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Human Eye Tracking and Related Issues: A Review

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Abstract- Eye tracking refers to the process of tracking the movement of the eye and determining where the user is looking. The aim of this paper is to present a review on various techniques used for eye tracking. There are a number of principles used in measuring eye movements, including measurements of electric and photoelectric signals, tracking a number of visual features in the image of the eye, measuring relative reflection of infra-red (IR) light, and using either mechanical or optical levers or a magnetic field. This paper also includes the factors involved in the selection of a particular eye tracking method. Finally, it includes a light on some of the applications of the eye tracking technique.

Index Terms- Eye Tracking, Electrooculography (EOG), Video-occulography (VOG), InfraRed Occulography (IROG), Scleral Search Coil.

I. INTRODUCTION

The term *eye tracking* as it is used here means the estimation of direction of the user's gaze. In most of the cases the estimation of the gaze direction means the identification of the object upon which the gaze falls [2,6,42].

The history of eye tracking reaches back to the 18th century [6,42]. In 1792, Wells used after images (ghost images) to describe the movements of the eyes [6]. In the 19th century, Javal (1879) and Lamare (1892) obtained audible eye movements using a mechanical coupling of the eyes and the ears with a rubber band. In the year 1901, Dodge and Cline made the first unobtrusive measurements of eye movements (horizontal eye movements only) using a photographic method and light reflections from the eyes [6,8,42].

In 1939, Jung measured vertical and horizontal eye movements simultaneously with electrodes applied at the skin close to the eyes [6]. This method also called ElectroOculoGraphy (EOG) measures the electric fields of the eye-ball which is a dipole [7,21]. The method also gave the first (theoretical) possibility of real-time processing of gaze data by means of analogue electronics.

In the 1980s, mini computers became powerful enough to do real-time eye tracking and this gave the possibility using video-based eye trackers (Video-OculoGraphy) for human computer interaction. From the 1990s up to now, there has been a steady increase in the use of eye trackers. Falling prices for the tracking systems caused wider use typically for marketing research or usability studies. Scientists started to research the possibilities of eye trackers for human computer interaction.

The aim of this paper is to discuss various methods of eye tracking and compare their performance based on certain factors like accuracy, ease to use, cost involved, portability and versatility. Before the detailed discussion of the eye tracking techniques, it becomes necessary to have a look on the anatomy of the eye and various movements involved with the eye.

II. HUMAN EYE ANATOMY AND PHYSIOLOGY

The anatomy of the eye is presented in Figure 1. A hard, transparent layer called the cornea forms the front of the eyeball. Surrounding this is the opaque sclera, inside of which the blood vessels form the choroid. On the front side, under the cornea, the iris extends the choroid. The iris has a round aperture in the middle called pupil. The eyeball is filled by a glasslike humor, the vitreous body. And finally, the inside of the choroid holds the retina[42].

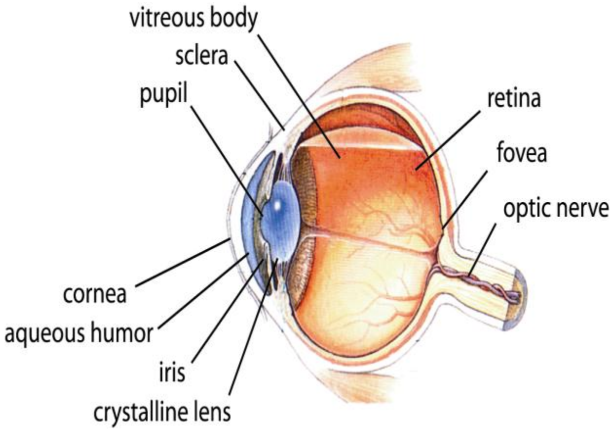


Figure 1: The structure of the human eye [10,12,15,42]

The iris is responsible for regulating the amount of light that is admitted on the retina, and does this by expanding and contracting the pupil. Behind the pupil lies a soft membrane, the crystalline lens, responsible for accommodating and focusing the image on the retina. The retina, in turn, is responsible for transforming the received image or visual stimuli to electric signals, and passing them on via the optic nerve to the visual cortex, located in the occipital lobes of the brain.

The axons of the receptor cells of the retina coil together at a single spot before they exit the back of the eye through an area called the optic disk. Since no receptor cells are located in this area, for each eye, a blind spot exists in the representation of the external world. Because each eye compensates for the blind spot of the opposite eye, we are not usually aware of its presence.

