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

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Summary

We developed a new binocular eye tracking system by adopting a USB-3.0 digital camera that provides high sensitivity, resolution and frame rate. The system is non-invasive and inexpensive and can be used for monkeys and humans. Infrared light illuminates two eyes and the reflected image of the iris and the black image of the pupil of each eye are captured by the camera. The center of the pupil is calculated and tracked over time. The system was originally developed to measure movements of one eye. In the present study, we have improved it for binocular eye movements by adopting a new wide-field, hi-resolution, and hi-frame-rate camera. Since the camera has a 2048x2048 pixels resolution, we can capture the images of both eyes simultaneously and calculate positions of the two eyes at each frame. The eye position data can be read out on line via computer network. The adoption of the WINDOWS 7/8/8.1 x 64 as the operation system makes this binocular eye tracking system user-friendly. Because of the high frame rate of the digital camera, the sampling rate of the system can be as high as 700Hz. By using this system, we succeeded in characterizing vergence eye movements of humans when ocular fixation shifts between two targets placed at different distances in the 3-D space.

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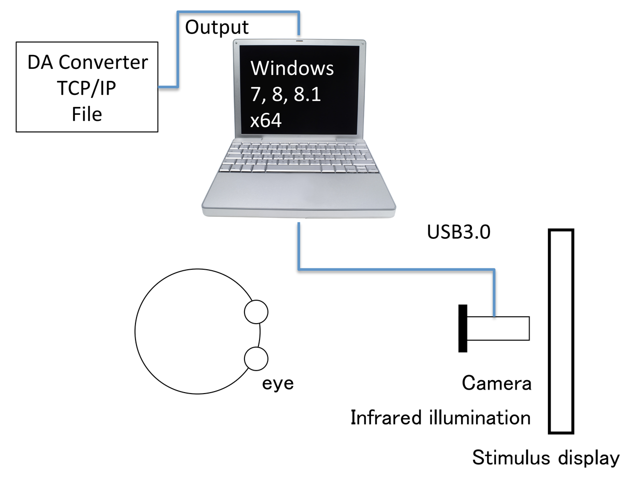
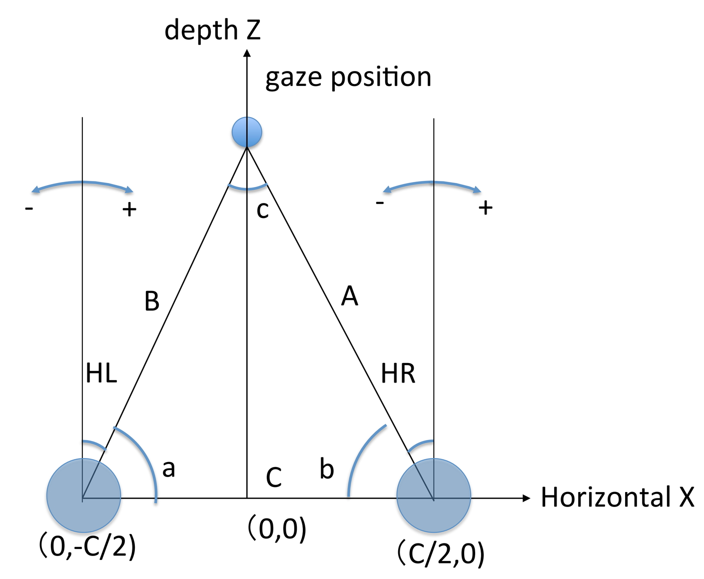
System outline



	model	Company	Option/Memo
Camera	Grasshopper3 GS3-U3-41C6NIR-C	Point Grey Research, Inc.	USB 3.0 Cable
Lens	Ai AF Micro-Nikkor 60mm f/2.8D	Nikon	
Lens mount converter	C-Mount ADAPTER for Nikon	Kenko	for Nikon Micro-Nikkor 60mm
Infrared filter	62S PRO1D R-72	Kenko	for Nikon Micro-Nikkor 60mm
Infrared illumination	AVC-1004	akibasecurity.com	
PC	Windows7, 8, 8.1 x64		

Methods

We calculated the horizontal/vertical gaze angle of each eye by processing its video-image. The origin was set on the center of eyes. The horizontal gaze angle of the left eye (HL) and that of the right eye (HR) were calculated by the our software. "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.



a, b, c: the three angle of the triangle.
A, B, C: the three sides of the triangle.

