A Survey on Methods and Models of Eye Tracking, Head Pose and Gaze Estimation

[1]Rohit P. Gaur, [2]Krupa N. Jariwala
[1]M.E. - GTU PG School, [2]Assistant Professor – SVNIT - Surat
[1]CO - Wireless and Mobile Computing
[1]GTU, Ahmedabad, India

***Abstract* – Eye tracking and Gaze estimation are the most challenging areas in computer vision. Even though we have achieved a significant progress in the last few decades, some domains are still facing the limitations. Be it the lack of accuracy due to the design of fovea or the tracking challenges in visible spectrum, this paper covers an in-depth research survey of the recent as well as the archaic methods and models used for eye tracking, head pose and gaze estimation.**

***Index Terms* – Eye detection and tracking, methods and models of eye tracking, head pose and gaze estimation, research survey paper, visible spectrum.**

I.INTRODUCTION

Human body is a house of sensors. We touch, we hear, we smell, we see and we feel. Our brain analyses the data and responds by the means of gestures or language. As the natural tendency of a human being is to learn, eyes become our best friend. It gives us the sense of light. The importance of the eye cannot be scaled or compared. In the latest technology, where we are moving towards human and computer interaction (HCI), the first sense is our sight. What we see next depends on what we saw initially while our face reactions, along with the gestures, are the outcome of every input our brain receives. For example, even for simple events like a button click on a webpage, our brain first analyses the data from what we see and then sends the signal to our hand that is controlling the mouse at that particular moment. All of this happens in fractions of a second. Today we live in the world of high processing speed and hence it is possible to enhance the way we interact with computers.

Eye tracking and gaze estimation opened many doors in the field of HCI because now we can use our eyes to interact with the computers. This not only helps the physically disabled people of our society but also provides a better path where one day we will be able to interact in a faster and a better sense. It also helps us learn how a human reacts to a particular situation, for example, how we look at things and what we first see in a product or an advertisement so that we can enhance or change the old techniques to make them efficient and less time consuming. This research survey paper focuses on the methods and models of eye tracking and gaze estimation. In section 2, we will go through and understand the various methods of eye tracking. In section 3, we will go through the categories of the eye models and review the techniques that use that particular model. Section 4 will cover the methods of gaze estimation and section 5 will be categorizing the models of gaze estimation where we review the techniques working on that particular model. Section 5 will cover category-divided tabular information of all the techniques used along with the models. The paper concludes in section 6 with the description of the possibilities of future work on eye and gaze tracking.

II.METHODS OF EYE TRACKING

Electro-Oculography is a method in which the potential between the back and the front of the human eye is measured as it acts like a dipole. In this method, electrodes are attached to the skin around the eyes (see figure 1) that makes it possible to record the vertical and horizontal movements separately. Electrodes are placed at the left and the right of the eye for horizontal tracking whereas above and below for vertical tracking. When the eye moves from center position towards one of those electrodes, the approached one experiences positive side while the other one experiences the negative side of the retina resulting in potential difference which helps in locating the eye's position.

One advantage of this method is that it can track the eye gaze even when the eye is closed [1]. This technique is not suitable for domestic or commercial use as it has to deal with close contact of electrodes near eye region but it is used for clinical purposes as well as in projects like MONEOG [http://www.metrovision.fr].

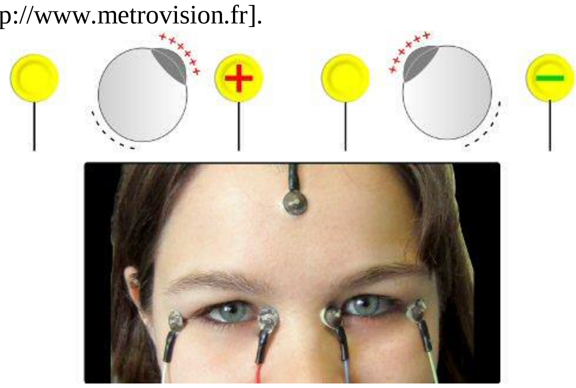

Figure 1: Human eye acting like a dipole and electrodes attached around it [63].

Scleral Search Coils is a method in which a coil is encapsulated within a contact lens along with a mirror. The mirror allows us to measure the reflected light while the coil allows us to detect the coil's orientation in a magnetic field (see figure 2).