1. *Eye muscles*

The eye is rotated by two pairs of direct muscles and a pair of oblique muscles functioning as antagonist pairs, see Figure 2. The rotations are approximately symmetrical.

The muscles control the six degrees of freedom of the eye presented in Figure 3. The lateral rectus abducts the eye toward the nose and the medial rectus adducts the eye away from the nose. These muscles move the eye in the horizontal plane. The remaining four muscles, the superior and inferior rectus (elevating and depressing the eye) and the superior and inferior oblique (controlling intorsion and extorsion) control the vertical motion of the eye. The optic nerve is encased by the muscles of the eye as it is lead backwards from the eye.

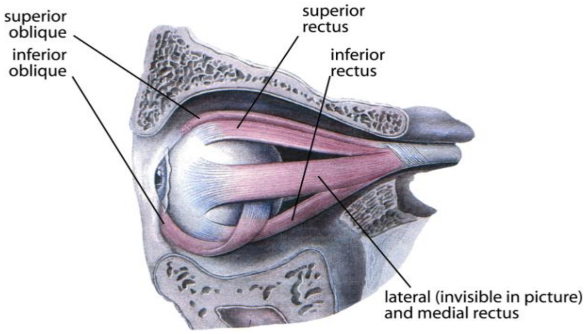


Figure 2: The muscles of the eye [42]

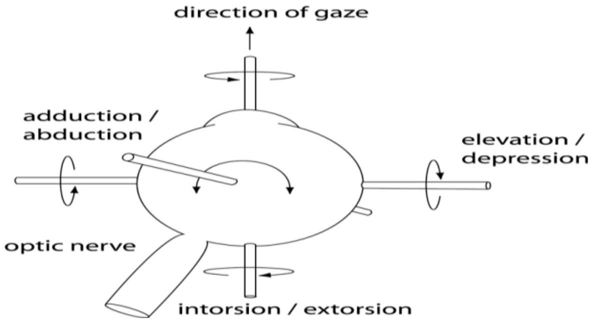


Figure 3: The six degrees of freedom of the eye [42]

2. *Eye Movements*

Eye movements can be broadly categorized into two main categories. Stabilizing movements that try to hold the eye, or rather the image on the retina, and saccadic movements that move the eye around the visual field and bring objects of interest to the area of sharp vision. Stabilizing eye movements include fixations, smooth pursuit movements, and nystagmus. Saccadic eye movements include saccades and vergence movements.

Eye movements are typically measured as degrees of visual angle. One degree of visual angle spans approximately 1 cm on a distance of 57 cm from the viewer's eye [42].

Saccades

Saccades are fast and accurate ballistic eye movements used in repositioning the fovea to a new location in the visual environment. They can reach peak accelerations of 40000 deg/s^2 and a peak velocity of 400-600 deg/s, varying with the amplitude of the saccade. Saccadic eye movements can be executed voluntarily, reflexively as a response to a visual stimulus, and as a corrective movement associated with optokinetic or vestibular movement [8,10,22,33,40,42,49,59].

Fixation

When directing gaze onto an object, the eyes move so that the image of the target object appears on the fovea of the retina. This is the high acuity area of vision, and it covers approximately one degree of visual angle. During fixations, the image of an object of interest is held approximately stable on the retina. Fixations generally last between 100-1000 ms, with the majority being between 200-500 ms, depending mainly on the quality of information being processed and current cognitive load [22,40,42,49,59].

Miniature eye movements

Miniature eye movements are movements occurring during a fixation, namely tremor, drift and microsaccades. Tremor is a high-frequency oscillatory component ranging from 30 to 100Hz, and drift is a slow random motion of the eye away from a fixation point. Velocities of these types of movements are only a few arc min/s, and they have been interpreted as noise in the oculomotor system. Microsaccades are eye movements that are more or less spatially random, varying over 1 to 2 minutes of arc in amplitude [42].

Smooth pursuit

Smooth pursuit movements are involved in the visual tracking of a slowly moving target. Smooth pursuit eye movements follow a slowly moving target, keeping the image of the object on the retina more or less stable. Smooth pursuit movements are capable of tracking an object moving 5-30 deg/s. Above this velocity, saccadic movements compensate for the lag, "catching up" the target. Smooth pursuit movements cannot be induced voluntarily, that is, without a slowly moving target to follow [10,42].

