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Survey of eye movement recording methods

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This paper reviews most of the known techniques for measuring eye movements, explaining their principle of operation and their primary advantages and disadvantages. The five sections of the paper cover the following topics: (1) types of eye movement, (2) characteristics of the eye which lend themselves to measurement and the principal approaches to the measurement of eye movement, (3) practical methods of measurement with especial attention to the new techniques, (4) general considerations guiding a selection of method, and (5) summarizing of the major findings in a concise table.

TYPES OF EYE MOVEMENT[1]

For any application of eye movement instrumentation, the kinds of eye movements to be observed must be clearly understood so that the instrument specifications may be properly assigned. The following list summarizes the types of known eye movements. Eye movements are considered here as rotations about a horizontal axis, an (initially vertical) axis which rotates with the globe about the horizontal, and a torsion axis along the angle of gaze. The eye does not rotate about a fixed center, but this is not of practical importance for most measurement applications (Park & Park, 1933). Several types of horizontal eye movements are illustrated in Figure 1.

Saccadic eye movements are the rapid conjugate movements by which we change fixation from one point to another voluntarily. They include the "jump and rest" fixation movements observed in scanning a visual scene or reading. They are characterized by very high initial acceleration and final deceleration (up to 40,000 deg/sec^2) and a peak velocity during the motion which varies with the amplitude of the saccade and may be as high as 400 to 600 deg/sec. The duration of a saccadic eye movement also varies with its magnitude from 30 to 120 msec (Mackensen, 1958). Saccadic eye movements generally observed in searching are of the range of 1 to 40 deg. Head motion is often involved when the target motion exceeds 30 deg. In response to a visual stimulus, saccadic eye movements exhibit a latency of 100 to 300 msec. Vertical or oblique saccadic eye movements may have a torsional component associated with them because of the arrangement of the six extraocular muscles. The purpose of the saccadic eye movement system appears to be fixation of the image of the target on the fovea, or high-acuity region of the retina, corresponding to .6 to 1 deg of visual angle. There is a minimum delay or refractory period between saccadic eye movements of 100 to 200 msec. The visual threshold is significantly elevated during the period just prior to and during a saccadic eye movement (Cook, 1965; Robinson, 1964; Vossius, 1960; Young, Zuber, & Stark, Note 1).

Pursuit, or slow-tracking, movements are conjugate eye movements used to track slowly moving visual targets in the range of 1 to 30 deg/sec. Pursuit movements are smoothly graded and appear to partially stabilize the image of the moving target or background on the retina, independent of the saccadic eye movement system. The pursuit-movement system appears to be limited in acceleration as well as in velocity. Smooth pursuit movements are not generally under voluntary control and usually require the existence of a moving visual field for their execution (Robinson, 1965; Westheimer, 1954).

Compensatory eye movements are smooth movements, closely related to pursuit movements, which compensate for active or passive motion of the head or trunk. They tend to stabilize the retinal image of fixed objects during head motion and are attributable both to semicircular-canal stimulation sensing head motion and to neck proprioception associated with the turning of the head on the trunk. Compensatory eye movements are closely related to the slow-phase eye movements of vestibular nystagmus discussed below.

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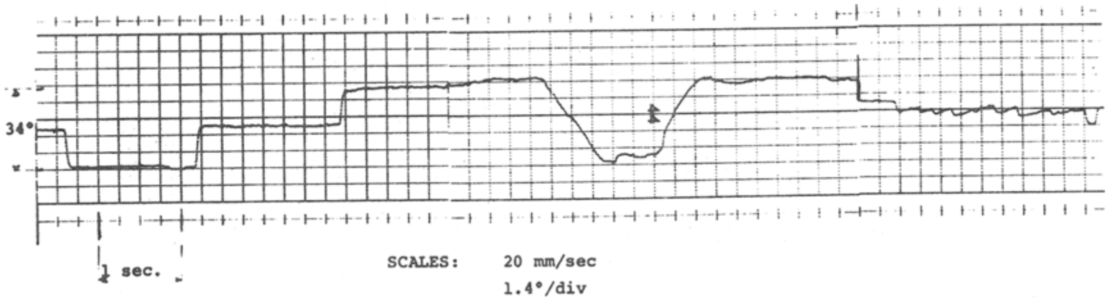


