Chapter 5
Eye Tracking Techniques

The measurement device most often used for measuring eye movements is commonly known as an eye tracker. In general, there are two types of eye movement monitoring techniques: those that measure the position of the eye relative to the head, and those that measure the orientation of the eye in space, or the "point of regard (POR)" (Young and Sheena 1975). The latter measurement is typically used when the concern is the identification of elements in a visual scene, e.g., in (graphical) interactive applications. Possibly the most widely applied apparatus for measurement of the POR is the video-based corneal reflection eye tracker. In this chapter, most of the popular eye movement measurement techniques are briefly discussed first before covering video-based trackers in greater detail.

There are four broad categories of eye movement measurement methodologies involving the use or measurement of: Electro-OculoGraphy (EOG), scleral contact lens/search coil, Photo-OculoGraphy (POG) or Video-OculoGraphy (VOG), and video-based combined pupil and corneal reflection.

Electro-oculography relies on (d.c. signal) recordings of the electric potential differences of the skin surrounding the ocular cavity. During the mid-1970s, this technique was the most widely applied eye movement method (Young and Sheena 1975). Today, possibly the most widely applied eye movement technique, primarily used for point of regard measurements, is the method based on corneal reflection.

The first method for objective eye measurements using corneal reflection was reported in 1901 (Robinson 1968). To improve accuracy, techniques using a contact lens were developed in the 1950s. Devices attached to the contact lens ranged from small mirrors to coils of wire. Measurement devices relying on physical contact with the eyeball generally provide very sensitive measurements. The obvious drawback of these devices is their invasive requirement of wearing the contact lens. So-called non-invasive (sometimes called remote) eye trackers typically rely on the measurement of visible features of the eye, e.g., the pupil, iris–sclera boundary, or a corneal reflection of a closely positioned, directed light source. These techniques often involve

A.T. Duchowski, *Eye Tracking Methodology*, DOI 10.1007/978-3-319-57883-5_5

either manual or automatic (computer-based) analysis of video recordings of the movements of the eyes, either off-line or in real-time. The availability of fast image processing hardware has facilitated the development of real-time video-based point of regard turnkey systems.

5.1 Electro-OculoGraphy (EOG)

Electro-oculography, the most widely applied eye movement recording method some 40 years ago (and still used today), relies on measurement of the skin's electric potential differences, of electrodes placed around the eye. A picture of a subject wearing the EOG apparatus is shown in Fig. 5.1. The recorded potentials are in the range 15–200 μV, with nominal sensitivities of order of 20 μV/deg of eye movement. This technique measures eye movements relative to head position, and so is not generally suitable for point of regard measurements unless head position is also measured (e.g., using a head tracker).

Fig. 5.1 Example of electro-oculography (EOG) eye movement measurement. Courtesy of Metro-Vision, Pérenchies, France (http://www.metrovision.fr). Reproduced with permission

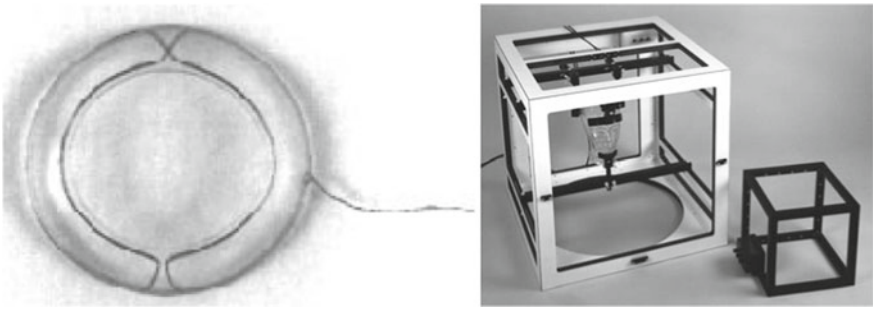


Fig. 5.2 Example of search coil embedded in contact lens and electromagnetic field frames for search coil eye movement measurement. Courtesy of Skalar Medical, Delft, The Netherlands (http://www.skalar.nl). Reproduced with permission