Vergence movements

Vergence movements rotate the eyes inwards and outwards, so that they fixate roughly the same point in space regardless of the distance. Vergence movements are slow, 10 °/s, disconjugate movements, i.e. the eyes move in opposite directions relative to one another. The eyes rotate toward each other in order to focus on near targets, and in the opposite direction, or more parallel, for far targets. [10,42]

Nystagmus

Physiological nystagmus can occur in response to motions of the head (vestibular nystagmus), or patterns in the visual field (optokinetic nystagmus). These are a pattern of smooth motion to track an object (as the head motion causes it to move across the visual field), followed by a rapid motion in the opposite direction to select another object. [10,42]

Torsional movements

Torsional movements are rotations of the eye about the line of gaze, and are generally limited to angles of less than 10 deg.

The rolling motions may be stimulated by rotational optokinetic nystagmus or by vestibular responses. The torsional component of vestibular nystagmus or compensatory eye movement in response to head rotation, is similar to the horizontal and vertical vestibular nystagmus. That is, they respond to the head tilting sideways, compensating for the rotation of the visual field. [42]

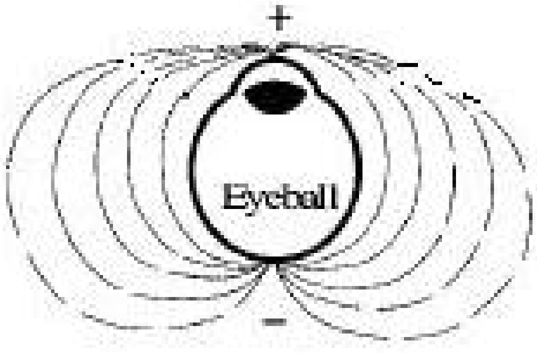


Figure 4: Flow of the micro-currents from the positive pole to the negative pole [21]

III. ELECTRICAL PROPERTIES OF THE EYE

A human eyeball can be assumable as a spherical battery that the centre of cornea is positive and the retina is negative [21]. It is possible to regard that the battery like this is embedded in an eye socket and rotates around the torsional centre of eye. Consequently, the micro-currents flow radially from the positive pole to the negative pole of the battery through the conductive tissue in the orbit as shown in Figure 4. These currents generate the standing potentials around the eye.

IV. EYE TRACKING METHODS

The eye tracking methods can be divided into two groups: those measuring angular eye position relative to the head, including electro-oculography, IR-reflection oculography, and head mounted video systems, and those measuring eye position relative to the surroundings, including table-top video systems and the magnetic scleral search coil method [42]. General classification of the eye tracking methods is as follows:

1. Scleral search coil method [2,6]
2. Infrared occulography (IROG) [4,6,35]
3. Electro-occulography (EOG) [2,6,7,8,10,27,34, 4,48]
4. Video Occulography (VOG) [2,6,9,11,12,13,25, 38,53]

1. Scleral Search Coil Method

When a coil of wire moves in a magnetic field, the field induces a voltage in the coil. If the coil is attached to the eye, then a signal of eye position will be produced. In order to measure human eye movements, small coils of wire are embedded in a modified contact lens or anulus. This is inserted into the eye after local anaesthetic has been introduced. A wire from the coil leaves the eye at the temporal canthus. The field is generated by two field coils placed either side of the head. This allows horizontal eye movement to be recorded. If it is necessary to also monitor vertical eye movements, then a second set of field coils, usually set orthogonally to the first set, is used. The two signals (one for horizontal, one for vertical eye movement) generated in the eye coil can then be disentangled using appropriate electronics.