Figure 1. Typical horizontal eye movements recorded with a photoelectric monitor showing saccadic jumps, fixation movements, smooth pursuit, and optokinetic nystagmus. From Young, 1970 (Copyright 1970, McGraw-Hill Book Company. Used with permission of McGraw-Hill Book Company).

Vergence eye movements are movements of the two eyes in opposite directions in order to fuse the image of near or far objects. The vergence movements are considerably slower and smoother than conjugate eye movements, appear to be nonpredictive, and reach maximum velocities on the order of 10 deg/sec over a range of nearly 15 deg. They are stimulated by focusing error (accommodative convergence) as well as binocular disparity (Rashbass & Westheimer, 1961; Zuber & Stark, 1968).

Miniature eye movements, or fixation movements, include a variety of motions which are generally less than 1 deg in amplitude and occur during attempted steady fixation on a target. Drift is the slow random motion of the eye away from a fixation point at velocities of only a few minutes of arc per second occurring within the foveal dead zone. Flicks, or microsaccades, are small rapid eye movements which have been shown to be dynamically of the same nature as large voluntary saccades, of magnitudes as large as 1 deg, occurring at intervals separated by as little as 30 msec and which generally redirect the eye toward the position necessary for fixation on the target (Zuber, 1965). Both flicks and drifts tend to occur along a single preferred axis in any individual (Nachmias, 1959). There is currently no general agreement on the error-correcting nature of the flicks or drifts. In addition, normal individuals fixating on targets exhibit a high-frequency tremor in the range of 30 to 150 Hz with peak amplitudes of approximately 30 arc sec in the region of 70 Hz. (Because of the presence of these fixation movements, accuracy of .5 to 1 deg is often sufficient in eye-monitoring tasks designed to show what part of the visual field is being fixated.)

Optokinetic nystagmus, also known as "train nystagmus," is a characteristic sawtooth pattern of eye motion elicited by a moving visual field containing repeated patterns. Optokinetic nystagmus consists of a slow phase in which the eye fixates on a portion of the moving field and follows it with pursuit motion and a fast phase or return saccadic jump in which the eye fixates on a new portion of the field. The minimum time between fast phases is approximately .2 sec, resulting in a maximum frequency of approximately 5 Hz, although the nystagmus frequency may be considerably less for slow field motions. The amplitude of optokinetic nystagmus is variable, generally from 1 to 10 deg. If a nonmoving fixation point is present in the visual field, the nystagmus response may be reduced to a fraction of a degree, which is not noticeable by direct observation. Attempts have been made to use optokinetic nystagmus as an objective measurement of visual acuity by determining the minimum line width which induces nystagmus.

Figure 1 shows typical single-eyed horizontal eye movements recorded by the photoelectric technique. The rapid saccadic jumps and fixation movements are seen in the early part of the trace, followed by smooth pursuit movements in tracking a target, and finally optokinetic nystagmus induced by horizontal movement of a sheet of lined paper.

Vestibular nystagmus is an oscillatory motion of the eye, similar in appearance to optokinetic nystagmus, containing a slow phase and a fast saccadic-like return. It is primarily attributable to stimulation of the semicircular canals during rotation of the head with respect to inertial space. A counterclockwise head rotation about a vertical axis leads to deflection of the cupulas of the horizontal semicircular canals, which induces image-stabilizing slow-phase eye movement in a clockwise direction. As head motion continues, the eyes jump back rapidly to pick up another position and repeat the sawtooth pattern. Measurement of vestibular nystagmus in various axes is a commonly used test of the semicircular-canal function, either through the threshold of angular acceleration impulse required to induce nystagmus or through the duration of "postrotation nystagmus." The latter test constitutes a part of the nystagmus or objective cupulogram. The amplitude and frequency of vestibular nystagmus are similar to those of optokinetic nystagmus. It has recently been demonstrated that vestibular nystagmus can be induced by pure linear acceleration and by a rotating linear-acceleration vector; the former may reflect otolith contribution, while the latter is attributable to deformation of the semicircular canals