$$a = \frac{\pi}{2} - HL$$

$$b = \frac{\pi}{2} + HR$$

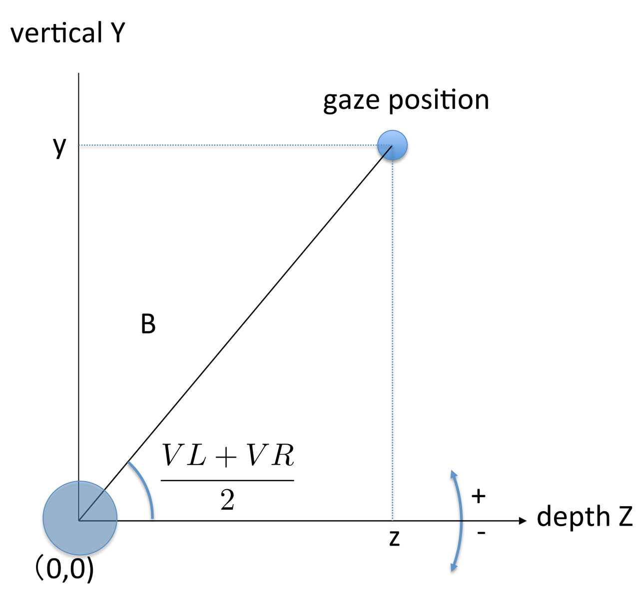
$$c = \pi - a - b$$

$$\frac{A}{\sin a} = \frac{B}{\sin b} = \frac{C}{\sin c}$$

$$(x, z) = (B\cos a - \frac{C}{2}, B\sin a)$$

$$= (C\frac{\cos a \sin b}{\sin c} - \frac{C}{2}, C\frac{\sin a \sin b}{\sin c})$$

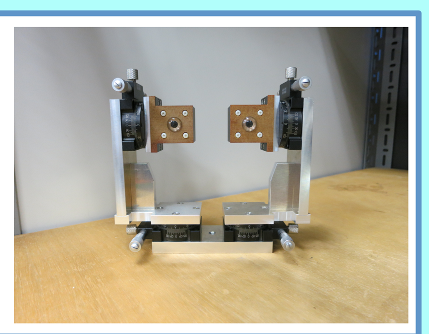
Then we calculated the vertical position. The vertical gaze angle of the left eye (VL) and that of the right eye (VR) were calculated by the our software. We used average of them.



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

Experiment 1

We evaluated system accuracy by using the synthetic eyes. We set left and right 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.