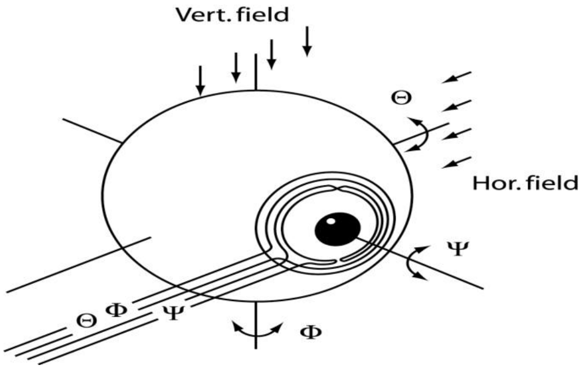


Figure 5: Scleral search coil method: Principle of operation

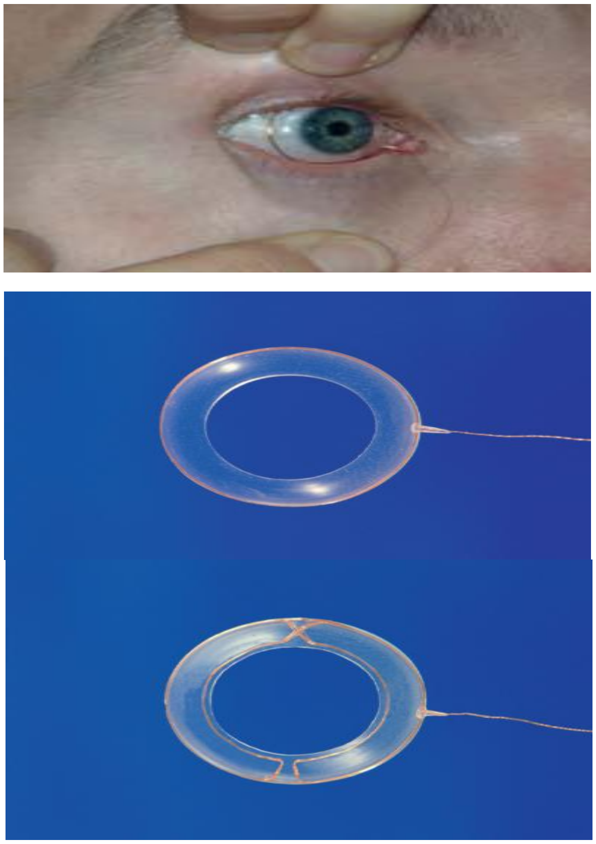


Figure 6: Search coil places in the human eye, 2D search coil, and 3D search coil [6].

The big advantage of such a method is the high accuracy and the nearly unlimited resolution in time. For this reason, medical and psychological research uses this method. If the eye coil is of an appropriate design, then torsional movements can also be recorded. This method has a very high temporal and spatial resolution allowing even the small types of eye movements (eg microsaccades) to be studied. But the problem with this method is that, the thin wire connecting the coil with the measuring device is not comfortable for the subject. It is an invasive method, requiring something to be placed into the eye. This method is rarely used clinically, but is an invaluable research tool.

2. *Infrared OcculoGraphy (IROG)*

It is based on the principal that, if a fixed light source is directed at the eye, the amount of light reflected back to a fixed detector will vary with the eye's position. This method utilizes measuring the diffused reflection of infra-red light from the frontal surface of the eyeball. A number of IR light sources are used for illumination, and photo detectors aimed at receiving the reflected light for picking up the signal. The systems track the limbus (the boundary between sclera and iris), or the pupil-iris-boundary, to measure relative eye rotation.

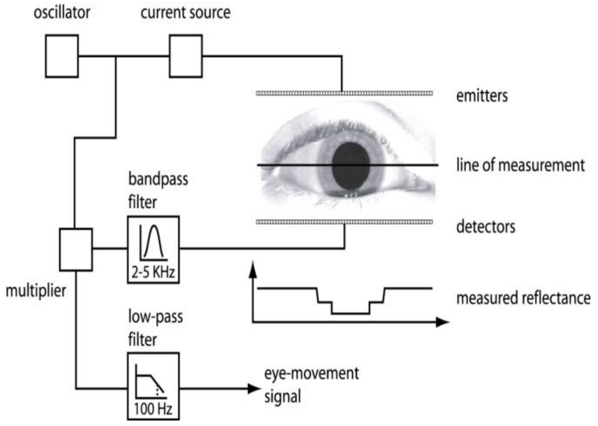


Figure 8: Eye movement measurement using IROG [42]

Infra-red light is used as this is "invisible" to the eye, and doesn't serve as a distraction to the subject. As infra-red detectors are not influenced to any great extent by other light sources, the ambient lighting level does not affect measurements. Spatial resolution (the size of the smallest movement that can reliably be detected) is good for this technique, it is of the order of 0.1° , and temporal resolutions of 1ms can be achieved. The detection works well for measuring horizontal eye movements over a fairly large range between ±15° and ±40° depending on system design. For vertical movements, the signal is much worse if not non-existent, due to the fact that the eyelids occlude the iris-sclera boundary.