(Steer, 1967; Young, 1969). A variety of rotational tests are used with eye movement measurements to indicate the pathology of the nonauditory labyrinth. A related type of eye movement induced in the clinical situation is caloric nystagmus. The external semicircular canals are stimulated by the convection currents induced in the canals upon introduction of water above or below body temperature into the external ear. The temperature change necessary to induce nystagmus and the duration and strength of nystagmus for standard temperatures constitute a set of clinical measurements useful in the diagnosis of vestibular disease.

Spontaneous nystagmus, or gaze nystagmus, is an anomaly of nystagmus associated with a number of neurological disorders. This nystagmus may be either large enough for direct observation or less than 1 deg, requiring recording for detection. Gaze nystagmus is observed only when the subject looks in a certain direction. The nystagmus may be either asymmetric, containing a slow phase and a fast phase, or "pendular," showing fine high-frequency oscillations of from 4 to 10 Hz. Some of these abnormal eye movements are too small to be observed in close clinical examination and are important diagnostically. Recording of nystagmus as well as the ability of subjects to follow targets with normal saccadic and pursuit tracking has become widespread.

Torsional eye movements are rotation movements of the eye about the line of gaze, and they are generally limited to angles of less than 10 deg. The rolling motions may be stimulated by rotational optokinetic nystagmus or by two types of 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 mentioned above. In addition, the phenomenon of counterrolling or steady state offset of the eye about the torsional axis in response to tilt of the head with respect to the vertical, has been demonstrated and shown to be attributable to the human otolith or vestibular gravity receptors. As such, it has been suggested as an important measurement of otolith function (Woellner & Graybiel, 1959).

PHYSICAL CHARACTERISTICS OF THE EYE WHICH ARE USED IN EYE MOVEMENT MEASUREMENT

The Retina

The eye has no proprioceptive feedback, in terms of conscious position sense. It does, however, contain the retina which moves with the eye and makes possible the subjective assessment of eye movement. Among the earliest quantitative techniques for determining the velocity of the eye during pursuit and saccadic eye movements was after-images. A small light, flashed periodically, will leave a trace of after-images, the density of which indicates fixation duration and the spacing of which indicates the velocity of eye movements. After-images separated by as little as 15 arc min can be resolved, and the technique is usable over the entire range of eye movements. Its chief drawbacks are, of course, the subjective nature of the measurement and the fact that it can only be used for a brief interval, after which the subject must report on the number and placement of his after-images. It is of practical use currently only for the measurement of ocular torsion, where it provides a convenient and relatively accurate measurement and for which there are no readily available automatic methods which are economical, simple to apply, and easily analyzed.

The fovea contains thousands of light-absorbing radially oriented crystals which selectively absorb linearly polarized light. Kaufman and Richards (Kaufman & Richards, 1969; Richards & Kaufman, 1969) used rotating polarized blue light to form a "spinning propeller" after-image relative to the subject's fovea to determine fixation points.

Corneo-Retinal Potential

A potential difference of up to 1 mV between the cornea and the retina (cornea positive) normally exists in the eye and is used as the basis of the most widely applied clinical eye movement technique–electro-oculography. The precise basis of this potential difference, once attributable to the electrical activity of the retina itself, is now in question once again. This potential has important variations diurnally and also with the level of light adaptation, decreasing following steady periods in the dark (Gonshoor & Malcolm, 1971). For stable electro-oculographic measurements, especially in the dark, the subject should be permitted to adapt to the ambient illumination level to be used in the experiment for 30 to 60 min prior to the experiment.

