An Advanced Real-Time Eye Tracking System Using a High Frame-Rate Digital Camera
高速撮影カメラを用いた汎用リアルタイム眼球運動計測システム

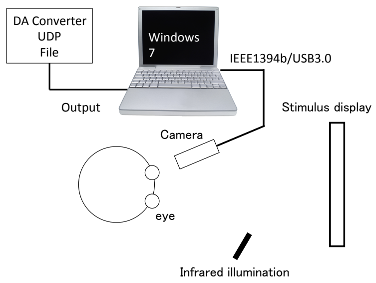
Keiji Matsuda[1],Kenji Kawano[2],Kenichirou Miura[2]
松田圭司[1]、河野憲二[2]、三浦健一郎[2]
1. Human Technology Research Institute, AIST, Tsukuba, Japan, 2. Dept.Integ Brain Sci. Grad.Sch.Med. Kyoto University, Kyoto, Japan
1. 産総研ヒューマンライフ 2. 京都大院医認知行動脳科学

Summary

We developed a new eye tracking system by adopting an IEEE-1394b digital camera and an USB3.0 digital camera that provides high sensitivity, resolution and frame rate. The system is non-invasive and inexpensive and can be used for mice, monkeys, and humans. Infrared light illuminates the eye and the reflected image of the cornea and the black image of the pupil are captured by the camera. The center of the pupil is calculated and tracked over time. The movement of the head is compensated by using the reflected image of the infrared light. Because of the high frame rate of the digital camera, the sampling rate of the system can be as high as 333Hz(IEEE1394b)/460Hz(USB3.0). The eye position data can be read out on line via computer network and digital-analog converter. The adoption of the WINDOWS 7 x 64 as the operation system makes this eye tracking system user-friendly.

Supported by KAKENHI (24650105).

System outline



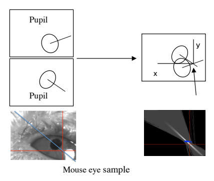
System equipment

	model	Company	Option/Memo
Camera	Grasshopper GRAS-03K2M-C	Point Grey Research,Inc.	DEVKIT-01-0002（IEEE1394b card,cable,etc）
	Flea3(USB3.0) FL3-U3-13Y3M-C	Point Grey Research,Inc.	ACC-01-2300（USB3.0 cable）
Lens	Ai AF Micro-Nikkor 60mm f/2.8D	Nikon	
	M7528-MP2 75mm	CBC	
Lens mount converter	C-Mount ADAPTER for Nikon	Kenko	for Nikon Micro-Nikkor 60mm
Ir filter	62S PRO1D R-72	Kenko	for Nikon Micro-Nikkor 60mm
	R-72 M30.5 X 0.5	Edmund optics	for M7528-MP2 75mm
x2 Rear converter lens	TV rear converter x2		for Nikon Micro-Nikkor 60mm
Infrared illumination	K-00094（IrLED）	Akizukidenshi	Swap IrLED to Toshiba TLN233（850nm）
	LA-100IR（halogen lamp）	HAYASHI WATCH-WORKS CO.,,LTD	
Light guide	LGA1-5L500N	HAYASHI WATCH-WORKS CO.,,LTD	for LA-100IR
DA Converter	AO-1604L-LPE	CONTEC Co.,Ltd	
PC	Window7 x64 Ready		

The passive calibration

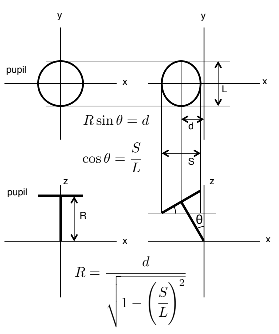
When the subject spontaneously moves its eye, the system defines the rotation center of the pupil, the rotation radius of the pupil center, the cornea curvature center and the length between the pupil center and the cornea curvature center.

The rotation center of the pupil center



The rotation center projected to xy plane exists on the extended lines of ellipses' minor axes.