5.2 Scleral Contact Lens/Search Coil

One of the most precise eye movement measurement methods involves attaching a mechanical or optical reference object mounted on a contact lens which is then worn directly on the eye. Such early recordings (ca. 1898; Young and Sheena 1975) used a plaster of paris ring attached directly to the cornea and through mechanical linkages to recording pens. This technique evolved to the use of a modern contact lens to which a mounting stalk is attached. The contact lens is necessarily large, extending over the cornea and sclera (the lens is subject to slippage if the lens only covers the cornea). Various mechanical or optical devices have been placed on the stalk attached to the lens: reflecting phosphors, line diagrams, and wire coils have been the most popular implements in magneto-optical configurations. The principle method employs a wire coil, which is then measured moving through an electromagnetic field.[1] A picture of the search coil embedded in a scleral contact lens and the electromagnetic field frame are shown in Fig. 5.2. The manner of insertion of the contact lens is shown in Fig. 5.3. Although the scleral search coil is the most precise eye movement measurement method (accurate to about 5–10 arc-seconds over a limited range of about 5°; Young and Sheena 1975), it is also the most intrusive method. Insertion of the lens requires care and practice. Wearing of the lens causes discomfort. This method also measures eye position relative to the head, and is not generally suitable for point of regard measurement.

[1]This is similar in principle to magnetic position/orientation trackers often employed in virtual reality applications; e.g., Ascension's Flock Of Birds (FOB) uses this type of method for tracking the position/orientation of the head. See Chap. 7.

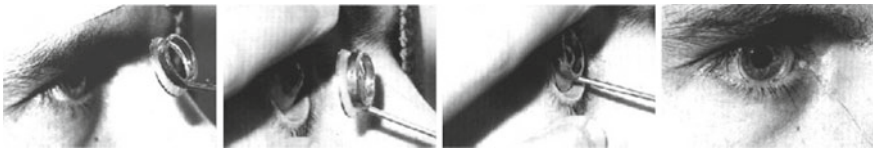


Fig. 5.3 Example of scleral suction ring insertion for search coil eye movement measurement. Courtesy of Skalar Medical, Delft, The Netherlands (http://www.skalar.nl). Reproduced with permission

5.3 Photo-OculoGraphy (POG) or Video-OculoGraphy (VOG)

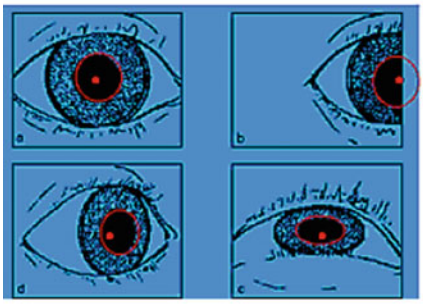
This category groups together a wide variety of eye movement recording techniques involving the measurement of distinguishable features of the eyes under rotation/translation, e.g., the apparent shape of the pupil, the position of the limbus (the iris-sclera boundary), and corneal reflections of a closely situated directed light source (often infra-red). Although different in approach, these techniques are grouped here because they often do not provide point of regard measurement. Examples of apparatus and recorded images of the eye used in photo- or video-oculography and/or limbus tracking are shown in Fig. 5.4. Measurement of ocular features provided by these measurement techniques may or may not be made automatically, and may involve visual inspection of recorded eye movements (typically recorded on videotape). Visual assessment performed manually (e.g., stepping through a videotape frame-by-frame), can be extremely tedious and prone to error, and limited to the temporal sampling rate of the video device.

Automatic limbus tracking often involves the use of photodiodes mounted on spectacle frames (see Fig. 5.4b, c), and almost always involves the use of invisible (usually infra-red) illumination (see Fig. 5.4d). Several of these methods require the head to be fixed, e.g., either by using a head/chin rest or a bite bar (Young and Sheena 1975).

