters.

i) Click mouse suitable position and find average pupil center Pn(Xpn, Ypn) and illumination's reflect center on cornea Rn(Xrn, Yrn) correspond to each target.

$P_1(X_{p1}, Y_{p1})$ $R_1(X_{r1}, Y_{r1})$

$P_2(X_{p2}, Y_{p2})$ $R_2(X_{r2}, Y_{r2})$

$P_3(X_{p3}, Y_{p3})$ $R_3(X_{r3}, Y_{r3})$

$P_4(X_{p4}, Y_{p4})$ $R_4(X_{r4}, Y_{r4})$

$P_5(X_{p5}, Y_{p5})$ $R_5(X_{r5}, Y_{r5})$

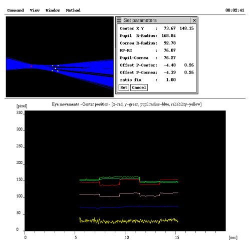
ii) Calculate values listed below.

The eye rotation center (Xo,Yo).

The pupil center rotation radius (Rp).

The cornea curvature center rotation radius (Rc).

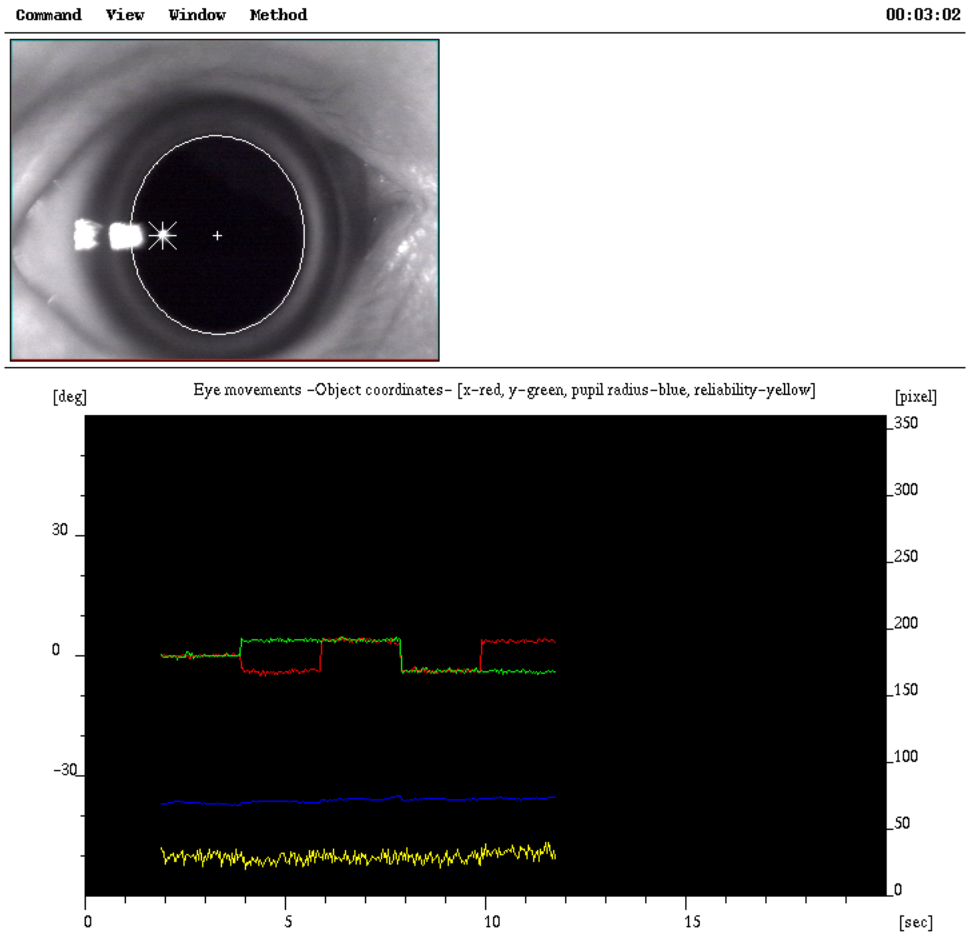
The length between reflection on cornea and the cornea curvature center in each axis (α, β).



iii) Calculate the transformation matrix from i) and ii).

