An advanced real-time monocular/binocular eye tracking system using a high frame-rate digital camera.

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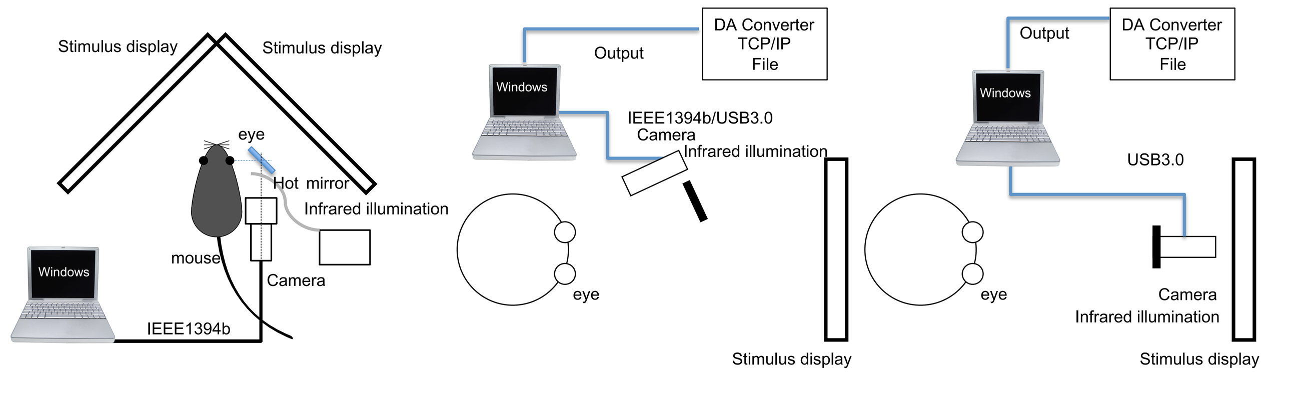
Introduction

We developed a new eye tracking system by adopting an IEEE-1394b or an USB3.0 digital camera that provides high sensitivity, high resolution, and high 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 iris 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.