The negative electrical pole lies approximately at the optic disk, 15 deg displaced from the macula. Since the electric field is not aligned with the optic axis, any torsional rotation of the eye introduces a potential change which can be mistaken for horizontal or vertical eye movement. This very geometry, however, makes electro-oculography a possible, though difficult, method for measuring ocular torsion (Gabersek, 1969).

Electrical Impedance

The impedance measured between electrodes placed at the outer canthi of the two eyes varies with eye position. The variation in this resistive component is either associated with the nonhomogeneous or anisotropic nature of electrical characteristics of the tissues in the globe or with the nonspherical characteristics of the globe so that the resistivity of the path between the two electrodes changes with position (Geddes, McGrady, & Hoff, 1965; Sullivan & Weltman, 1963).

The Corneal Bulge

The cornea, attached to the sclera at the front of the eye and centered close to the optic axis, has a smaller radius of curvature than the eye itself. This forms the basis for a number of important methods of eye movement measurement. In the early days of research on eye movements, attachments were made directly to the cornea by a plaster of paris ring and mechanical linkages to recording pens (Delabarre, 1898). The bulge of the cornea can be felt through the eyelid of the closed eye, and pressure transducers placed over the eyelid can detect these changes. In more recent times, the cornea has acted as a mechanical post to center tight fitting scleral contact lenses to which other measurement devices are attached. It should be noted that the cornea itself slips slightly with respect to the sclera when forces are applied to the cornea and probably slips slightly during the eye acceleration phase of saccadic eye movements. Contact lenses applied to the cornea itself are not an adequate base for the accurate measurement of eye position, and large contact lenses conforming to the sclera as well as the cornea are necessary for systems in which stability of better than a few minutes of arc is desired. The nominal curvature of the cornea for an adult human is approximately an 8-mm radius for an eye of 13.3-mm radius. Once a contact lens is fitted, its position can be measured by any of a number of methods.

Corneal Reflections

The front surface of the cornea, although not a perfect optical surface, approximates a spherical section over its central 25 deg. As with a convex mirror, reflections of a bright object from this surface form a virtual image behind the surface which can be imaged and photographed or recorded. The position of the corneal reflection, commonly seen as the highlight in the eye, is a function of eye position. Rotation of the eye about its center produces a relative translation, as well as rotation of the cornea, forming the bases for the important class of eye movement instruments known as corneal reflection systems.

Reflections from Other Optical Curvatures in the Eye—Purkinje Images

Although the brightest reflections of incident light come from the front surface of the cornea, light is also reflected from each surface of the eye at which there is a change in refractive index. Reflections come also from the back surface of the cornea, the front surface of the lens, and the rear surface of the lens. These four are referred to as the Purkinje Images. After the bright front surface reflection, the next most visible Purkinje image is the fourth, coming from the posterior surface of the lens. Measurements of the relative displacement between the first and fourth images, representing, as they do, points focused and imaged from planes of different depths in the eye, represent one technique for actively measuring the orientation of the eye in space independent of its relation to head position.

The Limbus

The iris of the eye is normally visible and clearly distinguishable from the sclera and is the basis for the normal visual assessment of the angle of gaze. The position of the iris-scleral boundary (the limbus) may be measured with respect to the head. The ratio between dark iris and bright sclera observed on the left and right sides of the eye may either be measured directly with photosensors or indirectly on an image of the eye. This ratio is directly related to the horizontal position of the eye. The best wavelength for making the distinction between iris and sclera depends to some extent on the iris color; however, white light is normally reasonably effective.