The rotation radius of the pupil center

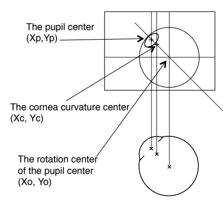


$$R\sin\theta = d$$

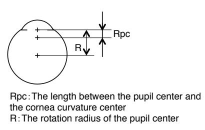
$$\cos\theta = \frac{S}{L}$$

$$R = \frac{d}{\sqrt{1-\left(\frac{S}{L}\right)^2}}$$

The cornea curvature center and the length between the pupil center and the cornea curvature center

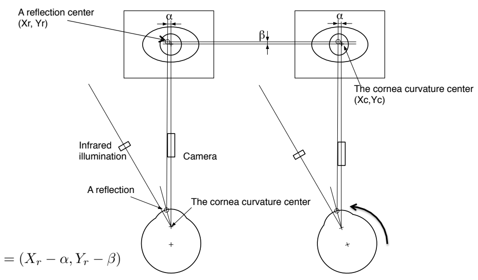


The pupil center, the cornea curvature center and rotation center of the pupil exist on the same line.



Rpc : The length between the pupil center and the cornea curvature center
R : The rotation radius of the pupil center

$$R_{pc} = R\sqrt{\frac{(X_p - X_c)^2 - (Y_p - Y_c)^2}{(X_p - X_o)^2 - (Y_p - Y_o)^2}}$$

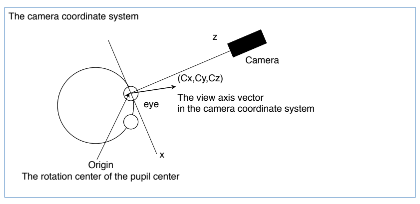


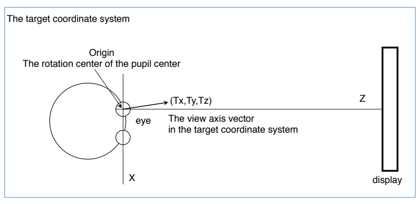
$$(X_c, Y_c) = (X_r - \alpha, Y_r - \beta)$$

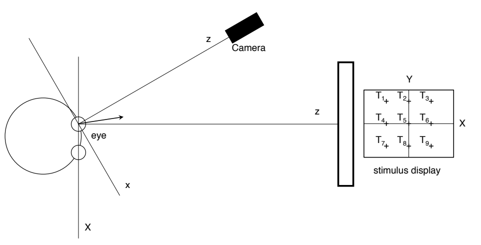
Suppose that a cornea is a part of a sphere, we refer to the center of that sphere as a cornea curvature center. If the illumination and camera is located farther enough from the cornea curvature center shifts, the position between the cornea curvature center and the reflection is always the same. In this figure α and β are fixed.

The active calibration

When the subject fixates small targets (more than 3 points) that appear on the computer display, the system provides a transition matrix for the eye position from the camera coordinate system to the target coordinate system.







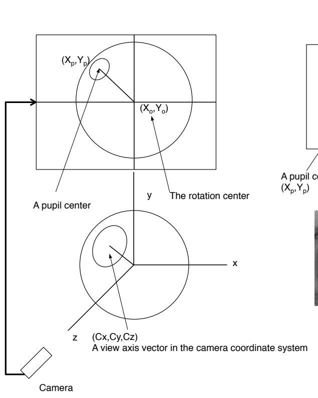
$$\begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \begin{pmatrix} C_x \\ C_y \\ C_z \end{pmatrix}$$

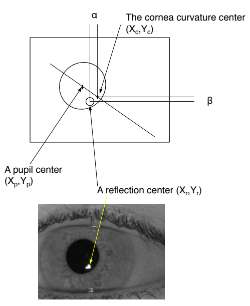
$$\begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} = \begin{pmatrix} \sum_{i=1}^{n} C_{ix}^2 & \sum_{i=1}^{n} C_{ix}C_{iy} & \sum_{i=1}^{n} C_{iz}C_{ix} \\ \sum_{i=1}^{n} C_{ix}C_{iy} & \sum_{i=1}^{n} C_{iy}^2 & \sum_{i=1}^{n} C_{iy}C_{iz} \\ \sum_{i=1}^{n} C_{iz}C_{ix} & \sum_{i=1}^{n} C_{iy}C_{iz} & \sum_{i=1}^{n} C_{iz}^2 \end{pmatrix}^{-1} \begin{pmatrix} \sum_{i=1}^{n} C_{ix}T_{ix} & \sum_{i=1}^{n} C_{ix}T_{iy} & \sum_{i=1}^{n} C_{ix}T_{iz} \\ \sum_{i=1}^{n} C_{iy}T_{ix} & \sum_{i=1}^{n} C_{iy}T_{iy} & \sum_{i=1}^{n} C_{iy}T_{iz} \\ \sum_{i=1}^{n} C_{iz}T_{ix} & \sum_{i=1}^{n} C_{iz}T_{iy} & \sum_{i=1}^{n} C_{iz}T_{iz} \end{pmatrix}$$