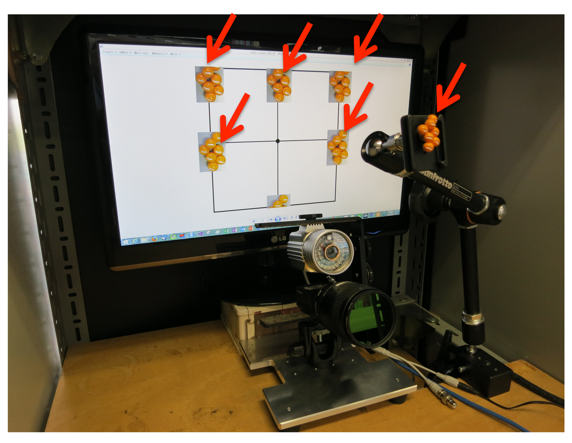


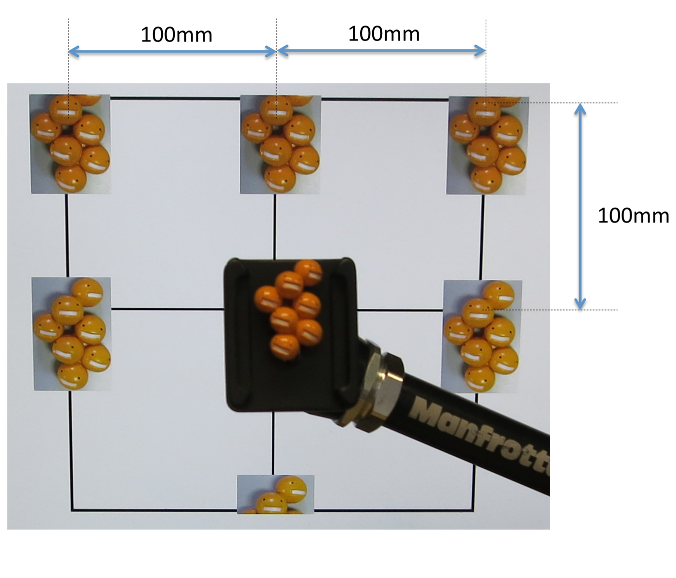
synthetic eyes

Experiment 2

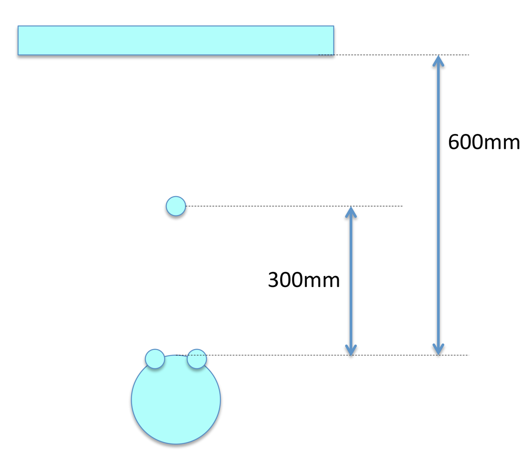
We measured gaze positions in 3-D space, sampling frequency was 500Hz.
The subject moved his gaze 5 ways.

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





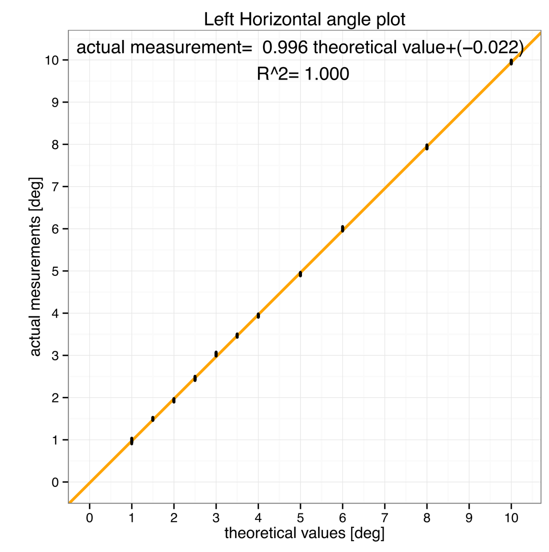
The target positions from the view point of the human subject.

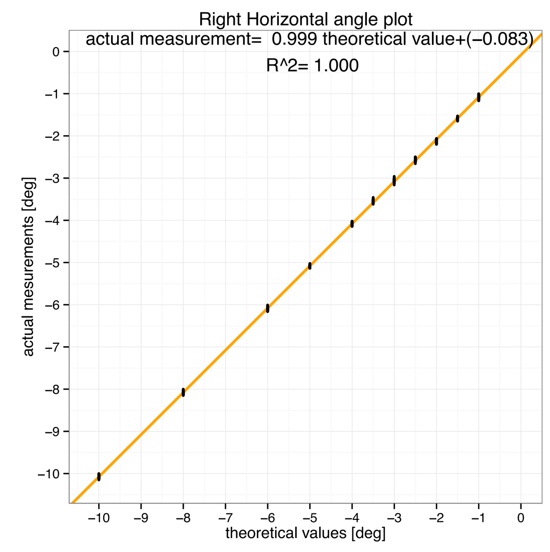


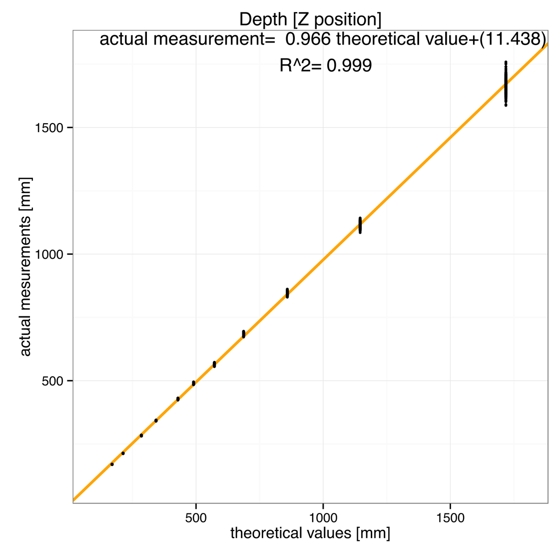
The positions of the visual objects.