System outline

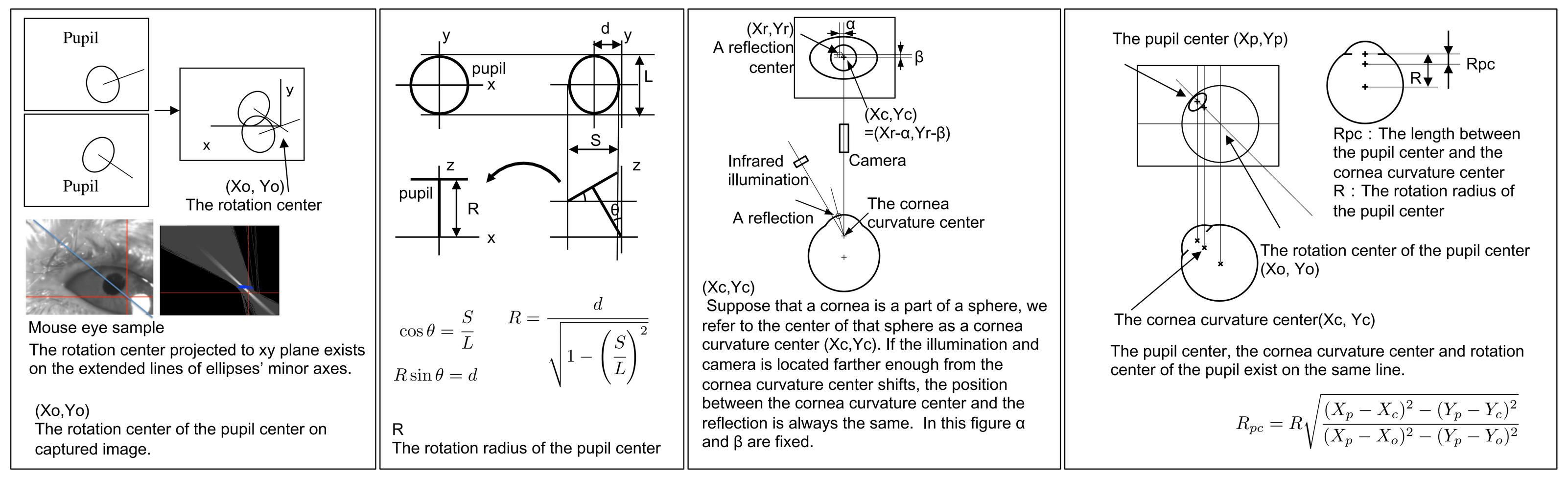


	model
Camera	Grasshopper3 GS3-U3-41C6NIR-C(USB3) Grasshopper GRAS-03K2M-C(IEEE1394b)
Lens	Ai AF Micro-Nikkor 60mm f/2.8D
Lens mount	C-Mount ADAPTER for Nikon
IR filter	62S PRO1D R-72

Methods

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 view axis vector in the camera coordinate system

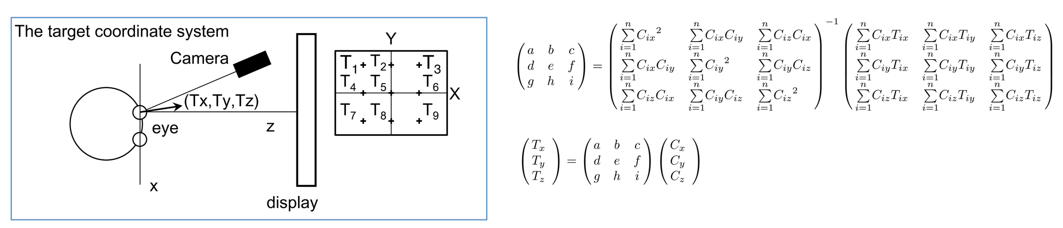
There are two way to measure the view axis. The first method [A] treats only the pupil center position. This method is used when the subject's head is fixed tightly. The second method [B] treats the pupil center position and the center position of illumination's reflection on the cornea. This method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

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

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

The active calibration and the target coordinate system

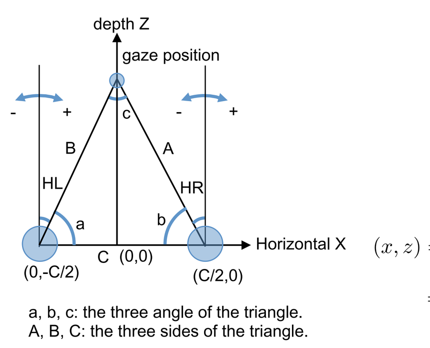
When the subject fixates small targets (more than 3 points) that appear on the computer display, the system provides a transition matrix for the eye position from the camera coordinate system to the target coordinate system.



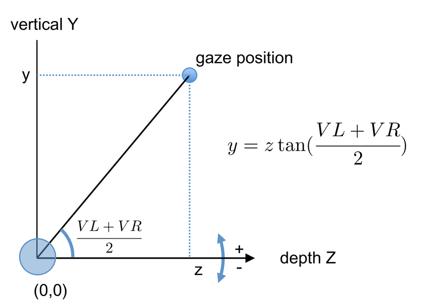
We ask the subject to fixate each of 9 (more than 3 points) targets displayed on a screen. We measure the subject's view axis vectors (C1-9) in the camera coordinate system and calculate transition matrix from these vectors and the respective required view axis vectors (T1-9) in the target coordinate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

The gaze point in 3D space

We calculated the horizontal/vertical gaze angle of each eye by processing its video-image. The origin was set on the center of eyes. "HL" is the horizontal gaze angle of the left eye and "HR" is that of the right eye. "HL" is positive and "HR" is negative in the figure. C corresponds to the inter-ocular distance, ~60mm, though differences can be detected among individuals. According to the law of sines, the target position of the gaze in X-Z plane can be described as follows. Then we calculated the vertical position. "VL" and "VR" is the vertical gaze angle of each eye. We used average of them .