Step 4) Measurement.

The red line indicates x view axis angle in the target-coordinate system. The green line indicates y view axis angle in the target-coordinate system. The blue line indicates pupil radius.



# Conclusions

This system is very inexpensive compared with other products.

By using an ellipse approximation, this system can measure the exact eye position and pupil diameter even if the pupil is hidden by the eyelid.

This system can measure eye position without fixing subject's head.

This system can measure subject's head movement.

The accuracy of the measurement is better than 1 degree.

Sampling frequency is 60Hz(save to file) or 30Hz (D/A converter).

This system can be used for human, monkey and mouse.

# Appendix

Ellipse expression : $x^2+axy+by^2+cx+dy+e=0$

Center of pupil:

$$(X_p, Y_p)=\left(\frac{aY_p+c}{2}, \frac{ac-2d}{4b-a^2}\right)$$

$r1>r2$ $a\neq0$ Pupil radius:r1 miner axis slope a2

$r1<r2$ $a\neq0$ Pupil radius:r2 miner axis slope a1

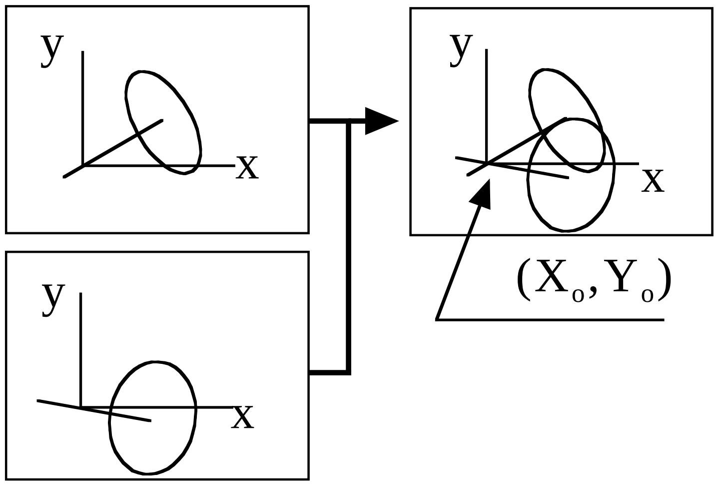
$r1>r2$ $a=0$ Pupil radius:r1 miner axis slope $\infty$

$r1<r2$ $a=0$ Pupil radius:r2 miner axis slope 0

| | | |
|---|---|---|
| $C_1=X_p^2+aX_pY_p+bY_p^2+cX_p+dY_p+e$ | | |
| $a\neq0$ | $a_1=\frac{b-1}{a}+\sqrt{\left(\frac{b-1}{a}\right)^2+1}$ | $a_2=\frac{b-1}{a}-\sqrt{\left(\frac{b-1}{a}\right)^2+1}$ |
| | $r_1=\sqrt{\frac{-C_1(a_1^2+1)}{ba_1^2+aa_1+1}}$ | $r_2=\sqrt{\frac{-C_1(a_2^2+1)}{ba_2^2+aa_2+1}}$ |
| $a=0$ | $r_1=\sqrt{-C_1}$ | $r_2=\sqrt{\frac{-C_1}{b}}$ |

