Mapping Functions in Gaze Tracking

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ABSTRACT

Eye gaze is one of the powerful modes for interaction with the computer. Gaze estimation systems compute the direction of eye gaze. The gaze region on the screen determines the focus and attention of an individual. The gaze tracking systems consists of two major functionalities, feature extraction and determination of gaze mapping functions. The features are the parameters that characterize the pupil and the iris. The gaze mapping functions determine the coordinates on the screen based on interpolation or approximation. In this paper, an in depth analysis of mapping functions is dealt. An attempt has been made to understand the literature of gaze tracking systems.

Keywords

Appearance based method, Feature based method, Calibration, Gaze mapping function

1. INTRODUCTION

Eye gaze offers a natural way of communicating human intentions to a computer. It is observed that the vision enabled applications are much faster than voice enabled applications or other modes of communication. The displays in real-time monitoring systems depend on spatial and temporal characteristics of eye movement [1]. Analysis of the fixations and saccades are important for visual behavior. Visual fixations refer to pausing of eye gaze in certain positions. Saccades refer to movement of eye gaze from one position to another. Most information required for eye gaze is retrieved by fixations. Eye movement data is analyzed using fixation duration, number of fixations and spatial density [2]. The fixation period is typically from 200 to 600 milliseconds. The accuracy of gaze tracking system depends on size of eye's visual field, range of eyeball rotation, diameter of the fovea and radius of the eyeball. The major challenges are due to illumination, variability in position, faster saccades and eye blinks [3]. The gaze tracking system captures focus of a person on the screen. The gaze region (GR) determines the direction of where an individual is looking at, as shown in Fig. 1.

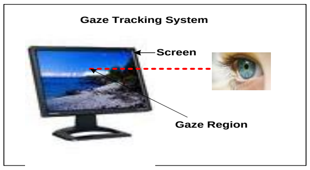

Fig. 1 Gaze tracking system

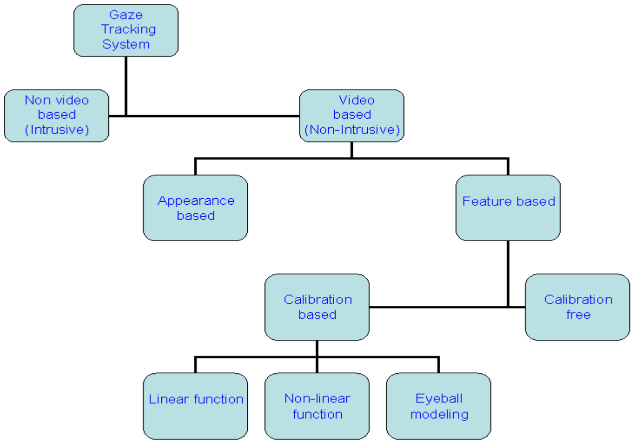

Fig. 2 Classification of Gaze tracking system

The existing gaze tracking techniques are broadly classified into intrusive and non-intrusive as shown in Fig. 2. Intrusive techniques require special attachments such as electrodes, contact lenses or head mounted devices [4]. The contacting devices attached to the skin interfere with the user. The electrodes measure changes due to potential difference around eye socket. Accurate gaze directions are estimated with intrusive techniques. The attachments make these techniques limited to laboratory tasks. The experimental setup for intrusive methods is shown in Fig. 3(a)-(c).

Fig. 3 Experimental set up (a)-(c) Intrusive methods (d)-(e) Video based methods

Non-intrusive techniques use video cameras to capture images of the eye using infrared and natural light [5]. The setup for non-intrusive methods is shown in Fig. 3(d)-(e).

The gaze tracking system comprises of two salient components, extraction component and gaze mapping component.