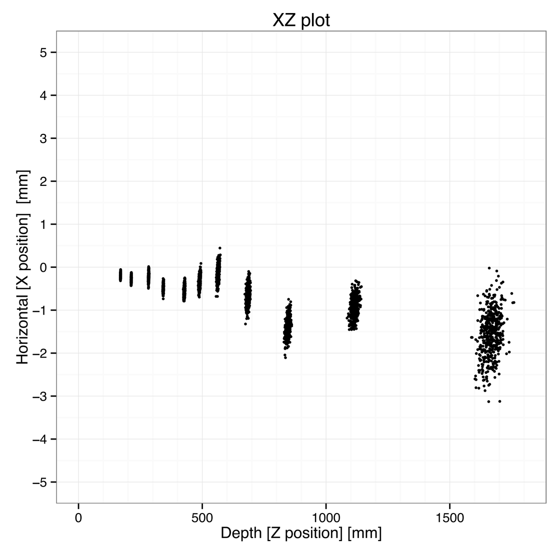
Result 1

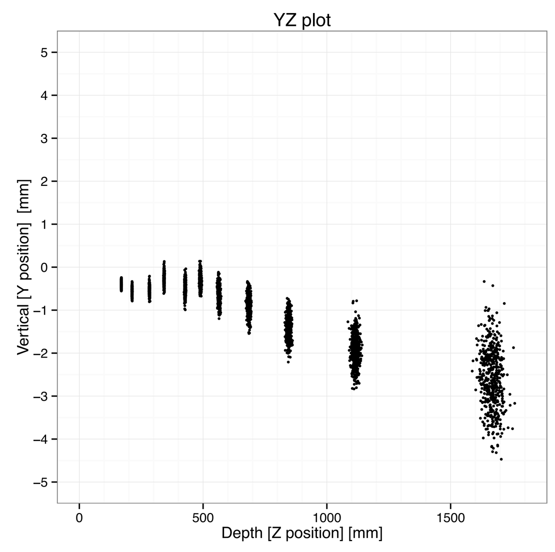
Gaze angles and position calculated by the data measured from the synthetic eyes. Left and right horizontal angle mean errors are -0.037, -0.084 [deg]. Their standard deviations are 0.036,0.030 [deg]. Maximum error was 15.1mm at depth 687.1mm, after applied a 10 points (20ms) moving average filter, maximum error decreased.