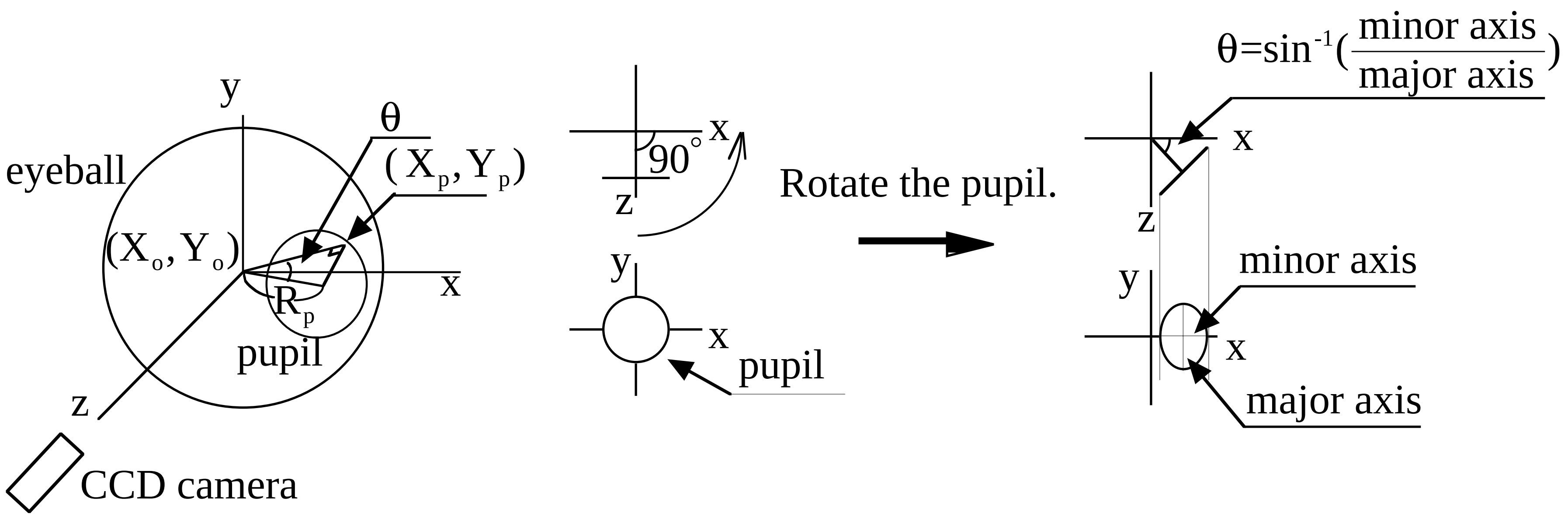
The rotation center (Xo,Yo).

The rotation center projected on xy plane exists on the extended line of ellipses' minor axes. The subject's head movement must be restricted. The rotation center is calculated from many images by using least squares.



The pupil rotation radius Rp.

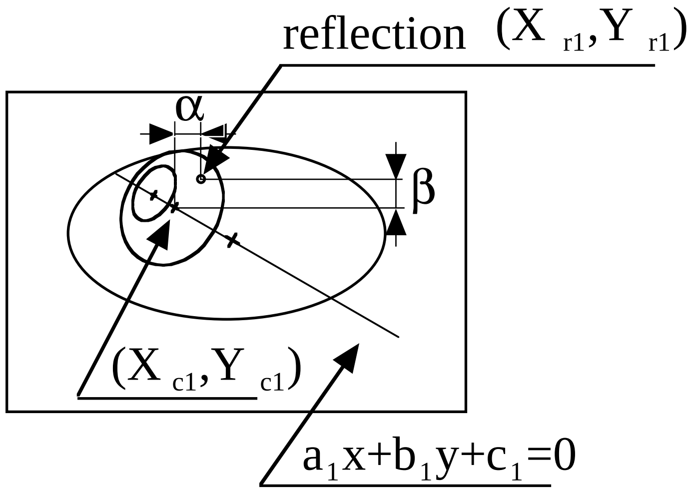
The angle between view axis and xy plane is arcsin of (minor axis / major axis). The pupil rotation center is calculated from this angle and length between the rotation center projected on xy plane (Xo, Yo) and the pupil center projected on xy plane (Xp, Yp). The subject's head movement must be restricted.