We ask the subject to fixate each of 9 (more than 3 points) targets displayed on a screen. We measure the subject's view axis vectors (C1-9) in the camera coordinate system and calculate transition matrix from these vectors and the respective required view axis vectors (T1-9) in the target coordinate system .

The view axis vector in the camera coordinate system

There are two way to measure the view axis. The first method [A] treats only the pupil center position. This method is used when the subject's head is fixed tightly. The second method [B] treats the pupil center position and the center position of illumination's reflection on the cornea. This method is used when subject's head is fairly stationary.





Method A

$$(C_x, C_y, C_z) = \left(\frac{X_p - X_o}{R}, \frac{Y_p - Y_o}{R}, \frac{\sqrt{R^2 - (X_p - X_o)^2 - (Y_p - Y_o)^2}}{R}\right)$$

Method B

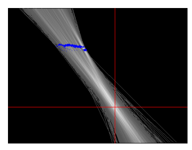
$$(C_x, C_y, C_z) = \left(\frac{X_p - X_c}{R_{pc}}, \frac{Y_p - Y_c}{R_{pc}}, \frac{\sqrt{R_{pc}^2 - (X_p - X_c)^2 - (Y_p - Y_c)^2}}{R_{pc}}\right)$$

$$(X_{angle}, Y_{angle}) = \left(\arctan\frac{C_x}{C_z}, \arctan\frac{C_y}{C_z}\right)$$

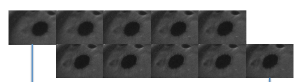
Result 1

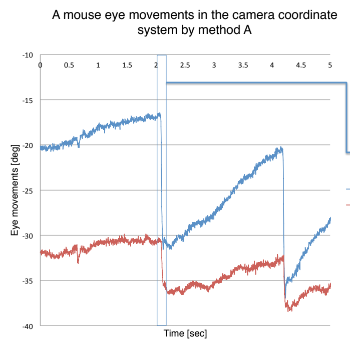
An example of mouse eye movements in the camera coordinate system by method A.

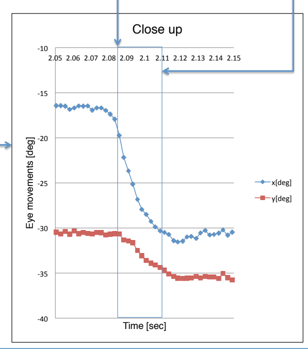
The rotation center of the pupil center



Example of Captured images



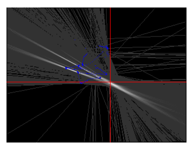


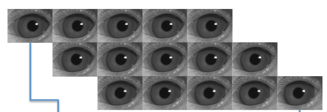


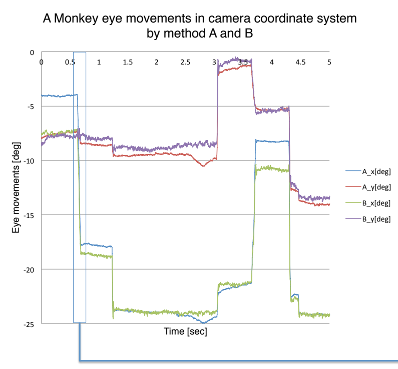
Result 2

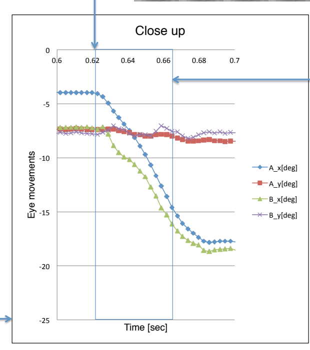
An example of monkey eye movements in the camera coordinate system by Method A and B

The rotation center of the pupil center









Result 3

An example of monkey eye movements in the target coordinate system by Method A and B