The Pupil

The pupil is easily distinguished from the surrounding iris by its difference in reflectance. The pupil can be made to appear much darker than the iris under most lighting conditions when the majority of light does not come in directly along the axis of measurement and, consequently, is not reflected out. On the other hand, the pupil can be made to appear very bright (as often seen in amateur full-face flash photography) when most of the light enters along the optic axis and is reflected back from the retina. In either case, the pupil can be separated from the surrounding iris optically. This can be especially sharpened with the use of infrared light which will be nearly entirely absorbed once entering the eye, consequently making the pupil much darker than the surrounding iris. The pupil normally varies between 2 and 8 mm in diam in adult humans. Although it is actually slightly elliptical in shape, it can be approximated closely by tracing the best-fitting circle to the pupil circumference with an image dissector technique. The center of the pupil is also easily located electro-optically or on film for hand analysis.

The pupil appears elliptical when viewed other than along the optic axis, with the minor axis shortening as the eye rotates. The pupil eccentricity could serve as a basis for eye angle measurement.

Other Optical and Nonoptical Landmarks

In addition to the iris and the pupil, other optical landmarks can be traced. Scleral blood vessels or folds of the iris can be identified by hand or traced with optical tracing techniques. (These are of practical application only in the measurement of ocular counterrolling.) The retinal vessels, which can also be imaged and tracked, provide one of the most accurate techniques for determining the place on the retina where a given target is imaged and consequently the exact fixation point of the eye. The retinal vessels, approximately .2 mm in diam, radiate from the optic disk.

Some artificial landmarks have also been placed on the eye and their positions recorded. A globule of mercury (Barlow, 1952), chalk, and egg membrane have been used for optical tracking. A small piece of metal imbedded in the sclera has also been used for magnetic tracking of the eye position.

MAJOR EYE MOVEMENT MEASUREMENT TECHNIQUES

Electro-Oculography

Principle. Mowrer, Ruch, and Miller (1936) and Schott (1922) found that the position of the eye could be measured by placing skin electrodes around the eye and recording potential differences. The source of the electrical energy is the corneoretinal potential, or electrostatic field which rotates with respect to the eye. The cornea remains .40 to 1.0 mV positive with respect to the retina; this is attributable to the higher metabolic rate at the retina. As the eye rotates, the electrostatic dipole rotates with it, and consequently the potential difference in a plane normal to the principal axis varies, theoretically, as the sine of the angle of deviation. Of course, the nonhomogeneous nature of the conducting medium causes wide departure from the theoretical values. These techniques were reviewed by Marg (1951) and more recently by Kris (1960) and by Shackel (1967). Skin electrodes placed on the outer canthi measure conjugate horizontal eye position. By reference to any third electrode over the bridge of the nose, some measure of horizontal eye vergence may also be detected. The recorded potentials are small, in the range of 15 to 200 microV, with nominal sensitivities of the order of 20 microV/deg of eye movement (Shackel, 1967).

Implementation. The signals are at times difficult to detect in the presence of large muscle-action-potential artifacts, also picked up as potential differences by the skin electrodes (Shackel, 1960). The presence of external electrical interference is troublesome unless care is taken to shield the system.

Normally, but not always, the dc recording method, which is necessary to determine eye *position* is referred to as electro-oculography (EOG); ac recording, which is useful for measurement of eye movement, including the fast and slow phases of nystagmus, is referred to as electronystagmography (ENG). Until recent years, the problem of drift in both electrodes and dc amplifiers made dc recording a difficult and frustrating practice. Gross patterns of reading movements (number of saccades per line; number of regressions and fixation durations) can easily be obtained from ac recording with time constants of 3 to 10 sec or more. With longer time constants, even the approximate position on a line can be determined. An advantage of ac recording is that a high-sensitivity recording can be made without fear of having the record drift off scale.