3. *Electrooculography (EOG)*

The Electro-Oculography (EOG) method was introduced by Fenn and Hursh in 1934 [42]. It is a method for sensing eye movement and is based on recording the standing corneal retinal potential arising from hyperpolarizations and depolarizations existing between the cornea and the retina; this is commonly known as an electrooculogram (EOG) [7,21]. As discussed earlier, a human eyeball can be assumable as a spherical battery that the centre of cornea is positive and the retina is negative. Consequently, the micro-currents flow radially from the positive pole to the negative pole of the battery through the conductive tissue in the orbit as shown in Fig. 4. These currents generate the standing potentials around the eye. The standing potentials in the eye can thus be estimated by measuring the voltage induced across a system of electrodes placed around the eyes as the eye-gaze changes, thus obtaining the EOG (measurement of the electric signal of the ocular dipole). Sometimes, the EOG is also known as the electronystagmographic potential (ENG) [21].

The EOG is captured by five electrodes placed around the eye as shown in Figure 9. The EOG signals are obtained by placing two electrodes to the right and left of the outer canthi (D-E) to detect horizontal movement and another pair above and below the eye (B-C) to detect vertical movement [50]. A reference electrode is placed on the forehead (A). The EOG changes approximately 14-20 microvolts for each degree of eye movement [8,10,27,33,50,59]. The magnitude of EOG signal varies from 50-3500 microvolts [8,22,50,52,59]. The EOG signal is a result of a number of factors, including eyeball rotation and movement, eyelid movement, different sources of artifact such as EEG, electrode placement, head movements etc. It is therefore necessary to eliminate the shifting resting potential (mean value) because this value changes. To avoid this problem an ac high-gain differential amplifier (1000-5000) is used [8,27] and CMRR 70-90 dB [7,10,40], together with a high pass filter with cutoff frequency at 0.05 Hz and a low pass filter with cutoff frequency at 35 Hz [8,23]. A sampling rate of 176 Hz is sufficient [7,10,34]. Figure 10 shows schematic for EOG recording for one channel and figure 11 indicates simultaneous recording of vertical and horizontal eye movements. Simple Ag-AgCl electrodes are used in this recording. Silicon-rubber electrodes of impedance below 10 KΩ can also be used for measurement of EOG [10,32]. Due to the low impedance range starting from 40 -200 Ω, the silicon-rubber conducting electrode is more suitable to sense the very low amplitude bio- signals as compared to other types of electrodes such as Ag-AgCl electrodes. Additionally, an electrolytic gel based on sodium chloride is applied to the skin since the upper layers of the skin are poor conductors of electricity. A gel concentration in the order of 0.1 M (molar concentration) results in a good conductivity and low junction potential without causing skin irritation [28]. An emery paper can be used to remove poorly conducting dead skin layer before the placement of the electrodes [37].The detailed circuit diagram of the acquisition system is given in [7,10]. To make the system portable and more user friendly a wearable EOG goggles has been designed by [22,36,59]. When the gaze vector is within the angular range of ±50° horizontally and ±30° vertically, the recorded EOG signals are almost proportional to the eye gaze displacement [21,40,41,48,51].

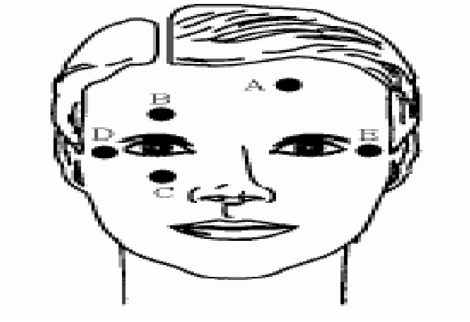


Figure 9: Placement of electrodes for EOG recording [6,7,8,10,21,22,32,48,50,52]

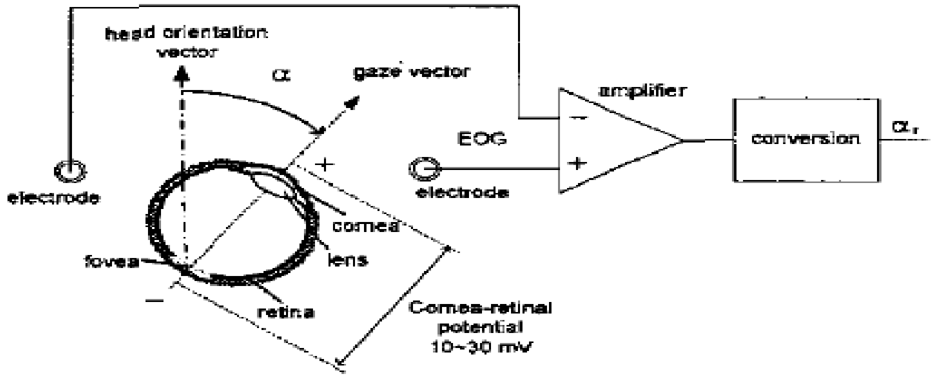


Figure 10: Electrical activity recorded on the facial skin reflects eye movements [21,40]