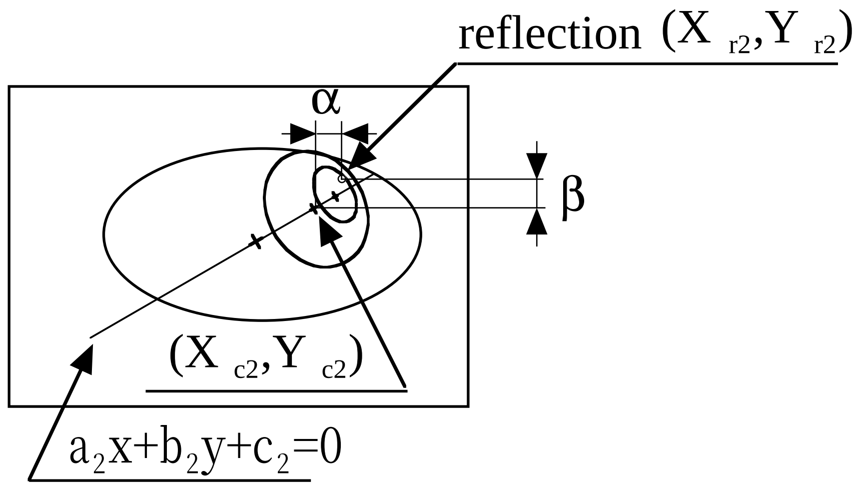



$$R_p = \frac{\sqrt{(X_p - X_o)^2 + (Y_p - Y_o)^2}}{\cos\theta} = \sqrt{\frac{(X_p - X_o)^2 + (Y_p - Y_o)^2}{1 - \left(\frac{\text{minor axis}}{\text{major axis}}\right)^2}}$$

The length between the reflection on cornea and the cornea curvature center in each axis (α,β).

The pupil center, the cornea curvature center and the rotation center exist on the same line, and α and β are always the same. So α and β are calculated from captured images by using least squares. The subject's head movement must be restricted.




$$\begin{cases} X_{c1}=X_{r1}-\alpha \\ Y_{c1}=Y_{r1}-\beta \\ a_1X_{c1}+b_1Y_{c1}+c_1=0 \end{cases}$$

$$\begin{cases} X_{c2}=X_{r2}-\alpha \\ Y_{c2}=Y_{r2}-\beta \\ a_2X_{c2}+b_2Y_{c2}+c_2=0 \end{cases}$$