$$a=\frac{\pi}{2}-HL$$
$$b=\frac{\pi}{2}+HR$$
$$c=\pi-a-b$$
$$\frac{A}{\sin a}=\frac{B}{\sin b}=\frac{C}{\sin c}$$
$$(x,z)=\left(B\cos a-\frac{C}{2},B\sin a\right)=\left(C\frac{\cos a\sin b}{\sin c}-\frac{C}{2},C\frac{\sin a\sin b}{\sin c}\right)$$

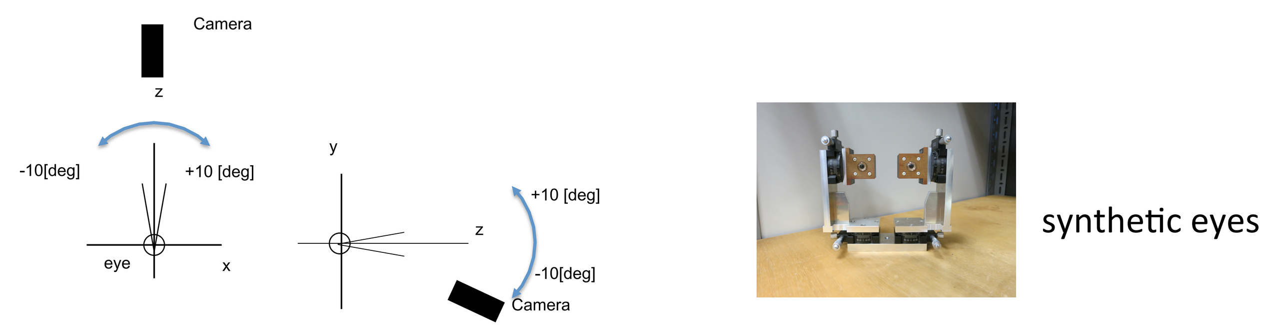


$$y=z\tan\left(\frac{VL+VR}{2}\right)$$

Experiments

1. Evaluation of the System's Accuracy

We evaluated system accuracy by using the synthetic eye. We used 8 calibration points (-10,10), (0,10), (10,10), (-10,0), (0,0), (10,0), (-10,-10), (10,-10). We set the eye 25 points, horizontal angle -10 to +10 degrees and vertical angle -10 to 10 degrees at intervals of 5degrees. We measured the eyes' gaze angles for 1 second at each setting.



2. Measuring of Mouse's Eye Movements

3. Measuring of Monkey's Eye Movements

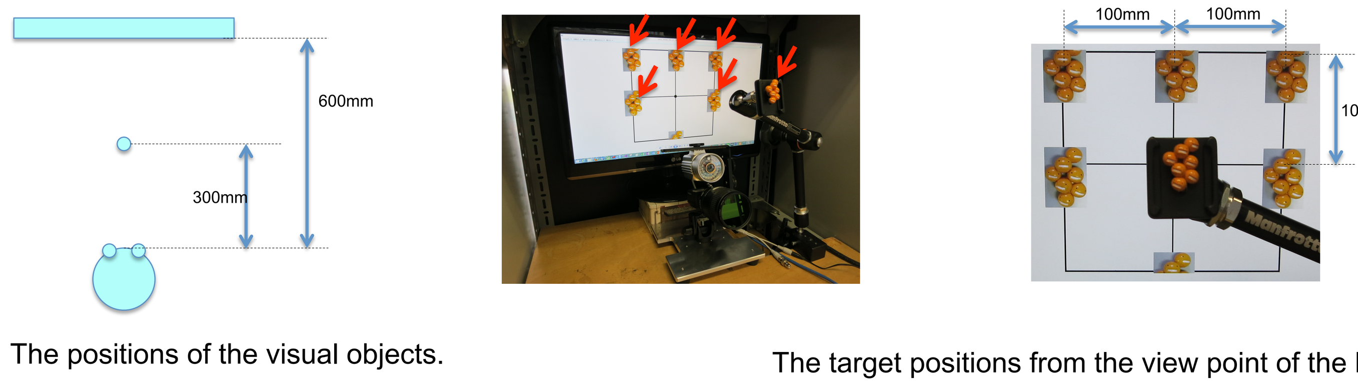
We measured monkey's eye movements by our method and the search coil method at the same time.