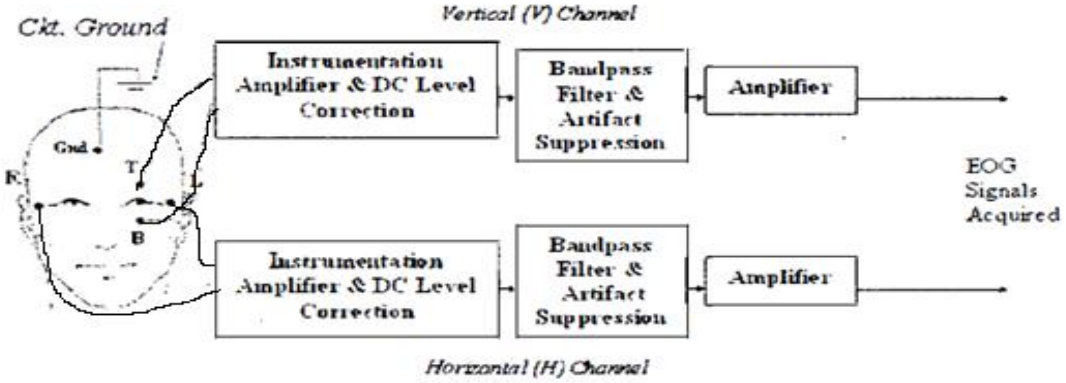


Figure 11: Simultaneous recording of horizontal and vertical EOG [21,37]

4. Video-occulography (VOG)

The task of a video-based eye tracker is to estimate the direction of gaze from the pictures delivered by a video camera. This method can perform eye tracking in ways: measuring angular eye position relative to the head (head mounted video systems), and measuring eye position relative to the surroundings (remote systems) [12,42]. As a general rule, the methods measuring eye position relative to the head are more accurate, and intended for the study of oculomotor dynamics, whereas the methods measuring eye position relative to the surrounding environment are used for gaze point measurements on a user interface. Whatever is the type of system either head mounted or table-top, the steps involved in eye tracking are the same. These steps are illustrated in Figure 12.

Image/video acquisition

The first step of video-occulography is the image/video acquisition. This can be done by using a single camera/webcam/IR camera. Sometimes multiple cameras may require for head tracking. It depends upon the technique used to localize face/eyes in the image. The camera, to be used for acquisition, is attached to the PC through USB and its deriver software is installed. Then the camera is triggered by hardware/software means for the acquisition of video. This can be performed in MATLAB. For this purpose, we can use the specifications of the camera mentioned in Table 1.

Face localization

Given an arbitrary image, the goal of *face detection* is to determine whether or not there are any faces in the image and, if present return the image location and extent of each face. *Face localisation* aims to determine the image position of a single face in an image [47]. This is a simplified detection problem with the assumption that there is only one face in the image. There are so many methods reported in the literature for face detection viz Face localization based on skin colour [5,16,17,20,24,29,39,43,45,46,57], Knowledge based method [47], Facial feature based method [47], Texture based face localization [47], Face localization using template matching [47], Appearance based method [47], Face localization using Haar like features [13,14].

The selection of a particular method depends upon the environmental conditions, accuracy required, processing speed, complexity etc. Although any method can be used for face detection, but skin-colour based method is very fast and simple to use. It has 100% detection rate when the image contains only one face and controlled lighting conditions.