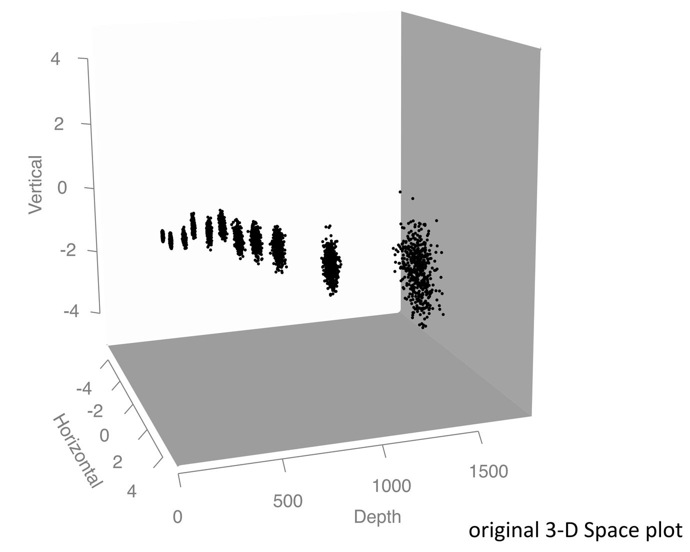




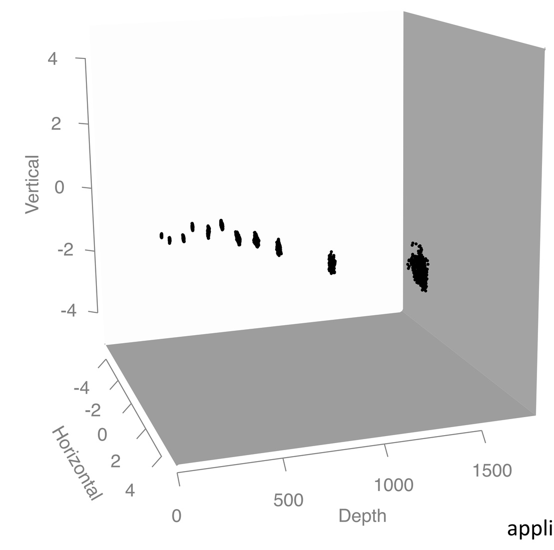




theoretical depth[mm]	mean error[mm]	maximum error[mm]	maximum error applied mav [mm]
1718.7	52.2	131.3	75.1
1145.7	29.9	60.5	39.2
859.1	12.9	28.9	19.6
687.1	1.7	15.1	6.3
572.4	8.0	16.5	11.5
490.5	1.4	6.9	3.2
429.0	1.3	5.7	3.1
342.9	0.4	2.8	1.3
285.4	2.0	4.2	2.8
213.5	0.2	1.4	0.5
170.1	0.3	1.0	0.5