It is uncomfortable for a person because of the thin wire connecting the coil with the measuring device (see figure 3). Several tests have also been performed to check the visual effects of search coil wear. Elizabethet al. [2] summarized in their paper that there are no significant effects of the search coil on visual function. However, to ensure that no adverse effects have been caused, post-wear checks and a thorough prescreening of subjects should be carried out on all coil wearers. High accuracy and nearly unlimited resolution in time are the advantages of this method and for the same reason it is mostly used in psychological and medical research. Skalar Medical is the original manufacturer of the search coils and Chronos Vision became their official successor after they closed. [http://www.chronos-vision.de].

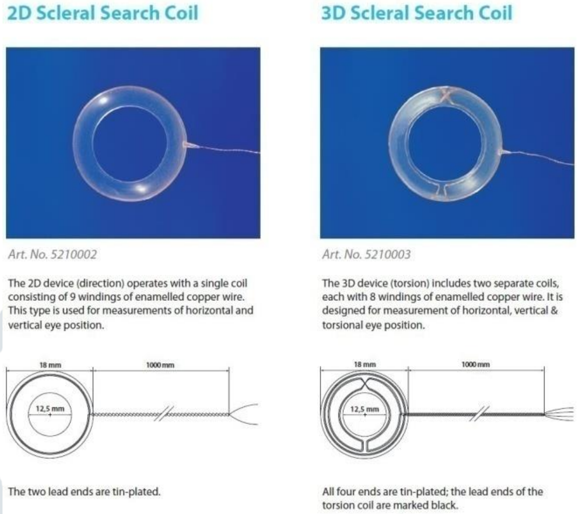

Figure 2: 2D and 3D Scleral Search Coils with their measurements and specifications [64].

Video-based eye tracking method is used most widely, especially in domestic or commercial eye trackers. This method was very complex and costly before but with the rapid enhancement in technology, the cost came down and the efficiency of eye – gaze tracking increased. Video Oculography can be of two types – Invasive (Head mounted) and Non-Invasive (remote). Both types can have either visible or infrared light for eye tracking. This method generally uses single or multi cameras for eye tracking.
Eye tracking in infrared spectrum basically works by illuminating the eye with an infrared light source. This produces a glint on the cornea of the eye and is called corneal reflection.

Figure 3: Modified contact lens (comprising the coil and mirror) are inserted on the eye with the thin connecting wire exiting nasally [64].

Generally in the existing work, glint has been used as the reference point for gaze estimation. This is because the difference vector of pupil and glint remains constant when the head or the eye moves (see figure 4).

The very first work was done by Merchant et al. to produce the desired effect [3]. Much further research work has been done since then [4-12]. Similar work using infrared LED (see figure 5) has been done in EyeMMV by Vassilios et al. [13]. EyeMMV can perform metrics analysis, fixations identification, ROI (region of interest) analysis, and data visualizations. Vassilios et al. proposed an algorithm for fixation identification that is based on three parameters (one for minimum duration and two for spatial).

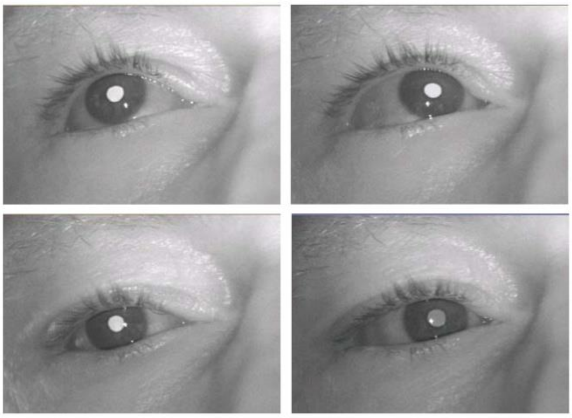

Figure 4: Looking to the four corners of the screen – the reflection stays in the same position [65].

Laura Sesma et al. proposed a gaze estimation system based on a web cam in the visible spectrum using center of pupil and eye corner vector as a feature for gaze estimation based on interpolation methods [14]. They came to the conclusion that the eye corners also move as the eye moves and hence the accuracy of gaze estimation gets affected. So this fact also needs to be taken into consideration regardless of the head movements.

With single camera systems that are fixed at a point, the difficulty faced is with the limited field of view for capturing images in high resolution. However, adding multiple light sources can help in providing a better result [9].