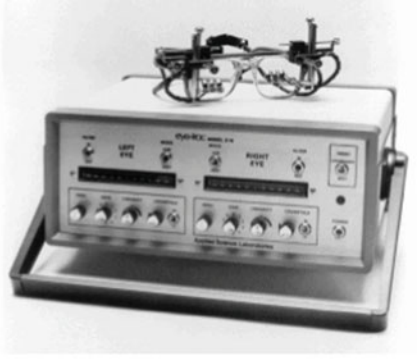
5.4 Video-Based Combined Pupil/Corneal Reflection

Although the above techniques are in general suitable for eye movement measurements, they do not often provide point of regard measurement. To provide this measurement, either the head must be fixed so that the eye's position relative to the head and point of regard coincide, or multiple ocular features must be measured in order to disambiguate head movement from eye rotation. Two such features are the corneal reflection (of a light source, usually infra-red) and the pupil center (see Fig. 5.4d).

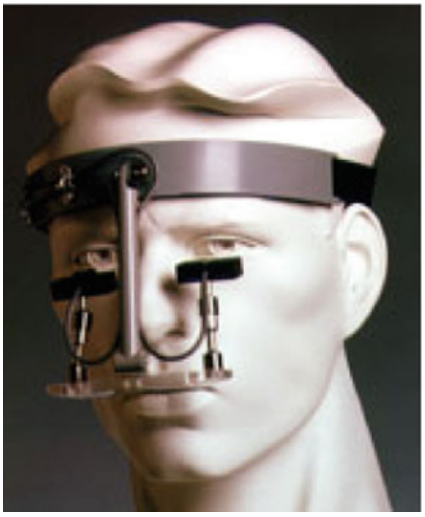
Video-based trackers utilize relatively inexpensive cameras and image processing hardware to compute the point of regard in real-time. The apparatus may be



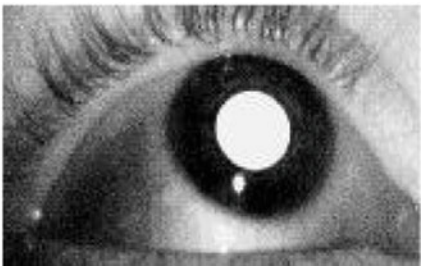
(a) Example of apparent pupil size. Courtesy of MetroVision, Pérenchies, France <http://www.metrovision.fr>. Reproduced with permission.



(b) Example of infra-red limbus tracker apparatus. Courtesy of Applied Science Laboratories (ASL), Bedford, MA <http://www.a-s-l.com>. Reproduced with permission.



(c) Another example of infra-red limbus tracker apparatus, as worn by subject. Courtesy of Microguide, Downers Grove, IL <http://www.eyemove.com>. Reproduced with permission.



(d) Example of "bright pupil" (and corneal reflection) illuminated by infra-red light. Courtesy of LC Technologies, Fairfax, VA <http://www.eyegaze.com>. Reproduced with permission.

Fig. 5.4 Examples of pupil, limbus, and corneal infra-red (IR) reflection eye movement measurements

(a) Operator. (b) Subject.

Fig. 5.5 Example of (an old) table-mounted video-based eye tracker. Modern eye trackers of the twenty first century are small, thin fixtures that mount below the monitor (they may even be built-in to the monitor). Notice in the dated picture above the size of the television set

Fig. 5.6 Example of head-mounted video-based eye tracker. Courtesy of IOTA AB, EyeTrace Systems, Sundsvall Business & Tech. Center, Sundsvall, Sweden (http://www.iota.se). Reproduced with permission

table-mounted, as shown in Fig. 5.5 or worn on the head, as shown in Fig. 5.6. The optics of both table-mounted or head-mounted systems are essentially identical, with the exception of size. These devices, which are becoming increasingly available, are most suitable for use in interactive systems.

The corneal reflection of the light source (typically infra-red) is measured relative to the location of the pupil center. Corneal reflections are known as the Purkinje reflections, or Purkinje images (Crane 1994). Due to the construction of the eye, four Purkinje reflections are formed, as shown in Fig. 5.7. Video-based eye trackers typically locate the first Purkinje image. With appropriate calibration procedures, these eye trackers are capable of measuring a viewer's point of regard on a suitably positioned (perpendicularly planar) surface on which calibration points are displayed.