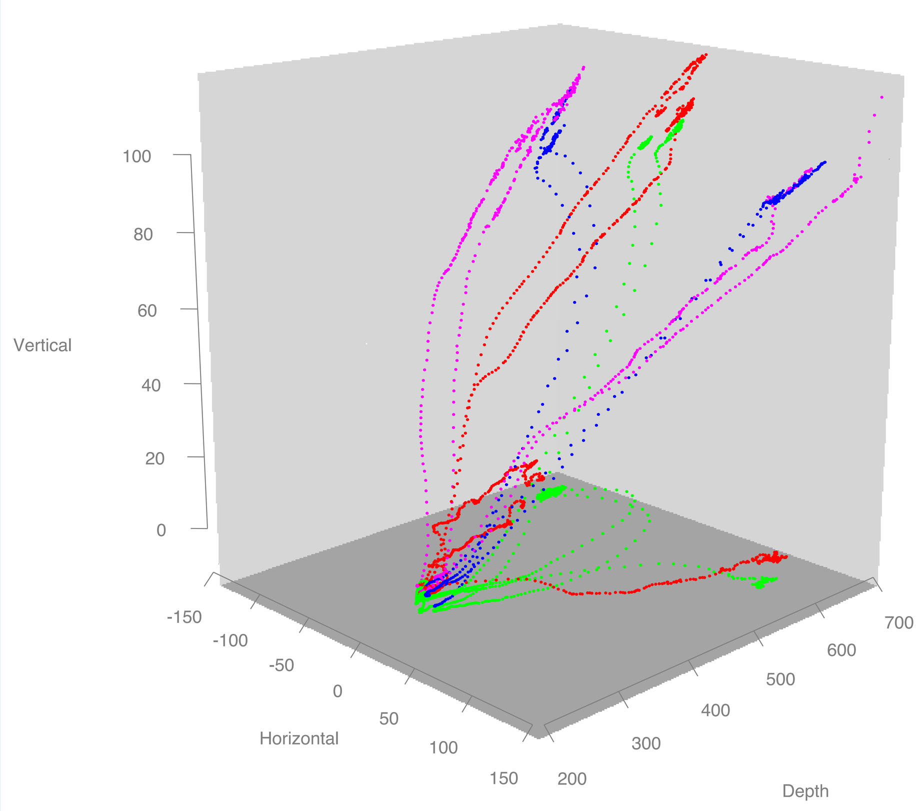
original 3-D Space plot

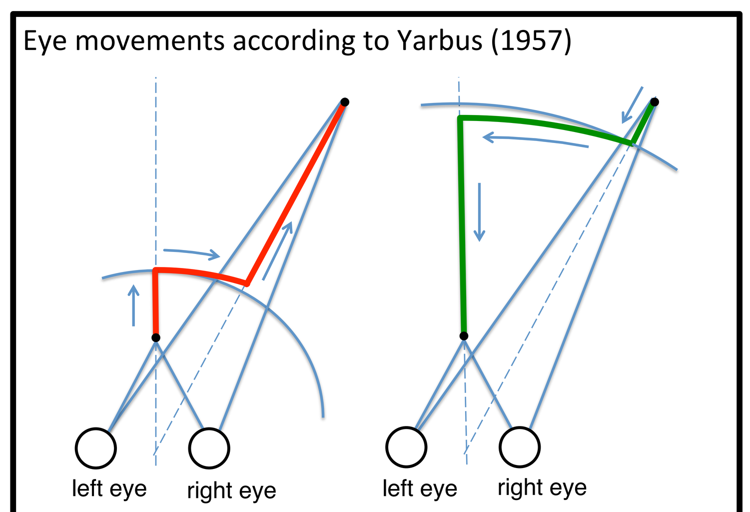


applied a moving average filter 3-D Space plot

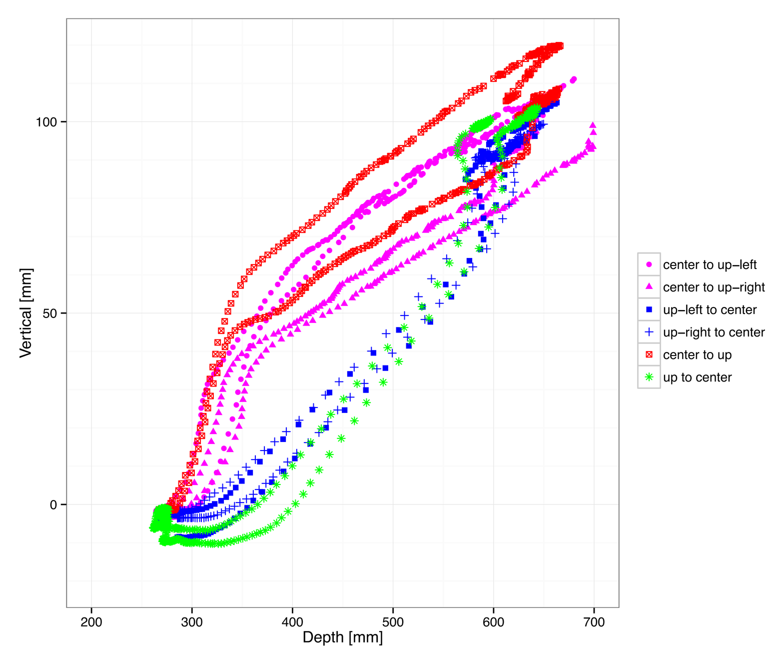
Result 2

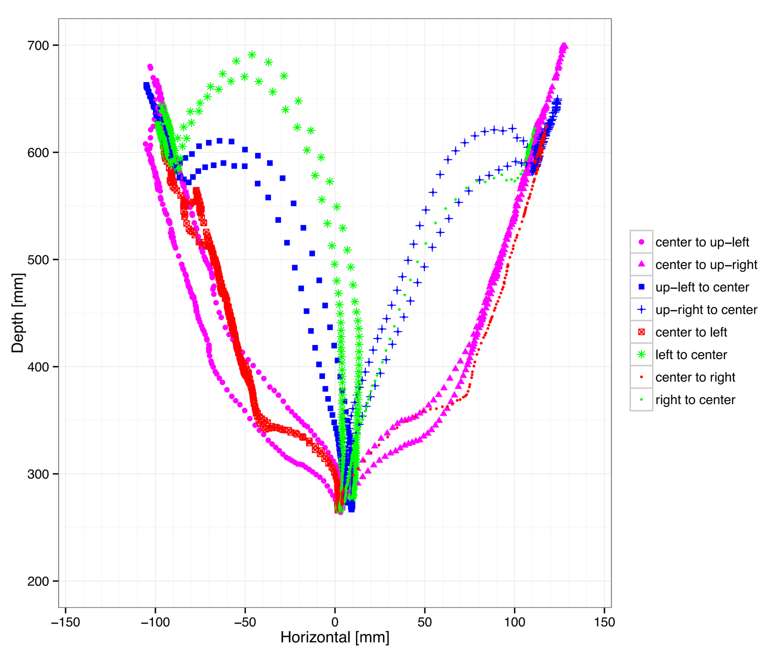
Gaze positions of a subject applied a 10 points (20ms) moving average filter.





Reference:
Enright JT, Changes in vergence mediated by saccades. J. Physiol. 350: 9-31, 1984
Yarbus AL, Eye movements during changes of the stationary points of fixation. Biophysics 2: 679-683, 1957





Conclusion

By using the data measured from the synthetic eyes, we found that the system can measure the eye movement within 0.2 [deg] accuracy (3sDs). The range of the accuracy is less than 15.1mm at 687mm from the subject and less than 2.8mm at 343mm.

By using this system, we succeeded in characterizing vergence eye movements of humans when ocular fixation shifts between two targets placed at different distances in 3-D space.