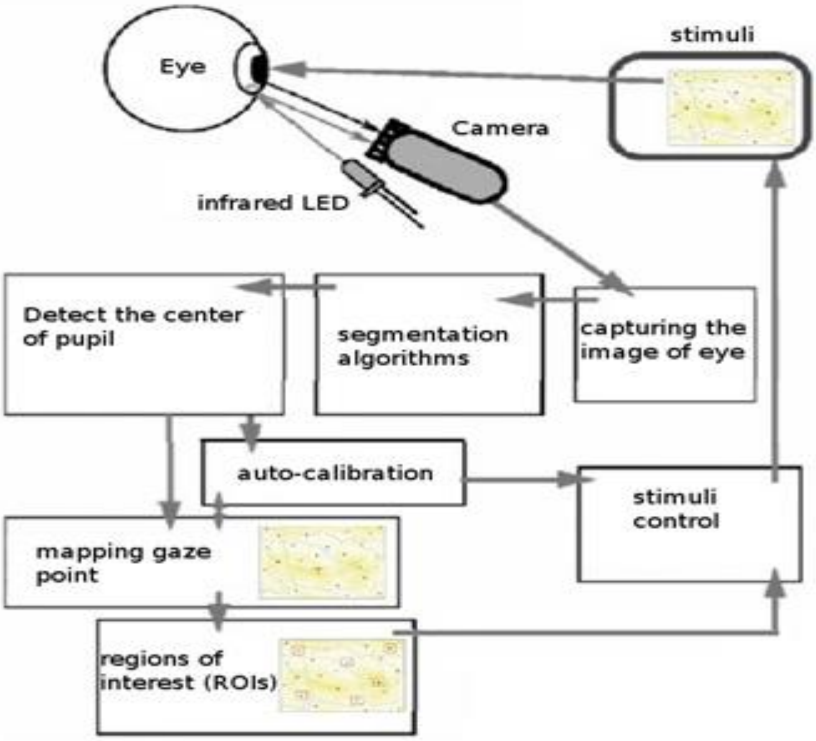

Figure 5: System's operation diagram [66].

An intelligent control scheme is proposed by Xiaohui et al. [21] for remotely tracking the gaze. This scheme includes four sources of infrared light and an ordinary camera. However, calibration is necessary. Tobii Technology [http://www.tobii.com] has developed many eye tracking systems ranging from glasses to standalone eye tracking units. They provide us with their own software and SDK for the same but the projects are not open source.

In previous related works, multiple camera systems use either one camera per eye or one for the eye and one for the head location to consider the changes in the head pose. Then the information from all the cameras is combined together to estimate the point of gaze.Zhu et al. [22] used two cameras to form a stereo vision system by calibrating them in such a way that the computation of the pupil center can be done in 3D coordinate system. The video cameras are placed under the monitor screen whereas the infrared illuminator is placed in front of one of the cameras to obtain the glint in the image of the eye. Pupil-glint vector is then extracted in 2D space and combined with the 3D center of pupil to provide it as the input for the function of gaze mapping.Another similar 3D approach is proposed by Ke Zhang et al. [23] where the eye gaze point is estimated by a method of 3D gaze tracking. They introduced a planar mirror that helps in calibrating the positions of the monitor and the LEDs without the need of any other device. Gaze point is then computed as the intersection of the estimated 3D gaze and the monitor. However, they have a limitation on the free head movement because of the narrow cameras used.

III.DETECTION BASED ON EYE MODELS

An eye is circular from front view and appears to be elliptical from side or when viewed from any other angle. This drastic change in the shape of the eye makes the identification of the model of the eye necessary. This helps the detection and tracking as the appearance and dynamics of the eye are then accounted for. A dexterous survey has been done by Hansen and Ji [15] in which they sorted out these models into Shape-Based Approaches, Feature-Based Shape Methods, Appearance-Based Methods and Hybrid Models. This section uses these categories and adds more information to the existing survey on models.

Shape-Based Approaches can be categorized into simple elliptical shape or complex shape model. There can be either voting-based methods (selects features that support a given hypothesis) or model fitting methods (fits selected features to the model) in simple ellipse model.

Simple models fail to capture the variations of eye corners, eyebrows, and eyelids. Perez et al. [24] propose the prototype of a real-time eye and gaze tracking system. For gaze detection, they have used four infrared lights that are specially shaped and to improve the accuracy they use sub-pixel determination of the pupil center. Their system recovers from the errors in tracking caused due to slow blinking or sudden movements of the head by determining the exact eye position and image processing of the camera which happens to have a wider field of view.