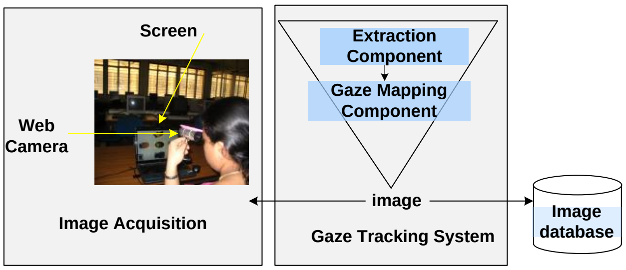

Fig. 4 Components of gaze tracking system

The function of extraction component is to extract the features necessary for determining the gaze direction. The features such as pupil position, limbus position and relative position of Purkinje images that characterize eye ball movements are extracted from eye images. The gaze features are classified into global gaze (head based), local gaze (ocular based) and combined head and ocular based [1]. The ocular based methods are either pupil based or iris based. The pupil center and glint or corneal reflection constitute feature vector in pupil based methods [5, 12, 13]. The center of iris, inner iris corner and edges of iris are determined using ellipse fitting in iris based approaches [14, 15]. The head based approaches use wavelet transform
to extract 3D face pose and facial expressions [16]. The local gaze features are pupil and glint position, iris center, eye corner, inner eye boundary and sclera region. The global gaze features are face skin color inter-pupil distance,
ratio between average intensity, shapes, sizes of both the pupil and orientation of pupil ellipse with respect to face pose [1, 17]. Combined head and ocular based methods combine local and global gaze features [1]. Kalman filter, morphological operations, adaptive template matching, contour tracking method and region detection are used for global gaze feature extraction. The gaze mapping component consists of mapping functions that relate the extracted features to the screen coordinates to estimate gaze direction. The mapping function is determined through calibration. The present investigation focus on various gaze mapping functions. The non-intrusive or video based techniques are classified into appearance based and feature based techniques. The extraction component and gaze mapping component are elucidated for each method. The methods form sacrosanct processing operations at foundation level, for the work done.

1.1 Appearance based methods

Appearance based techniques use image content to estimate gaze direction [3]. The real time gaze tracking with appearance based models determine shape of eyelid and iris [6]. These methods require several significant calibration points to infer the gaze direction from the images. Explicit camera calibration is eliminated. The major appearance based methods are based on morphable model, gray scale unit images, appearance manifold, Gaussian interpolation and cross ratios.

- Rikert's Method:

A morphable model is developed in this method [7]. The texture for a set of prototype images is mapped to the reference image based on shape transformation. The iris location, facial appearance, shape and texture of eye region form the extraction component. The model is built for the image region surrounding the eyes. The model combines linearly the textures of the eye prototypes to form the shape of the reference image. The gaze mapping function is determined from the position of the pupil using pixel wise correspondence. The parameters for shape and texture of the eye region are trained using neural networks. The high value of the parameter for a specific prototype during comparison of images gives the direction of gaze. The criteria for matching is the sum of squared differences error.

- Betke's Method:

Gaze direction is determined by gray scale unit images [8]. The extraction component consists of pupil center, ellipse parameters, unit images and its centers along the outline of ellipse. The model image of subject's eye is determined with pupil at the center position. An ellipse is constructed for the eye region using pupil center. The image region along the ellipse is segmented into unit images called as model units. The gaze mapping component involves learning process using self-organizing map based on correlation for different directions. The parameters for learning are number of units, unit width/height, number of epochs, neighborhood size, kernel width and learning rate. The outcome of the learning phase gives the arrangement of the unit images for test image. The comparison of the pupil positions in model image with various regions in test image using correlation coefficient provide the pupil position. The difference in pupil position between model image and test image estimates the direction of gaze.

- Tan's Method:

The method use appearance manifold for gaze estimation [9]. Every eye image is mapped to a point in high dimensional space, called appearance manifold. The manifold represent the extraction component. A set of sample eye images represent a continuous set of points called appearance manifold in the high dimensional space. The gaze mapping component determines the set of closest manifold points for a test image. A set of weights for the manifold points in the neighborhood is computed based on least squares criteria. The parameters of the test point are estimated by interpolation.

- Hansen's Method:

The gaze tracking method specific for eye typing application is presented [10]. The extraction component consists of shape, texture of eye, pixel intensity information of eye corners and pupil position obtained by active appearance model. The mapping function is based on Gaussian process interpolation method specified by mean and variance functions. The mean value of the interpolated point corresponds to the estimated position of the eye gaze. The confidence in the estimate is expressed by variance. Calibration is performed using twelve on-screen points in the user interface.

- Yoo's Method:

In this method, GR is determined based on the glint positions [11]. The four glints and pupil center form the extraction component. The four light sources at the corners of the monitor form four glint points corresponding to a polygon in image plane. The gaze mapping function is determined by dividing each side of the polygon into segments. Two intermediate points on each segment called as the crossing points are marked. The intermediate points and the corner points of each side are used to compute the cross ratios. The cross ratios are mapped to the monitor to determine GR.