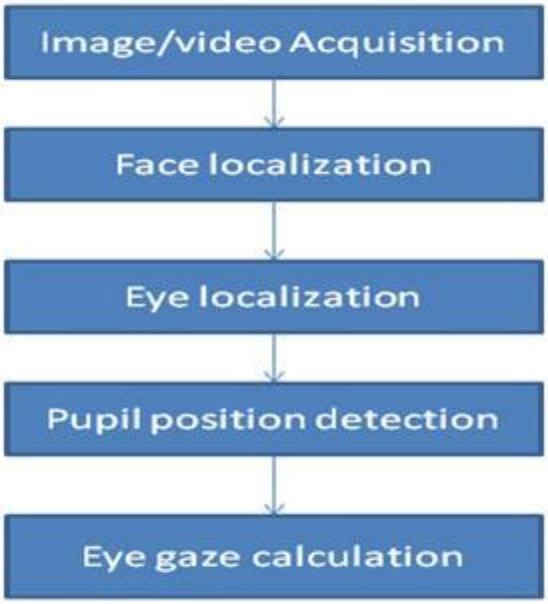
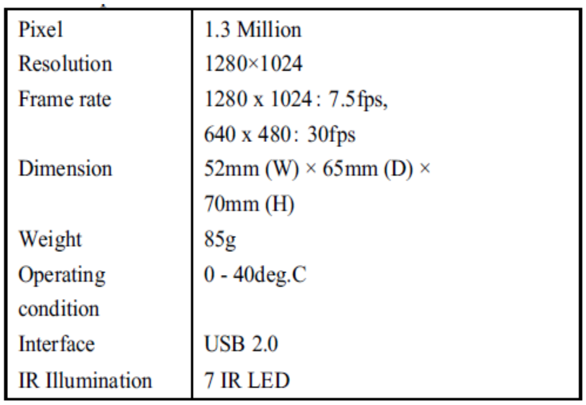


Figure 12: The process of video-occulography



Pixel	1.3 Million
Resolution	1280×1024
Frame rate	1280 x 1024 : 7.5fps, 640 x 480: 30fps
Dimension	52mm (W) × 65mm (D) × 70mm (H)
Weight	85g
Operating condition	0 - 40deg.C
Interface	USB 2.0
IR Illumination	7 IR LED

Table 1: Specifications of IR Camera [2,4]

Eye localization

Obtaining eye images is the next step of eye tracking. Eye images are generally extracted from face images. According to [47], there are two major approaches for eye detection. The first approach, i.e. the *holistic* approach, attempts to locate the eyes using global representations. The second approach, i.e. the *abstractive* approach, extracts and measures discrete local features, and then employs standard pattern recognition techniques to locate the eyes using these features. Any one of the following techniques can be used for eye localization:Gray projection model [9,19,24], Template matching [18], Kallman filtering [5], Geometric properties of the eyes [20,24,25], Projection function [15], Hybrid method (combination of two appropriate methods) [3,17], Corner detection method[56].

Eye pupil position detection

The following methods have been reported in the literature for eye pupil position detection: Cumulative distribution function (CDF) algorithm [1], Projection function (PF) algorithm [13,15,44], Edge analysis [1], Integral projection and Guassian model [13,28], Iris shape feature/template matching [2,14], Circular Hough transform [15], Harris corner detector [12,26] ,Isophotes curvature estimation [58].

Further, in video based eye tracking we can also use Limbus Tracking Method, Purkinje method or Fundus Haploscope [2].

Figure 13: VOG based remote eye tracker

V. APPLICATIONS OF EYE TRACKING

The first use of eye trackers was done in 1947 for the American air force to find out the best positions for the controls in an aircraft cockpit [6]. When offering a new device to somebody whose eyes are tracked, it is easy to see where the gaze moves in the expectation to find the control for solving the given task. With the advancements in the field of eye tracking technology, it becomes possible to use eye based interfaces in many fields like Gaze communication and human computer interaction (HCI) [2,10,23,26,30,31,34], Video Games, Rehabilitation [50,52], Driving simulation [13], Fatigue detection, Cognitive science, Marketing research and advertizing testing, Usability research, Medical research, Gaze interaction and car assistant systems, eye typing [2,10,49] and many more.

An eye-gaze interface seems to be a promising candidate for a new interface technique, which may be more convenient than the ones we use. Traditionally, disabled people who cannot move anything except their eyes use eye gaze interaction. These systems are designed to direct the computer solely by the eyes. Such systems work well and are a great help for people who need them, but for others they are cumbersome and less efficient than keyboard and mouse. But now days, due to advancements in the design of eye tracking systems and high processing speed, it becomes possible to use tracking based interaction by a normal person. Eye tracking based systems become more popular day by day because of advantages like Ease of use, Interaction speed-up, Maintenance free, Hygienic interface, Remote control, Safer interaction, More information on the user's activities etc. Eye-tracking interfaces could speed up the interaction, as the eyes are quick. Video-based eye tracking works contact free which means that no maintenance is necessary. In environments with high hygienic demands, like an operation room for surgery, an eye-gaze interface would be useful because it allows interacting without anything to touch.