Complex Shape models are the ones for such detailed work. One such method was proposed by Yuille et al. [16]. Here the initial position of the template is critical as there holds a possibility of the algorithm failure. For instance, eye detection might fail when initializing the template above the eyebrow. The template requires the presence of four corners (corners formed by the iris and the upper lid as well as the left and the right corners of the eye) but this holds only when the eye lid covers a part of the iris and the method fails when the eye are wide open.

Feature-Based Shape Methods are more inclined towards the features of face and eyes that are less sensitive to variations in viewing angle and illumination. It can be categorized in Pupil Detection and Local Features by Intensity or Filter Responses.

Pupil detection is based on the fact that iris and pupil are generally darker compared to their surroundings and if the contrast is large enough, a threshold can be applied. Pupil Detection technique can generally be applied indoors as the intensity of a pupil may vary with the change in illumination and when it comes to bright outdoor environments, the pupil becomes quite small. Y. Tian et al. [25] proposed a dual-state method for eye tracking that recovers the state of an eye model and its parameters. Open and closed are the two states considered in the proposed method. The method tracks the iris based on the information of edge and intensity. If the detection of iris is successful then the eye state is counted as open, otherwise closed. However this method gives a false positive on closed state for a narrow open eye. To deal with difficult cases, more eye states are needed and their future work is regarding the detection of the reliability of eye states by obtaining a face state.

Intensity based methods on the other hand locate a particular edge initially and then track the edge of the pupil or the corners of the eyes by using Gabor filters. In general, a sequential search is laid down to locate the position of eye and the corners depending on the model of the eye and the features included in the method. Hassaballah et al. [26] proposed a method for the detection of eyes which is based on the combination of Independent Components Analysis (ICA) and grey intensity variance in the eye region. To extract the eye, ICA is applied on a patch image. ICA basis vector is computed by using the FastICA algorithm [29]. The FastICA algorithm uses a kurtosis maximization process to maximize whitened data distribution's non-Gaussianity for computation of ICs. Similar work has been proposed by Montazeri et al. [28] where morphological operations and hybrid projection function detect the face region. Vertical edge dominance map is then used to identify the eye window. Pupil center is detected by applying two elliptical masks on image of the eye.

Filter responses deal with suppressing particular characteristics in order to enhance the required ones. This method requires high quality images. D'Orazio et al. [27] proposed an algorithm for detection of eyes. The algorithm determines the eye by using the geometrical information of iris. Distance and symmetry is used to locate the eye couple. Wenkai Xu and Eung-Joo Lee [30] proposed a new method based on rectangle features. They adopted the geometric characteristics with the symmetry characteristics for correction. Mean Shift algorithm has been combined with Kalman filter to overcome external illumination and eye closure effects.Similar work has been done by Zhiwei Zhu and Qiang Ji [31] with active IR illumination.

Appearance-Based Methods handle variations in the appearance by deriving a good representation based on the analysis of the intensity distribution of the appearance of the entire object using statistical techniques. Appearance based methods can also be categorized in intensity domain and filter responses.

Intensity domain is more focused towards eye detection and tracking by correlating through templates. Related work has been done by Hallinan [17] where he uses a model comprising of two regions (dark iris region and white sclera region) with uniform intensity. Zhu et al. [32] proposed a method that is robust and can track the eyes when the iris is not bright enough due to the interferences of external illumination. They combine the conventional technique of object recognition that is based on appearance and the bright-pupil effect resulted from the infrared light. It appears to work pretty well with ordinary ambient IR lighting and strong non-IR lighting. Hillman et al. [33] proposed a technique in which the skin is detected using PCA transformed CIE-Lab color space while excluding the eyes. Eigen images and region growing is used to process the eye regions.

Filter responses in appearance based methods are different from the ones in feature based methods. Instead of selecting the features to be used, the response value is used directly. Fasel et al. [34] proposed a generative approach which is robust to changes in illumination and lightning and it explicitly defines the conditions for its optimal use. D. W. Hansen et al. [35] proposed methods to accommodate image data uncertainties using robust statistical principles and obtained an accuracy of 3-4 degrees for gaze estimation.