4. Evaluation of the System's Accuracy of Gaze Points in 3D

We set left and right synthetic eyes horizontal angle (1,-1), (1.5,-1.5), (2.0,-2.0), (2.5, -2.5), (3.0,-3.0), (3.5,-3.5), (4.0,-4.0), (5.0,-5.0), (6.0, -6.0), (8.0, -8.0), (10.0, 10.0) [deg], vertical angle 0 [deg]. We measured left and right eyes' gaze angles and positions for 1 second at each setting.

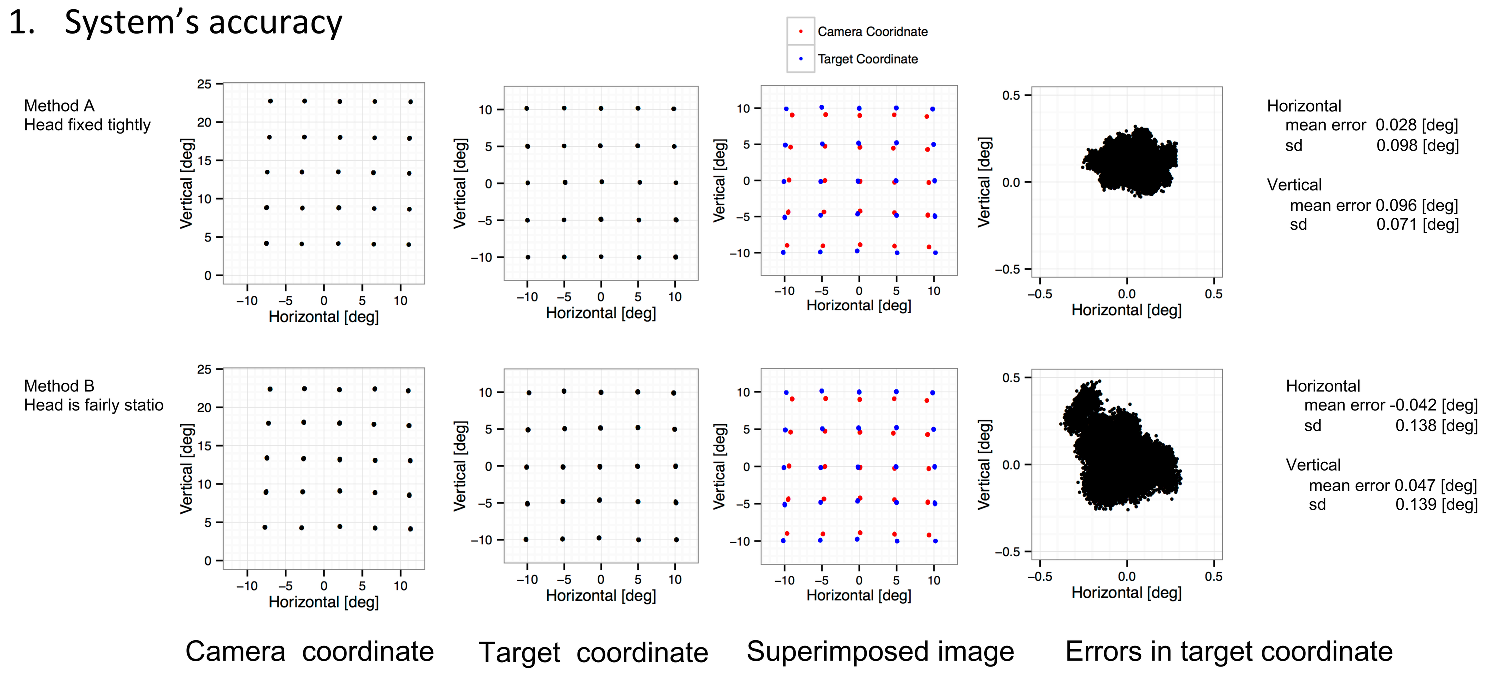
5. Measuring of Human Gaze Points in 3D

We measured gaze positions in 3-D space, sampling frequency was 500Hz. The subject moved his gaze 5 ways. 1)The center to left, left to center. 2)The center to up-left, up-left to center. 3)The center to up, and up to center. 4)The center to up-right, up-right to center. 5) The center to right, right to center.