In Rikert's method, accuracy is measured as difference of 200 pixels between actual position and target position. The actual position for 68% of the test samples are within 200 pixels from the target position. Matching the first frame in the sequence use iterative stochastic gradient descent method. This method decreases the speed to determine the initial guess for the morphable model parameters. In Betke's method, the pupil position is learnt by unsupervised learning process where as Rikert's method use supervised learning to train the shape and texture parameters of the eye. The mean angular error for 252 images is determined to be 0.46 in Tan's method. Maintaining a high dimensional space is computationally expensive in this method. In Hansen's method, shifts in eye position require additional model based on mean-shift. The performance of mean-shift tracker is low due to lack of handling multiple hypothesis. The mean on-screen deviation is obtained as 1.4 cm. In Yoo's method, improper threshold value during the extraction of pupil and glint results in a false estimation of GR. The average error obtained is 20 pixels. The polygon in the image is of size 80x80. An error of one pixel in the image maps to 12.8 pixels error in width and 9.6 pixels error in height.

1.2. Feature based methods

Gaze estimation is based on the extracted features. The pupil, iris and eye corners provide parametric data to determine the mapping function. Feature based methods are classified into calibration based and calibration free methods. In calibration based methods, calibration is performed before detecting the gaze direction. The calibration discussed in this paper is with respect to the parameters of the gaze mapping function. The user looks at several specific points on the screen to store the parameters. The methods that do not require explicit calibration for gaze mapping function are called calibration free methods.

1.2.1. Calibration based methods

In this approach, the gaze mapping functions are modeled as linear and non-linear equations. The calibration based methods also include eyeball modeling technique. The three categories are discussed in this section.

Methods based on linear mapping functions:

- Kim's Method:

The marker is fixed at the center of both eyes [18]. The features are position of the marker, radius of the iris and the vector from marker to the iris center. The radius of iris is obtained by circular edge matching algorithm. The matching process is performed for left and right curvatures of iris to determine its center. The calibration follows a specific order of GRs. The gaze mapping component includes computation of the displacement of other gaze directions with respect to reference gaze. The reference gaze is the gaze at the center of the screen. Using geometry based estimation technique, the distance between two GRs gives the current position of the gaze. The distance is computed as a function of eyeball radius, distance from eyeball to screen, distance from iris to marker and displacement of the marker. The adaptive estimation technique uses the displacement of the iris center and the displacement of the marker based on linear approximation.

- Yang's Method:

The eye corner and iris center positions are the features used in this method [15]. The two extreme points on the screen in vertical direction are used for calibration. The parametric boundary for gaze direction in vertical scenario is obtained. The four angles of calibration in x and y directions are saved $(\alpha_1, \alpha_2, \beta_1, \beta_2)$. The gaze mapping function is defined in terms of gaze angle. The eye corner-iris center vector (x, y)is provided as input to the gaze angle calculation. The incremental equation given below provides the two gaze direction angles (γ_1, γ_2) in (3). Given the angles in x and y direction, the GRs are calculated.

$$\gamma_1 = \alpha_1 + ((x - x_1) / (x_2 - x_1))(\alpha_2 - \alpha_1) \quad (2)$$

$$\gamma_2 = \beta_1 + ((y - y_1) / (y_2 - y_1))(\beta_2 - \beta_1) \quad (3)$$

where (x1, y1) and (x2, y2) are the corner-iris center vector of calibration points.

In Kim's method, the estimation of eye gaze requires prior information such as position of reference model, radius of iris and vector from reference model to iris center. The error of 10 pixels is obtained between target position and the result obtained. In Yang's method, the gaze estimation is based on local features and pattern instead of single pixels. The gaze angle error is 1.20. In Kim's method the estimation of GR is in terms of displacement where as in Yang's method, the estimation is with respect to gaze angle.

Methods based on non-linear mapping functions:

- Kiat's method:

The extraction component consists of pupil and glint parameters [19]. The pupil location is detected by the difference between the bright pupil and dark pupil images. The bright pupil is obtained by mounting the light source in coaxial with the camera. The dark pupil is obtained by illumination of light source placed uncoaxial with the camera. An ellipse fitting algorithm is used to determine the pupil centers. The system is calibrated for 20 GRs. The mapping function use radial basis function neural networks (RBFNN) for training parameters. The inputs to the network are the pupil centers, the areas of pupils, the orientation of the pupils and pupil-glint vectors.