Hybrid Models overcome the shortcomings of a single eye model by combining the advantages of different models into one system. Related work has been done by Xie et al. [18], [19] where the region of eye is detected in the initial phase by doing a binary search and threshold and then in the later phase it is divided into several parts. The strings get pulled on hybrid models when they fail to model the intensities of an image directly in the non-patch areas. Y. Matsumoto and A. Zelinsky [36] represent features of face on a 3D model by using 2D templates. This is done for matching purpose. Hough transformation is used for finding the location of the iris. Also, a model specific to a person needs to be built separately. Active appearance models (AAM) are the ones which in order to obtain a good fit, need to be initialized pretty close to the actual position of the eye. That is why AAM and deformable models depend on other mechanisms to deal with large head movements. By using Active Appearance Model, T. Ishikawa et al. [40] proposed a driver gaze estimation algorithm. Their system tracks the whole head using a global model of the head. The eye region, corners and head pose are extracted from the AAM for gaze estimation. D. Cristinacce and T. Cootes [38] generate likely feature templates using appearance model. They proposed an algorithm called Constrained Local Model search (CLM) by which a deformable object can be modeled. Instead of modeling the pixel values of the image, CLM method models the set of feature template's appearance. Aryuanto Soetedjo [39] proposed a 3-step approach based on color and shape features. In the first step, a projection technique is used to roughly localize the eye. In the next step sclera is extracted by applying a threshold of white color based on chromaticity diagram of normalized RGB. In the final step, the elliptical shape of an eye is fitted by an ellipse fitting. This approach achieves an eye detection rate of 91%, as specified. D. W. Hansen et al. [37] proposed a scheme for Eye typing that uses an Active Appearance Model (AAM) and a fast mean-shift color tracker and works efficiently with low cost web cameras.

Other methods are the ones that employ temporal information or symmetry operators etc. G. Loy and A. Zelinsky [41] proposed a method that suits well for real-time vision applications as its computational complexity is low and the runtime is fast. They used a gradient of image and presented the point of interest detector that locates the points of high radial symmetry. First a gradient is determined, then at each radius n, a magnitude projection image and an orientation projection image is formed which leads to the formation of a two-dimensional Gaussian. Over all the radii, the averages of the symmetry contributions are considered which is known as the full transform. The transform is efficient and hence suitable for real-time applications.

Blinks and Motion model is derived from the dynamic characteristic of the human eye that exploits the same for its detection. Blinking is natural, periodic and necessary for an eye to keep itself moist and clean. Relative work has been done by Bala et al. [20] where they first extract a face region by applying background subtraction using skin-color information and then they locate the eye region by exploiting the blink characteristic and analyzing the difference in luminance between successive images. This makes it easy to now locate the pupil (circular shaped - dark region).

IV.HEAD POSE ESTIMATION METHODS

Head pose estimation is a special case of human posture recognition. From digital imagery, the orientation of the head is inferred and this process is called head pose estimation. Everything in a digital image is represented in pixels. To transform that representation into a high level directional concept takes a series of steps. Here in this context, head pose estimation is the relative orientation of a person's head to the camera view.Various methods can be used to estimate the head pose. Padeleris et al. [61] proposed a method that uses a depth camera to snap images in 10 fps and estimate the head pose. The methods goes through an initialization phase where a reference image is obtained. They solved the problem of optimization by Particle Swarm Optimization. Anant Puri et al. [62] proposed an algorithm for pose estimation from a single image. They eliminated the irrelevant details from the image by using non-photorealistic rendering. Their method does not need an individual initialization and is not sensitive to changes in illumination. This section covers Template methods, Geometric methods, Flexible models, tracking methods, Hybrid methods, and other methods.

Template methods are based on appearance that have a set of models with corresponding labels to jibe a view of the head of a person using image-based metrics of comparison. In simple words, these methods compare the head to a set of examples acquired during training to find the most similar view. Ng and Gong [50] model the appearance of human face by extending Support Vector Machines (SVMs) which, over multiple views, experience change that is not linear. Their approach uses an algorithm on SVM classification and intrinsic factors in the nature of the images taken as input for detecting the face and estimating the pose. They show that by aligning the training set in a better way increases the accuracy for estimating the pose. However, computation time in multi-view Support Vector Machine classification is not up to the mark for real time use. Gourier et al. [51] addressed the problem of head pose estimation over a wide range of angles from degraded images. They used features based on chrominance to detect the face.Using the cosine values, they compare the reconstructed images with the original ones for head pose estimation.