Two points of reference on the eye are needed to separate eye movements from head movements. The positional difference between the pupil center and corneal

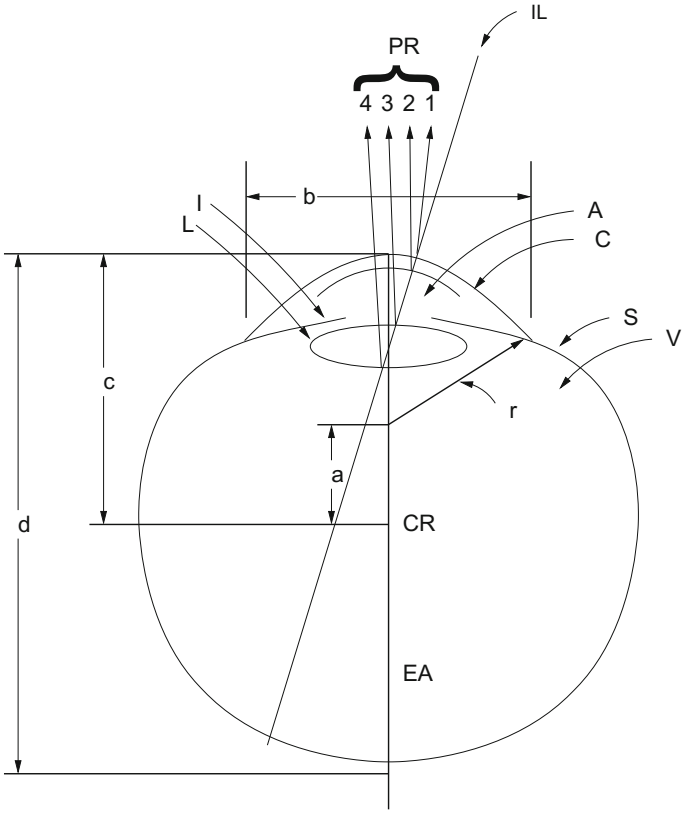


Fig. 5.7 Purkinje images. Reprinted in adapted form from Crane (1994) courtesy of Marcel Dekker, Inc. ©1994

reflection changes with pure eye rotation, but remains relatively constant with minor head movements. Approximate relative positions of pupil and first Purkinje reflections are graphically shown in Fig. 5.8, as the left eye rotates to fixate nine correspondingly placed calibration points. The Purkinje reflection is shown as a small white circle in close proximity to the pupil, represented by a black circle. Because the infra-red light source is usually placed at some fixed position relative to the eye, the Purkinje image is relatively stable whereas the eyeball, and hence the pupil, rotates in its orbit. So-called generation-V eye trackers also measure the fourth Purkinje image (Crane and Steele 1985). By measuring the first and fourth Purkinje reflections, these dual-Purkinje image (DPI) eye trackers separate translational and rotational eye movements. Both reflections move together through exactly the same distance upon eye translation but the images move through different distances (thus changing their separation) upon eye rotation. This device is shown in Fig. 5.9. Unfortunately, although the DPI eye tracker is quite precise, head stabilization may be required.

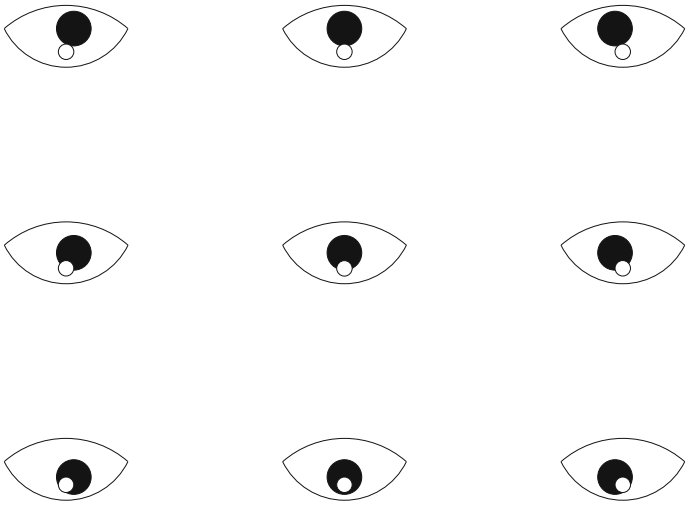


Fig. 5.8 Relative positions of pupil and first Purkinje images as seen by the eye tracker's camera