- Ji's method:

The pupil coordinates and glint are features for gaze detection [1]. Gaze mapping is based on the set of pupil geometric features. Gaze estimation is performed using generalized regression neural networks. The input layer consists of six parameters, the pupil glint displacement along x and y direction, ratio of major to minor axes of the ellipse that fits the pupil, pupil ellipse orientation and glint image coordinates. The parameters account for the changes in pupil positions. The training consists of data under different gaze directions. The neural networks are considered with output nodes representing GRs. Testing is performed by classifying the input vector to one of the eight regions on the screen. The correctness rate for each region is considered independently. The generalized gaze mapping function possess complicated non-linear structure. The extended work determines GR using support vector regression (SVR) [12]. SVR provides function approximation without the prior parametric model. The data is mapped to a high dimensional feature space and linear regression function is computed. The input to SVR is the gaze data vector Xg consisting of pupil glint vector V and 3D coordinate of the pupil center P. Xg = [dx, dy, px, py, pz], where V = [dx, dy] and P = [px, py, pz]. The SVR models are trained for GRs. The kernels such as linear, polynomial and RBF are used.

- Weston's method:

The intensity values of pupil and iris region extracted using template matching are the features [20]. The image processing operations such as histogram equalization and downsampling are used. The intensity of each pixel in the eye image is input to the neural network. The gaze tracking system employed 48 calibration points to train the neural network with two layers. Eight images are recorded at each marker. 40000 epochs are required for training the neural network. The output layer represents the x and y screen coordinates.

The average accuracy of gaze estimation in Kiat's method is 85.4%. Attaining the difference image in each frame is computationally expensive. Suitable threshold value is required to obtain difference image. In Ji's method, the error is estimated by the difference between actual and estimated GRs. The average horizontal and vertical errors are approximately 5.2 mm and 6.6 mm. Gaze mapping function in Kiat's method use RBFNN where as Ji's method use SVR. The average distance error is 3.680 in Weston's method. The gaze tracker is sensitive to head movements.

Methods based on eyeball modeling:

Eyeball modeling technique constructs the 3D model. The physical structure of the human eye with parameters like focal length, angle between Line of Sight (LoS) and Line of Gaze (LoG) and refractive index are used to determine the gaze direction. The LoG is the optical axis defined by the center of the eyeball and the center of the pupil. LoS is the line from the fovea through the center of the pupil. The visual attention of an individual, the GR, is determined by LoS [5]. The gaze tracking methods that use eyeball modeling are discussed.

- Ohno's method:

The pupil and centroid of the Purkinje image are features for gaze detection [21]. Purkinje images are reflections created at the external surface of cornea. The pupil is detected by fitting the ellipse twice on the segmented eye region. The ellipse is given by x2 + a1xy + a2y2 + a3x + a4y + a5 = 0 where a1, ..., a5 are ellipse parameters. The personal calibration is performed by looking at two points at the diagonal positions on the screen. The cornea is modeled as a sphere. The model derives two parameters, center of cornea curvature c and center of pupil e in the camera coordinate system. The parameters are transformed to the world coordinates, cw and ew. The gaze vector is given by vw = ew − cw. GR is obtained as the intersection of the gaze vector and the screen. The camera in this system is fixed, restricting the user's head movement. The gaze tracking method is enhanced by using stereo-camera based eye positioning system [22]. Calibration is performed using nine markers on the screen. Based on the eye position derived from the stereo image, the eye position in the world coordinate system is calculated.

- Wang's method:

The features used are iris contours [23]. Initially, the iris is detected using the morphological operators. By detecting upper and lower eyelids the iris ellipse is estimated using least squares. The projection of ellipse results in two circles in 3D space. The correct circle is identified based on distance constraint. The constraint states that the distances between the eyeball's center and the two eye corners are equal to each other. The eye model is constructed with radius R. The iris is located at the front of the eyeball with radius r. d is the distance from center of the eye ball to iris plane. The eyeball radius is given by R2 = r2+d2. Eye gaze is determined as the line joining the eyeball center and iris center in the eye model. Two extreme and two intermediate points on the screen are fixed as reference points for calibration. The accuracy of the GR is measured with respect to the reference points.