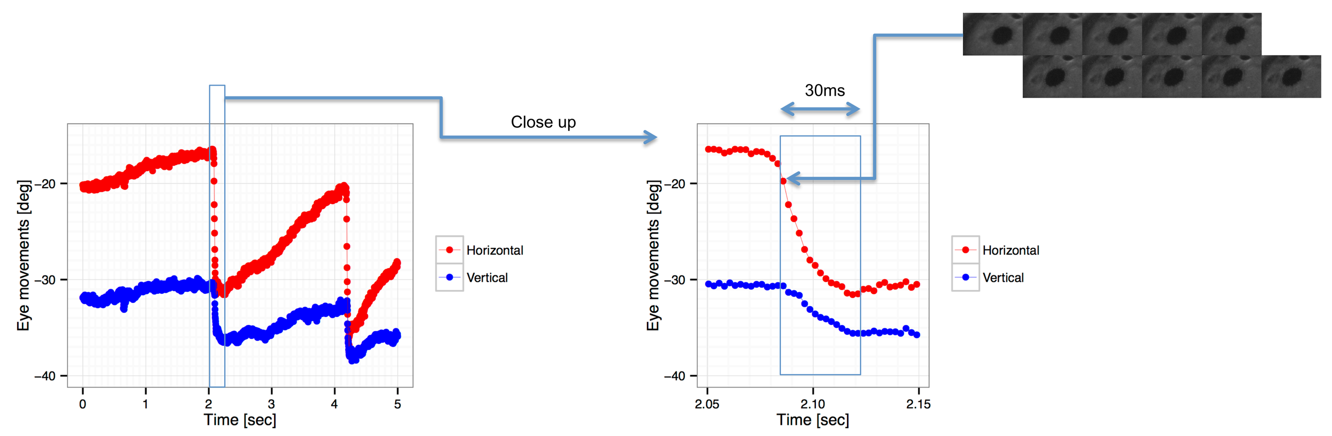


Results

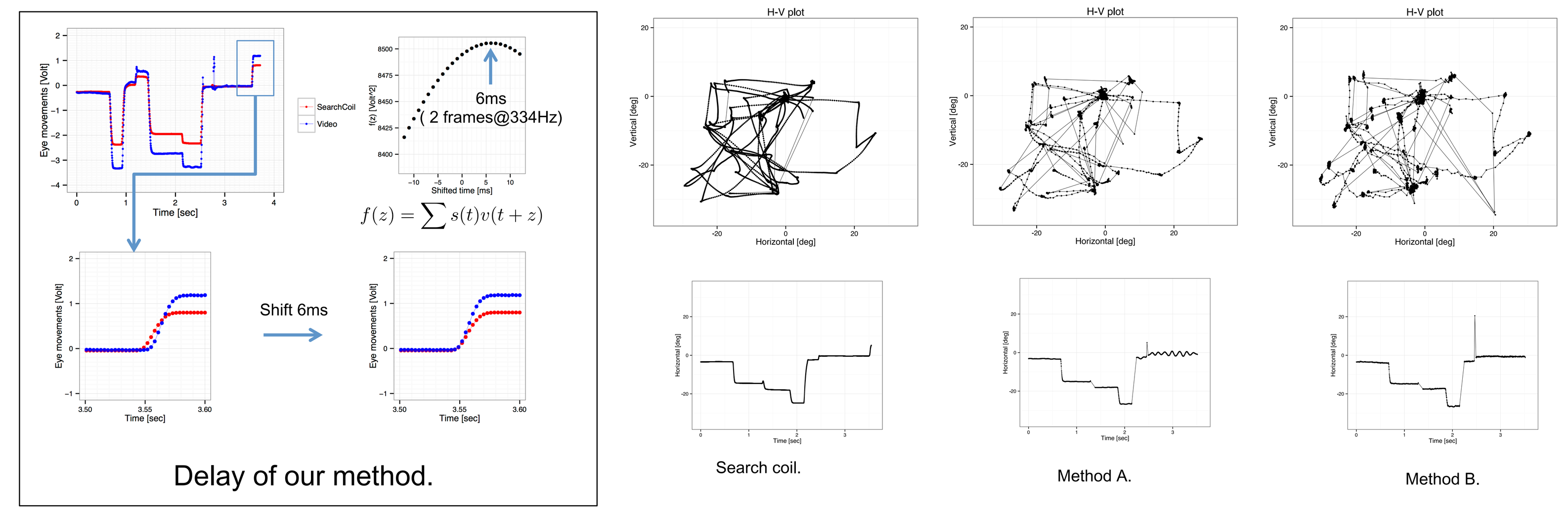
1. System's accuracy



2. An example of mouse eye movements (OKNs) in the camera coordinate system by method A

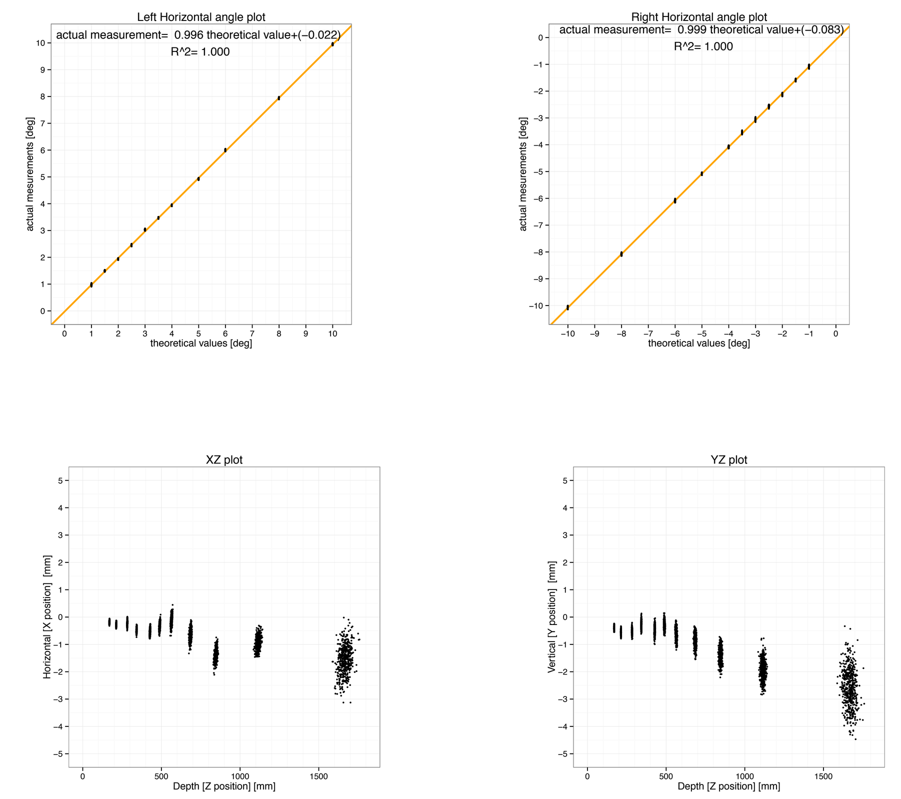


3. An example of monkey eye movements



4. Gaze angles and position calculated by the data measured from the synthetic eyes

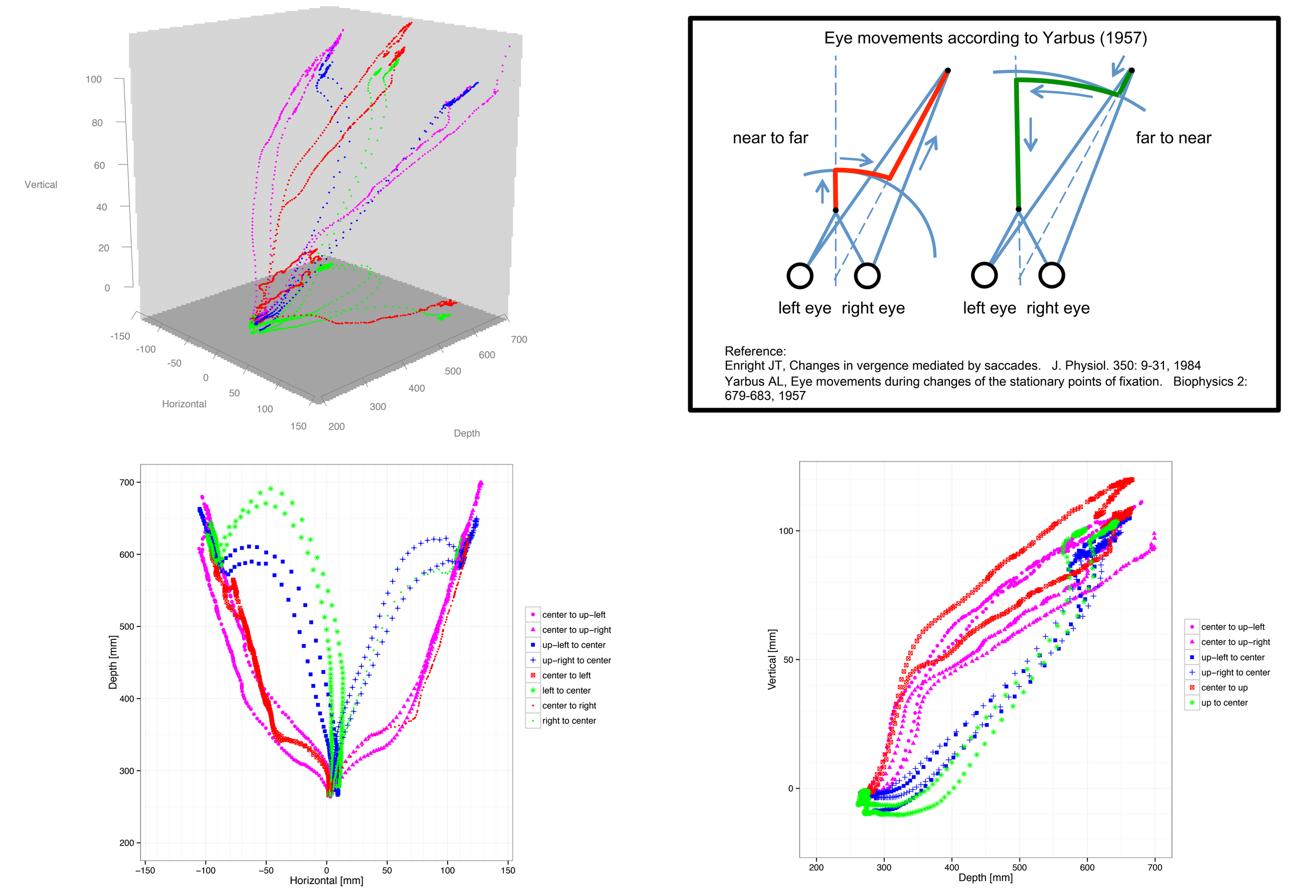
Left and right horizontal angle mean errors are -0.037, -0.084 [deg]. Their standard deviations are 0.036,0.030 [deg]. Maximum error was 15.1mm at depth 687.1mm, after applied a 10 points (20ms) moving average filter, maximum error decreased.



theoretical depth[mm]	mean error[mm]	maximum error[mm]	maximum error applied mav [mm]
1718.7	52.2	131.3	75.1
1145.7	29.9	60.5	39.2
859.1	12.9	28.9	19.6
687.1	1.7	15.1	6.3
572.4	8.0	16.5	11.5
490.5	1.4	6.9	3.2
429.0	1.3	5.7	3.1
342.9	0.4	2.8	1.3
285.4	2.0	4.2	2.8
213.5	0.2	1.4	0.5
170.1	0.3	1.0	0.5

5. An example of human gaze positions.

Gaze positions of a subject (with a 10 points (20ms) moving average filter).



Conclusion

By using the data measured from the synthetic eyes, we found that the system can measure the eye movement better than 1 degree accuracy and delay time is 6ms at 334Hz (depends on camera capturing sampling rate). This system can be used for mice, monkeys and humans. By using this system, we succeeded in characterizing vergence eye movements of humans when ocular fixation shifted between two targets placed at different distances in 3-D space.

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