$$a_1(X_{r1}-\alpha)+b_1(Y_{r1}-\beta)+c_1=0$$

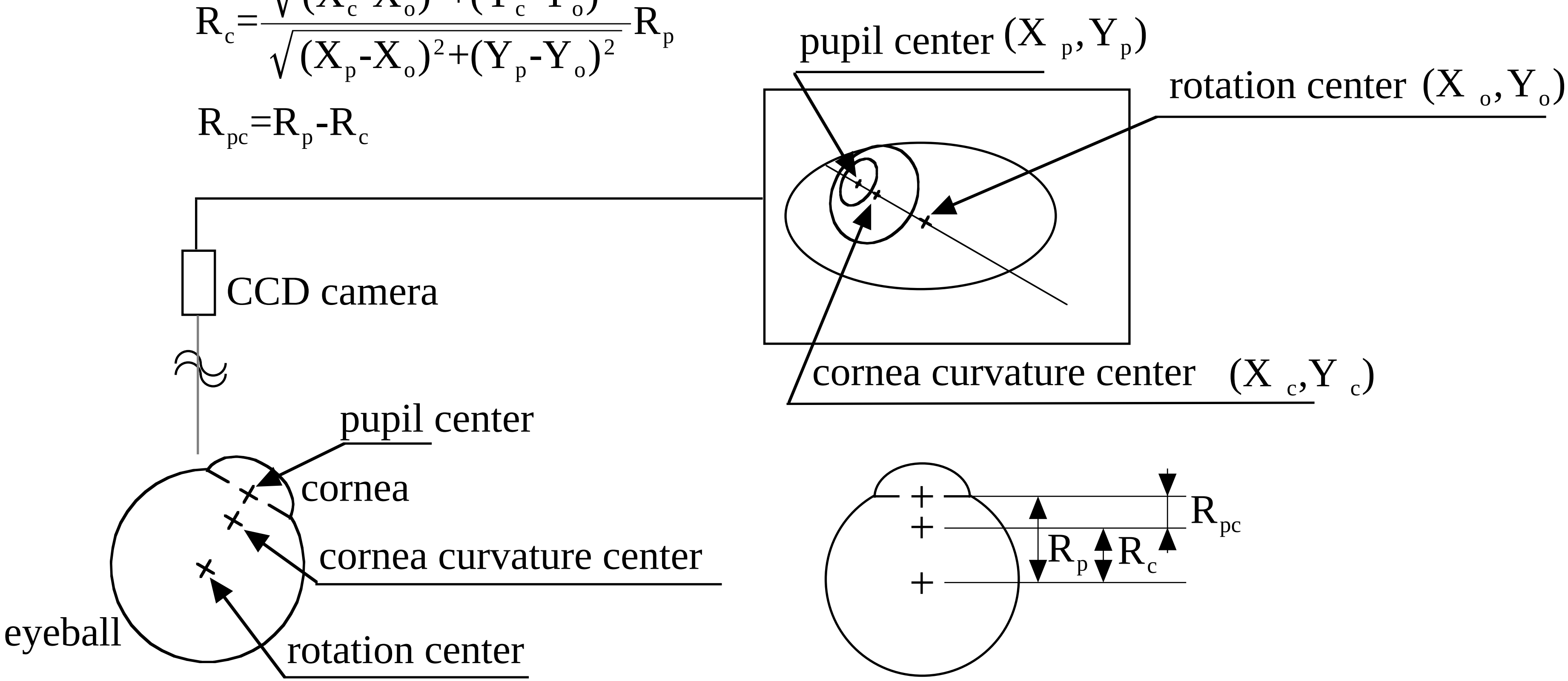
$$a_2(X_{r2}-\alpha)+b_2(Y_{r2}-\beta)+c_2=0$$

The cornea curvature center rotation radius Rc.

The cornea curvature center rotation radius Rc is obtained from length between the cornea curvature center and the rotation center projected on xy plane, and length between the pupil center and the rotation center projected on xy plane and the pupil rotation radius Rp.

$$R_c = \frac{\sqrt{(X_c - X_o)^2 + (Y_c - Y_o)^2}}{\sqrt{(X_p - X_o)^2 + (Y_p - Y_o)^2}} R_p$$