VI. DISCUSSION

The purpose of this paper is to promote eye based human computer interaction. Different methods of eye tracking have been reviewed in this paper. The choice of an eye tracking method in any study should be based on the particular demands of the application. None of the current methods is the universal best for all applications. The deciding factors in choosing equipment can be reduced to temporal and spatial accuracy, suitability for operational conditions, invasiveness, and cost. The temporal and spatial accuracy should be considered in relation to the objectives of the study. Higher temporal accuracy means massive data sets, whereas high spatial accuracy tends to require rigorous stabilization of the subject's head, or the use of more invasive methods [42]. Operational conditions restrict the choice of a system in freedom of movement for the subject, ambient lighting requirements, and the requirements imposed by special environments, such as a functional magnetic resonance imaging (fMRI) laboratory used in brain imaging.

Scleral coil method can be used for measurement of torsional movements with some modifications in the coil design. This method has very high accuracy and good resolution (can be used to measure micosaccades). Since this method is an invasive method, so its application is limited to medical and psychological research. From comfort point of view this method is not preferred.

Infrared occulography (IROG) method has good resolution and an eye movement of 0.1 degrees can be measured with this method. As infra-red detectors are not influenced to any great extent by other light sources, the ambient lighting level does not affect measurements. It can be used for both vertical as well as horizontal movement measurements. But this method suffers from the problem that eye movement detection using IROG is difficult to use over a long period because the eyes tend to become dry and fatigued [21].

Electrooculography (EOG) is also a good choice to be used in the human computer interaction applications. This signal has good stability as compared to other biological signals. Cost of this method is quite low and has good accuracy. It can measure eye movements in the range of 1 degrees with good linearity. It can be designed by using simple hardware and ECG electrodes. But the long term use of surface electrodes may cause skin problems and the subject feels uncomfortable with this method. Also, the signal is seldom deterministic, even for the same person in different experiments. It is result of number of factors, including eyeball rotation and movement, eyelid movement, the EMG signal produced by the muscles of the eye, eye blinks electrode placement, head movements, influence luminance etc [37].

It is well established that during an eye blink, the eyeballs shoot upwards and this should therefore result in some potential difference being generated across the V channel electrodes [37]. Therefore, V channel signal is processed to differentiate between sudden movement of the eyeballs from the centre towards the top position and normal gazing towards top direction, which is generally a slower action. Extensive analysis of V and H channel EOG signals has shown that the reliability of the V channel signal is inferior to that of the H channel, owing to its sensitivity to eye blinks, neck motion artefact and offset drift.

The merits of EOG based system are: (i) EOG signals can be acquired using cheap and simple electrodes. (ii) EOG signal can cover wide range of view. Its ranges are ±25° in vertical and ±35° in horizontal. (iii) EOG signals are very fast. Thus real time implementation is possible. (iv) The system is operated by human's eye signal command, which contains human decision i.e. intelligence [51]. Electrooculographic (EOG) method presents a good face access, good accuracy and resolution, great range of eye displacements, work in real time and is cheap [50]. One of the commercial eye trackers based upon EOG is BIOPAC MP 45/100 system.

One more alternative for eye tracking is the use of Video-occulography. This is a non-invasive method and requires a camera, a computer and software for eye position calculation. This method is easy to use from user point of view and has good accuracy. The performance of this method depends upon the quality of the camera and the response time of the software used. If we see the current scenario of the market then the cost of this system is quite high and efforts are being made to make this system economical. The future of human computer interaction research is based upon this method. If a person presents a good control on his/her head movements it is more comfortable to use video-oculography (VOG). Examples of commercial eye trackers are: ERICA and Tobii 1750 Eye Trackers.

Human computer interaction using eye tracking is not as simple as we think. As we know the eyes perform unconscious movements and this might disturb their use as computer input. It is not clear to which degree people are able to control the movement of their eyes. The primary function of the eyes is to enable vision. Using the eyes for computer input might result in conflicts. The well-known conflict is the Midas Touch problem [6,54] – for the eye-gaze interface it is difficult to decide whether our gaze is on an object just for inspection or for invoking an action. From other input devices we know that extensive use of particular muscles or muscle groups can cause physical problems called RSI (repetitive strain injury). There are fears that this might happen to the eye muscles too. The person's condition has to be considered carefully while designing eye tracking system for him/her.

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