Geometric methods estimate the pose from the relative configuration of the local features like the tip of the nose, mouth, and eyes after finding them. Locations of facial features helping in estimation of pose was the main focus in the approaches at the beginning. Nose tip, outside corners of eye and mouth collectively are the five facial points that help figure out the symmetry of face where the midpoints of eye and mouth connect a line with the nose point. This information is exploited to estimate the gaze. J.G. Wang and E. Sung [52] proposed a method where the mouth corners and the outer and inner corners of both eyes are detected automatically.

Flexible models are non-rigid models that are fit to the structure of the face of an individual. Estimation of head pose is done by comparing on the basis of feature-level or by instantiating the model parameters. This approach is better than appearance based as there is variation in the location of eyes, nose and mouth among people. Therefore, in each training image, manual labelling is done.

From views of several people, extraction of features can be done and by storing a few descriptors, the remaining invariance can be achieved. Such representations are known as EBG (Elastic Bunch Graph). Elastic Graph Matching is used to find the minimum variance of distance between the facial features. This is done by comparing the EGB to a new image of face. J. Wu and M. Trivedi [53] did a similar work where a discrete pose is assigned to the head by the EGB that is most similar to the new face image. They analyze the Gabor wavelets responses at first and then the refining of pose estimation is done by the analysis of details of geometrical structure by EBG in the final stage.

Tracking methods estimate the movement of the head by finding the relative movement between frames of video. Such systems are highly accurate if the pre-requisite of initial head position is taken care of. This is why it is necessary for a person to keep the front pose in front of the camera for initialization and at the time of reinitializing (that can happen when tracking is lost). S. Ohayon and E. Rivlin [54] proposed a method that uses prior knowledge of 3D face shape. Here a camera pose estimation formulation is used to recover the head pose and the estimation is done by solving the "Perspective n Point" problem in a robust version.

Hybrid methods combine various approaches or systems together like appearance methods and tracking methods for pose estimation. L.P. Morency et al. [55] proposed a method by combining point tracking with automatic geometric method. They estimate the pose by using a linear Gaussian filter whereas registration algorithm is used to recover the changes in pose. More such related work has been done in [56-60].

Other methods include detector array methods, nonlinear regression methods, and manifold embedding methods. Detector Array methods are the ones where a few detectors of head are trained and assigned to a specific pose. Nonlinear Regression tools are used in nonlinear regression methods to functionally map the feature from image to the measurement of a head pose. Continuous variation in head poses are modeled by low dimensional manifolds in Manifold Embedding methods. Here the matching is done after the new image is embedded in such manifolds.

V.ESTIMATION AND TRACKING OF GAZE DIRECTION

Eye tracking is the first step towards the estimation and tracking of gaze. To estimate or track the direction of gaze, iris is to be segmented from the eye that is tracked. Then the location of the iris with respect to the head pose is computed. Head pose plays a vital part in estimation of gaze because of the fact that a person can change the gaze either by moving the eyes or changing the head poses. For example, if a person is looking at the top of the screen while his head pose is up then the location of the iris will possibly be in the center block of a 3x3 grid domain. For the same situation, if the head pose is at the center then the location of iris will be in the top-center block of a 3x3 grid domain. Similar cases appear when the head pose is left and the iris position is in the top-right block or when the head pose is right and the iris position is in the top-left block (see figure 6).

If the gaze is to be stationary at a point then the head pose and eye movement are inversely relative to each other. An eye moves upwards, downwards, left and right relative to the downwards, upwards, right and left motion of the head respectively to maintain the gaze. This also leads to the possibility of the iris position to be in the same block for different head pose and gaze direction. For example, the iris remains in center-center block if both, the head pose and the gaze direction, go from center to upwards. Eye movements can be categorized into saccades or fixations. Saccades can be described as the fast movements of both eyes in the same direction. These movements can be jump-like, gradual and smooth or random. Fixations can be described as the time for which an eye rests at a particular gaze point. This paper covers Dual Purkinje Methods, Visible Spectrum Methods, Appearance Based Estimation Methods and Feature Based Estimation Methods.

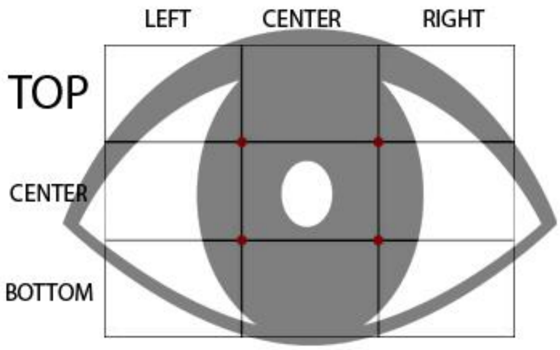

Figure 6: 3x3 Eye Grid Domain.