$$R_{pc} = R_p - R_c$$

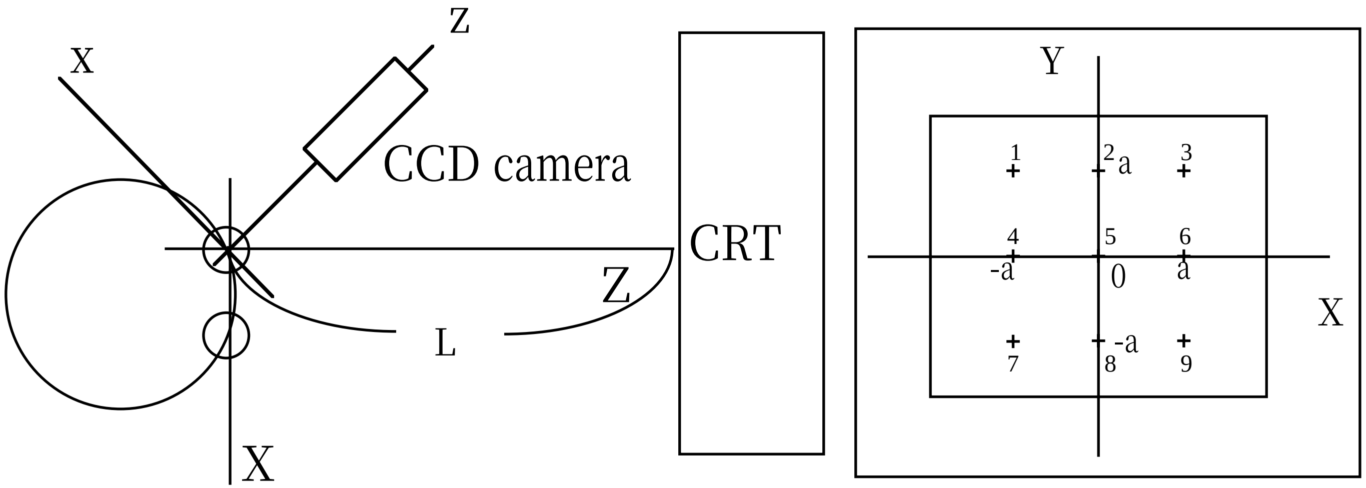


## The transformation matrix.

To obtain the transformation matrix, which transfers a vector from the camera-coordinate system to the target-coordinate system, we ask the subject to fixate each of the 9 (more than 3 points) targets displayed on a screen. We measure the subject's view axis vector (Cv1-9) in the camera-coordinate system, and calculate the transformation matrix from their vectors and their respective required view axis vector (Tv1-9) in the target-coordinate system by using least squares.

$$\begin{bmatrix} a & d & g \\ b & e & h \\ c & f & i \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{9} C_{xi}^2 & \sum_{i=1}^{9} C_{xi}C_{yi} & \sum_{i=1}^{9} C_{zi}C_{xi} \\ \sum_{i=1}^{9} C_{xi}C_{yi} & \sum_{i=1}^{9} C_{yi}^2 & \sum_{i=1}^{9} C_{yi}C_{zi} \\ \sum_{i=1}^{9} C_{zi}C_{xi} & \sum_{i=1}^{9} C_{yi}C_{zi} & \sum_{i=1}^{9} C_{zi}^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{9} C_{xi}T_{xi} & \sum_{i=1}^{9} C_{xi}T_{yi} & \sum_{i=1}^{9} C_{xi}T_{zi} \\ \sum_{i=1}^{9} C_{yi}T_{xi} & \sum_{i=1}^{9} C_{yi}T_{yi} & \sum_{i=1}^{9} C_{yi}T_{zi} \\ \sum_{i=1}^{9} C_{zi}T_{xi} & \sum_{i=1}^{9} C_{zi}T_{yi} & \sum_{i=1}^{9} C_{zi}T_{zi} \end{bmatrix}$$

$$C_{v1} = (C_{x1}, C_{y1}, C_{z1})$$
$$C_{v2} = (C_{x2}, C_{y2}, C_{z2})$$
$$\ldots$$
$$C_{v9} = (C_{x9}, C_{y9}, C_{z9})$$




$$T_{v1} = \left( \frac{-a}{\sqrt{a^2+0+L^2}}, \frac{0}{\sqrt{a^2+0+L^2}}, \frac{L}{\sqrt{a^2+0+L^2}} \right)$$
$$T_{v2} = \left( \frac{0}{\sqrt{0+a^2+L^2}}, \frac{a}{\sqrt{0+a^2+L^2}}, \frac{L}{\sqrt{0+a^2+L^2}} \right)$$
$$\ldots$$
$$T_{v9} = \left( \frac{a}{\sqrt{a^2+a^2+L^2}}, \frac{-a}{\sqrt{a^2+a^2+L^2}}, \frac{L}{\sqrt{a^2+a^2+L^2}} \right)$$