- Beymer's method:

A pair of stereo systems, wide angle stereo for face and narrow field of vision stereo for eye detection is used [24]. The image features, glints and pupil edges are the features. Pupil edges are detected by ellipse fitting using leave-one-out strategy. The 3D eyeball model is constructed that includes corneal ball, pupil and fovea. The cornea is modeled as an ellipsoid. The estimation of gaze for test image is performed with respect to calibration data by matching.

- Lee's method:

The method is based on 3D analysis of the human eye which is used in head mounted display environments [25]. The pupil center and the specular reflections by three IR-LEDs are the features. Two mapping functions are obtained. The first is linear interpolation mapping function and the second is geometric transform mapping function. In the first method, two calibrated points at upper right corner and lower left corner are recorded. The other gaze positions are calculated by linear interpolation. The second method require two additional calibration points at upper left and lower right positions. The four pupil centers (Cx1,Cy1) , (Cx4,Cy4) map to the distorted quadrangle (mx1,my1), (mx4,my4) on the head mounted display monitor using (4). The variables (a,b,…,h) are unknowns obtained by solving the equations.

$$\begin{aligned} m_{x1} &= aC_{x1} + bC_{y1} + cC_{x1}C_{y1} + d \\ m_{y1} &= eC_{x1} + fC_{y1} + gC_{x1}C_{y1} + h \end{aligned} \tag{4}$$

In Ohno's method, the error obtained is 18.9 pixels. The accuracy depends on the complete set-up consisting of eye positioning unit, stereo camera set, tracking unit and light source. The error obtained in Wang's method is 1.5 cm. The method uses an image of single eye. The zooming and tracking operations with single eye result in incorrect gaze estimation. Ohno's method is pupil based where as Wang's method is iris based. The average monitor error of 18.8 pixels is obtained in Beymer's method. The gaze error obtained in Lee's method is 0.8810 which corresponds to 33.9 pixels on a screen of 800x600.

1.2.2. Calibration free methods

The calibration of parameters for gaze mapping function are eliminated. The position of the camera, focal length and coordinate system with respect to cornea center determine the gaze direction.

- Shih's method:

The extraction component consists pupil center and Purkinje images [26]. The gaze direction is directly estimated by the orientation of the LoS. A 3D coordinate system is defined with origin at the cornea center, x-axis parallel to −kc, where kc is the cornea center, and x- y plane
contains the optical axis of the eye. The 3D coordinates of the pupil is defined in (5).

$$\begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} d\cos\phi - r_p\cos\theta\sin\phi \\ d\sin\phi + r_p\cos\theta\cos\phi \\ r_p\sin\theta \end{pmatrix} \quad (5)$$

where $\theta \in [0, 2\pi]$. The angle between pupil normal and x-axis is ϕ, the radius of the pupil is r_p and the distance between cornea center and pupil is d. The virtual image of the pupil is obtained due to refraction of convex lens, in the observation from camera. The coordinates of the virtual pupil image is given by $P_{vp} = \left[\rho - (n'l / R.l + n)m.p_y m.p_z\right]^T$, where $l = \rho - p_x$, $R = |(n' - n)/\rho|$, $m = n/(Rl + n)$, ρ is the cornea radius, n is the refraction index of the cornea and n' is the refraction index of the air. The geometric properties of monitors are resolved. The relationship between stereo cameras and screen is determined. The LoS is determined and transformed into screen coordinate system to compute the intersection point. The gaze direction is estimated by the orientation of LoS in terms of angle between LoS and optical axis.

- Noureddin's method:

The tracking system use wide angle (WA) and narrow angle (NA) cameras [27]. The WA camera locates the eyes. The NA camera rotates about the x, holds a mirror to rotate about y axis and is used for tracking. The pixel locations of the pupil in WA, NA cameras and the glint in the NA camera are the features for calculation of gaze direction. The gaze vector is calculated as $E' = (P - G)/r_p$ where P is the center of the pupil, G is the center of the glint and rp is the radius of the pupil. The gaze is computed as $E = G - \alpha E'$, $E_z = H_z$ where α is a scale factor, H is the origin of the monitor screen that is parallel to the x-y plane of the world coordinate system.