Dual Purkinje Methods are based on the fact that several glints maybe produced out of a single light source due to the reflections from different layers of the eye. First (reflection from the outer surface of the cornea) and the fourth (reflection from the posterior surface of the lens) Purkinje images are used as a feature to track. George McConkie and Lester Loschky [42] investigated the starting time of visual perception in fixations using dual Purkinje gaze tracking. They used a low-resolution picture at the beginning and changed it back to original after varying intervals. The detection of change starts after 6 msec of the end of the saccade and after the peak, the robust detection takes up to 32 msec.

Visible Spectrum Methods are used as an alternative to the methods used in Infrared spectrum. As IR light is sensitive to the ambient light and hence fails outdoors, visible spectrum methods are better suited there. R. Newman et al. [43] proposed a system that determines the head pose and direction of gaze. The face is tracked in the beginning by 3D Facial Model Acquisition then the pose is estimated by full perspective projection. The gaze direction is then estimated by examining each pupil's location. Hansen and Pece [44] proposed a system for gaze estimation that includes the combination of EM algorithm and particle filtering. Their method is robust to changes in illumination, occlusions and defocusing. However, the system restricts head movements.

Appearance Based Estimation methods use information of image as input instead of explicitly extracting the features. Tan et al. [45] proposed a method using linear interpolation and nearest neighbor in IR spectrum. The algorithm estimates the eye gaze with 0.38 degrees of mean angular error. The accuracy achieved and the usage of the number of calibration points does not seem to correlate. The prior information on the camera parameters and the geometry may be the cause of such variation. Wang et al. [46] proposed a method that uses a fully calibrated camera with 4 calibration points to estimate the direction of gaze. Their principle relies on the fact that iris has an outer boundary in the shape of a circle. Two circles are yielded by the back projections of the elliptical image in 3D space. This eye gaze method is integrated with head pose estimation to serve as an application.

Feature Based Estimation Methods can be categorized into Geometric and Regression Based methods. In feature based approach, the various features of the eye such as eye corners and contours are used for the estimation of gaze. J. Wang and E. Sung [47] proposed an approach where they model the contours of iris as two planar circles and then the estimation of projection is done on a retinal plane. Their gaze estimation is achieved with 0.5 degree error using the ellipse shape of the projection of eyes, known subject distance and anthropometric knowledge. Matsumoto et al. [48] proposed a behavior recognition system for estimation of eye gaze in which the location of the eye corners is determined using a 3D model of the head and a setup of stereo vision. Head pose and a 3D offset vector is used to calculate the eyeball position. Q. Ji and Z. Zhu [49] proposed a method for gaze tracking based on infrared, where no calibration is required. Their technique is non-intrusive and learns based on neural network hence allows free head movements. The only limitation is the IR spectrum itself as it is sensitive to ambient environment.

VI.SUMMARY AND CONCLUSION

The intention of this paper is to give an in-depth review of eye tracking, head pose and gaze estimation. We covered various methods used in eye tracking and had a follow through all the archaic models in the same. We had a good overview of head pose estimation techniques and methods and finally we went through the techniques of gaze estimation. The metrics in this field are not yet standardized, even though the research has been going on since decades. Possibilities of better systems and techniques still stand as the accuracy, robustness and cost areas continue to be challenging.

Category	Sub-category	Description and Reference
Appearance Based	Eye Tracking	[17], [32-35]
	Head Pose Estimation	[50], [51]
	Gaze Estimation	[45], [46]
Feature Based	Eye Tracking	[25-31]
	Gaze Estimation	[47], [48], [49]
Shape Based	Eye Tracking	[16], [24]
Hybrid	Eye Tracking	[18], [19], [36-40]
	Head Pose Estimation	[55-60]
Other	Eye Tracking	[20], [41]

Eye Tracking	Electro Oculography	[1]
	Scleral Search Coils	[2]
	Video Oculography	[3-14], [21-23]
Head Pose Estimation	Geometric Methods	[52]
	Flexible Models	[53]
	Tracking Methods	[54]
Gaze Estimation	Dual Purkinje Methods	[42]
	Visible Spectrum Methods	[43] , [44]

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