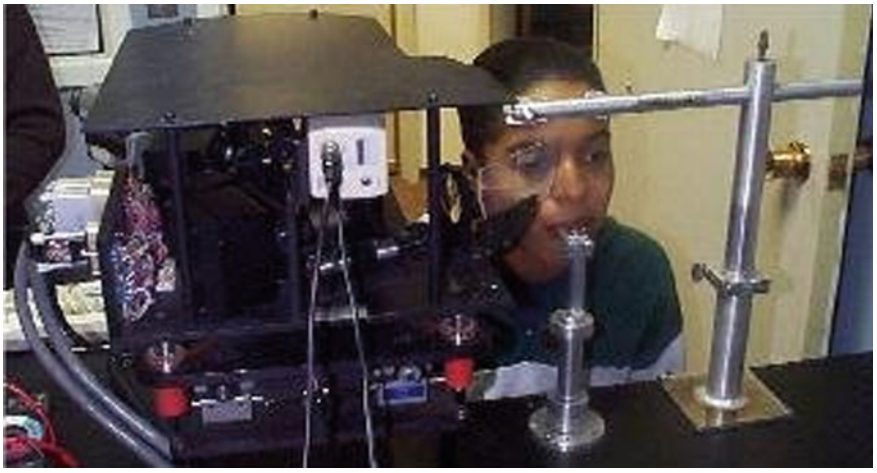


Fig. 5.9 Dual-Purkinje eye tracker. Courtesy of Fourward Optical Technologies, Buena Vista, VA (http://www.fourward.com). Reproduced with permission

5.5 Classifying Eye Trackers in "Mocap" Terminology

For readers familiar with motion capture ("mocap") techniques used in the special effects film industry, it is worthwhile to compare the various eye tracking methodologies with traditional mocap devices. Similarities between the two applications are intuitive and this is not surprising because the objective of both is recording the motion of objects in space. In eye tracking, the object measured is the eye, whereas

in mocap, it is (usually) the joints of the body. Eye trackers can be grouped using the same classification employed to describe motion capture devices.

EOG is essentially an electromechanical device. In mocap applications, sensors may be placed on the skin or joints. In eye tracking, sensors are placed on the skin around the eye cavity. Eye trackers using a contact lens are effectively electromagnetic trackers. The metallic stalk that is fixed to the contact lens is similar to the orthogonal coils of wire found in electromagnetic sensors used to obtain the position and orientation of limbs and head in virtual reality. Photo-oculography and video-oculography eye trackers are similar to the widely used optical motion capture devices in special effects film, video, and game production. In both cases a camera is used to record raw motion, which is then processed by (usually) digital means to calculate the motion path of the object being tracked. Finally, video-based corneal reflection eye trackers are similar to optical motion capture devices that use reflective markers (worn by the actors). In both cases, an infra-red light source is usually used, for the reason that it is invisible to the human eye, and hence nondistracting.

For a good introduction to motion capture for computer animation, as used in special effects film, video, and game production, see Menache (2000). Menache's book does a good job of describing motion capture techniques, although it is primarily aimed at practitioners in the field of special effects and animation production. Still, the description of mocap techniques, even at a comparatively large scale (i.e., capturing human motion vs. motion of the eye), provides a good classification scheme for eye tracking techniques.

5.6 Summary and Further Reading

For a short review of early eye tracking methods, see Robinson (1968, II). For another relatively more recent survey of eye tracking techniques, see Young and Sheena (1975). Although Young and Sheena's survey article is somewhat dated by today's standards, it is an excellent introductory article on eye movement recording techniques, and is still widely referenced. An up-to-date survey of eye tracking devices does not appear to be available, although the number of (video-based) eye tracking companies seems to be growing. Instead, one of the best comprehensive lists of eye tracking manufacturers is available on the Internet, the Eye Movement Equipment Database (EMED; see http://ibs.derby.ac.uk/emed/), initially setup by David Wooding of the Institute of Behavioural Sciences, University of Derby, United Kingdom.