- Park's method:

In this method, three camera systems, one wide view camera and two narrow view cameras are used [28]. The pupil center and six boundary points of pupil are the features used for gaze estimation. The 3D positions of pupil boundary P1 − P3 and Q1 − Q3 in the monitor coordinates are obtained. The gaze vector S is obtained by the average
of six gaze vectors, S1, S2, S3, S4, S5, S6 where S1= P0P1xP0P2, S2=P0P2xP0P3, S3= P0P3xP0P1, S4= P0Q1xP0Q2, S5=P0Q2xP0Q3 and S6=P0Q3xP0Q1. Alternatively, the Eigen vector matrix is used instead of average of six vectors.

In Shih's method, the root mean square error in horizontal and vertical directions are 18.4 and 13.8 pixels respectively. The method requires multiple cameras and multiple light sources. Calibration of each camera is important. The gaze error in Noureddin's method along horizontal and vertical directions is obtained to be 9.74% and 1.72%, respectively. Segmentation of pupil using WA camera is difficult. The root mean square error of gaze direction in Park's method is 0.627 cm. The gaze errors increased in lower regions due to the placement of wide and narrow angle cameras above the monitor. The sacrosanct knowledge for each gaze tracking method is listed in Table 1.

Table 1. Sacrosanct knowledge for gaze tracking methods

Author	Sacrosanct Knowledge
Rikert	The morphable model contains parametric information on shape and texture for different directions.
Betke	High correlation coefficient is obtained by considering a segment of the model image depending on the direction of pupil.
Tan	The method searches for the nearest neighbor manifold point in high dimension. The dimensionality depends on the size of the eye images. The topological information ensures that only the points from the single neighborhood on the manifold are selected.
Hansen	The appearance models are used for tracking small eye movements. The active appearance model is a hierarchical structure. The extraction of eye features is based on shape statistics.
Yoo	The monitor is projected to a polygon whose vertices are glints. Gaze direction is detected based on mapping of the glints. The accuracy of the system depends on feature extraction.
Kim	Edge detection techniques are used to segment limbus and pupil. The imaging system makes use of orthogonal projection. The displacement of iris center in the projection is proportional to the displacement of the eye gaze.
Yang	Interpolation is used to determine the gaze direction. The gaze angle directly determines the GRs, for desktop screens.
Kiat	Precise ellipse fitting is essential to obtain pupil center. Ellipse is constructed by eliminating the concavities in the pupil region due to glints.
Ji	Prior knowledge of gaze mapping function is eliminated. The nonlinear function approximation is obtained through SVR.
Weston	Image processing operations are required prior to neural network training.
Ohno	Performing double ellipse fitting eliminates overlapped noises like eyelashes, lower eyelid and Purkinje image.
Wang	The ratio of iris radius to eyeball radius is a constant.
Beymer	The intrinsic eye parameters, radius along optical axis and radii in two other directions are required.
Lee	The method is suitable for wearable computer applications. A virtual eyeball model is constructed based on the characteristics of the human eye. The eye coordinates are synchronized with monitor coordinates.
Shih	The LoS is estimated without user dependent parameters.
Noureddin	The computations use linear equations and are dependent on the geometry of eye model.
Park	The gaze vector is estimated based on only pupil parameters.

2. Applications of gaze tracking systems

An interactive system responds to observed eye movements. Eye tracking applications are classified into diagnostic and interactive [4]. Diagnostic systems record eye movements to ascertain the user's attention based patterns over a given stimulus. These systems are used for post-trial and off-line assessment of the viewer's gaze. Interactive systems respond to the users based on observed eye movements.

The major applications are in scientific domain, marketing and advertising, gaming, multimodal interfaces, media study and optical treatment. Efficient usage of bandwidth in web applications is possible by displaying high resolution information only at visual fixations [1]. Secure communication is achieved by typing the password with eye in conjunction with iris authentication procedure.

Fig. 5 Applications of gaze tracking systems. (a)Gaming
(b) Interactive (c) Eye typing (d) Web applications displays

3. CONCLUSION

The gaze tracking systems are important for human computer interaction. The gaze pointing systems is a replacement for existing input devices. In the present work, several techniques have been analyzed. The classification is based on gaze mapping function to determine GR. The implementation aspects of appearance based techniques based on image data are easier and simpler. The pupil corneal reflection or the pupil-glint vector is the most common feature used in feature based techniques. The function based approaches use interpolation or approximation to estimate the screen coordinates. Eyeball modeling is dependent on the geometry and calibration of camera. In this paper, an attempt has been made to understand the literature of gaze tracking systems with more emphasis on mapping functions.

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