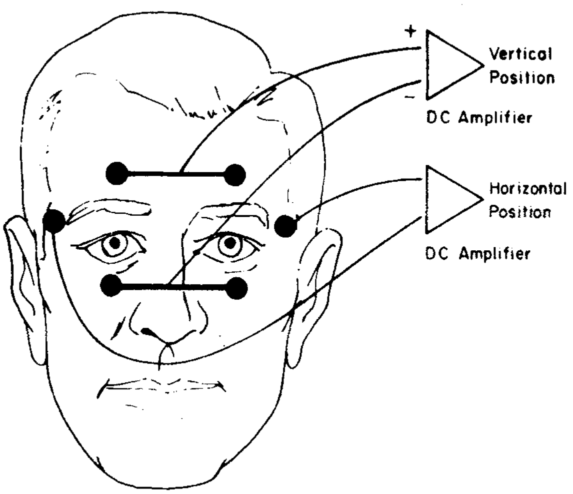


Figure 2. A method for reducing cross coupling in conjugate electro-oculography (Young, 1970 after Jeannerod et al., 1966).

Recently, dc recording has been made much more practical with two electronic advances. New skin electrodes, especially silver-silver chloride (Beckman or Becton-Dickinson, for example) are easily applied with adhesive tape rings, require no skin preparation other than cleaning with alcohol or acetone, are of minimal discomfort, and resist excessive polarization over many minutes of use. They also seem to be relatively less sensitive to changes in skin resistance when led into any of the newer high-input impedance (FET) preamplifiers. Gold-plated electrodes are also in use (Toglia, 1973). Placement of a high common mode rejection preamplifier very close to the subject's head, proper grounding of the subject through an ear electrode, and use of shielded cable can help eliminate the disturbance from electromagnetic pickup.

Conjugate horizontal eye movements are recorded between electrodes at the outer canthi of the eyes. Placement of the electrodes further back toward the temples reportedly reduces the artifacts from muscle activity. Separate recording of the horizontal movements of the eye is generally performed with the use of a third common electrode placed over the bridge of the nose.

When both vertical and horizontal recording from one or both eyes is performed, the errors introduced by coupling between the axes and by the nonlinearity of the records can be considerable. Some improvement in the cross coupling results from the use of "vector electro-oculography" introduced by Uenoyama, Uenoyama, and Iinuma (1964) and extended by Jeannerod, Gerin, and Rougier (1966). In addition to simultaneously displaying the x and y coordinates of eye movements, they electrically short circuit the two superior electrodes and the two inferior electrodes for the vertical eye movement recording as seen in Figure 2. A commonly observed overshoot artifact in EOG recording of vertical eye movements has been attributed to the motion of the upper eyelid.

An alternative combination of electrode outputs has been found useful for simultaneous separate recording of the vertical and horizontal movements of each eye (Bles & Kapteyn, 1973). By combining the individual electrode outputs of Figure 2, as indicated below, one can choose β and γ during calibration to virtually eliminate the effect of vertical eye movements:

Right eye vertical: D – E

Left eye vertical: F – G

Right eye horizontal: $(A - C) + \beta(D + E)$

Left eye horizontal: $(C - B) + \gamma(F + G)$

For animal work, the stability and signal-to-noise ratio of electro-oculography can be improved considerably by the use of fine platinum needle electrodes in the skin around the orbit or by the use of miniature permanently implanted silver-silver chloride electrodes placed in holes in the bony orbit (Bond & Ho, 1970).

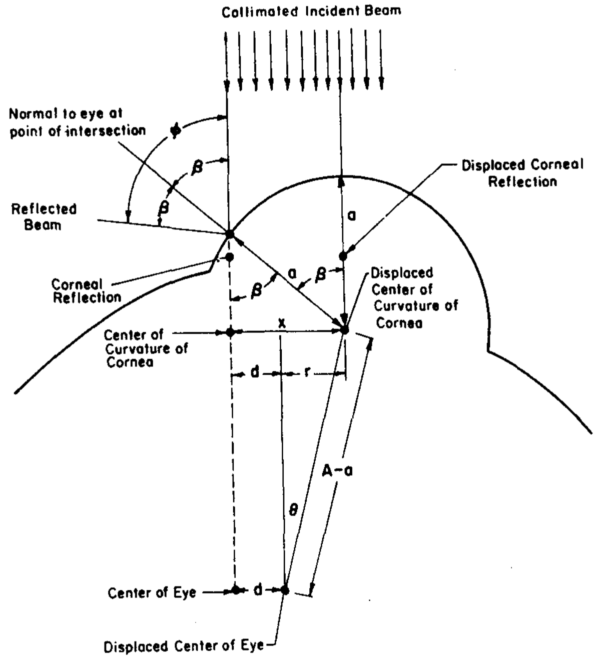
Evaluation of Electro-Oculography. EOG has the largest range of any of these objective methods practical for human studies, since it does not require visualization of the eye. The method is usable for eye movements up to ±70 deg (Wolf & Knemeyer, Note 2). Linearity becomes progressively worse at excursions greater than 30 deg, especially in the vertical. Typical accuracy with surface electrodes is ±1.5-2 deg.

The chief sources of error are muscle artifacts, eyelid interferences, basic nonlinearity in the technique, and variation in the corneoretinal potential attributable to light adaptation, diurnal variations, and the state of alertness.

Potential improvement in EOG performance could come with the making of integrated electrode amplifier assemblies attached directly to the skin to eliminate noise susceptibility and minimize shielding requirements.

Corneal Reflection

Principle. The corneal bulge produces a virtual image of bright lights in the visual field and region. Because the radius of curvature of the cornea is less than that of the eye, the corneal reflex moves in the direction of eye movement, relative to the head. Since it only moves about half as far as the eye, it is displaced opposite to the eye movement relative to the optic axis, or the center of the pupil, as seen in the accompanying figures.



$$x = d + r$$

$$\text{but } r = (A-a)\sin\theta$$

$$\boxed{x = d + (A-a)\sin\theta}$$

$$\sin\beta = x/a$$

$$\phi = 2\beta$$

$$\phi = 2\sin^{-1} x/a$$

$$\phi = 2\sin^{-1}\left((\frac{A}{a}-1)\sin\theta + \frac{d}{a}\right)$$

$$\sin\frac{\phi}{2} = \left((\frac{A}{a}-1)\sin\theta + \frac{d}{a}\right)$$

for small angles, $\sin\theta \approx \theta$

$$\sin\frac{\phi}{2} = \left((\frac{A}{a}-1)\theta + \frac{d}{a}\right)$$

$$\text{or } \boxed{\phi = 2\left((\frac{A}{a}-1)\theta + \frac{d}{a}\right)}$$

d = lateral displacement of eye center
r = lateral displacement of center of curvature of cornea due to rotation
A = radius of the eye (from center of rotation to outer central surface of cornea (~13.3 mm)
a = radius of curvature of outer surface of cornea (~8 mm)

Figure 3. Corneal reflection geometry.

The geometry of the corneal reflex principle is seen by reference to the accompanying Figure 3. Incident light from a source (which is here shown to be collimated for illustration) is reflected from the convex surface of the cornea in a pattern of diverging light and is imaged through a concave lens onto a film plate, television camera element, or photocells (Carmichael & Dearborn, 1947; Taylor, 1971; American Optical, Note 3). An incident ray is reflected at an angle ϕ, which varies with the displacement (x) of the center of curvature of the cornea perpendicular to the incident ray. As seen in the diagram, this displacement consists of two parts, a displacement (r) resulting from eyeball rotation relative to the light source and a displacement (d) equal to the linear displacement of the center of rotation of the eye normal to the incident ray. The apparent displacement of the corneal reflection to a stationary observer is $x = d + (A-a)\sin\theta$. The expected relationship among reflection angle (ϕ) of a single beam of light, eye rotation (θ), and lateral displacement of the center of the eye (d) is:

$$\sin\phi = 2\left|(\frac{A}{a} - 1)\sin\theta + \frac{d}{a}\right|.$$

Usually the small angle approximation for ϕ, as well as for θ, is used (Ditchburn and Ginsborg, 1953), yielding:

$$\phi \cong 2\left|(\frac{A}{a}-1)\theta + \frac{d}{a}\right|,$$

which is valid only for small eye rotations *and* for small

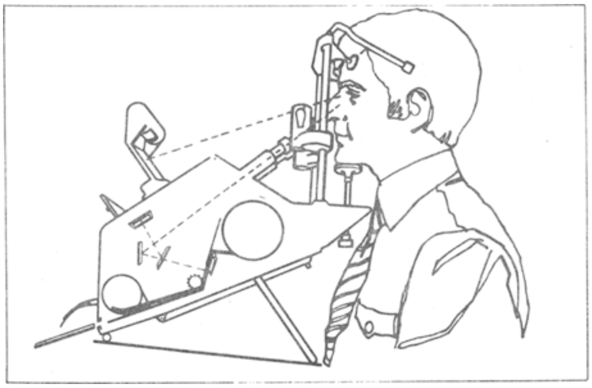


Figure 4. The AO ophthalmograph (Taylor, 1971). Courtesy of Educational Development Laboratories, A Division of McGraw-Hill Book Company .

ϕ, meaning that the reflected beam is close to the incident beam. For side lighting, with a large initial angle of reflection (ϕ_0), the appropriate equation is:

$$\sin(\phi_0 + \Delta\phi) = 2\left\{(\frac{A}{a} - 1)\sin\theta + \frac{d}{a}\right\},$$

or

$$\Delta\phi \cong 2\left\{(\frac{A}{a} - 1) + \frac{d}{a}\right\}/\cos\phi_0$$

for small eye rotations (θ) and any initial reflection angle.

The lateral head movement factor (d/a) can contribute a large error when the head moves relative to the light. Ditchburn and Ginsborg point out that, with $A = 13.3$ mm and $a = 8.0$ mm,

$$\phi = 1.3\theta + 860d,$$

with ϕ and θ measured in arc minutes and d in millimeters (1-mm change in head position is equivalent to an eye rotation of greater than 12 deg.) For this reason, many of the fixed head versions and the head-mounted devices require accurate stabilization of the light source and recording device with a bite board or head strap.

Specific implementations. There are two basic types of corneal reflex methods, depending on the location of the light source. In the first, and oldest, the light source is fixed with respect to the subject's head. To relate eye position to the material being fixated therefore requires either a fixed head system, a method for recording head position (linear and angular), or a technique for recording the field of view relative to the head at every sample. These methods are referred to as head-mounted or head-fixed corneal reflex techniques.

The second corneal reflex method fixes the light source in the target field rather than to the head. By placing the light source in the target field, movements of the corneal reflex relative to the pupil indicate the point of regard of the eye in the field, and not relative to the head. These techniques are referred to as corneal reflex point of regard instruments and are much less sensitive to head position. They are described in detail in a later section.

Laboratory corneal reflex camera. In the early AO ophthalmograph, and its descedent, the Reading Eye I, the head was fixed with a chin rest and head rest, and reading material was presented on fixed index cards. Small dim lights located temporally in the peripheral field reflected corneal highlights which were imaged by a camera (See Figure 4). The horizontal motion of the corneal reflex of each eye is recorded as a time trace on moving film, yielding a record such as that shown in Figure 5. Vertical and horizontal scan patterns can be shown simply by stopping the film for a period. Timing marks can be added by periodic interruptions of the light.

As a variation of the basic corneal reflection technique to permit continuous monitoring of vertical as well as horizontal eye motion, the corneal reflex is split into two beams by prisms. One beam is recorded on vertically moving film to yield horizontal eye movements, and the second beam is directed to a horizontally moving film to record vertical movements (Buswell, 1935).

One laboratory camera is presently available, the Polymetric eye movement recorder V-1164. It provides for the superposition of the corneal reflection spot on movie film or a television picture of the scene (Mackworth & Mackworth, 1958). It provides a ±.5-deg accuracy, but strict head fixation is required. The

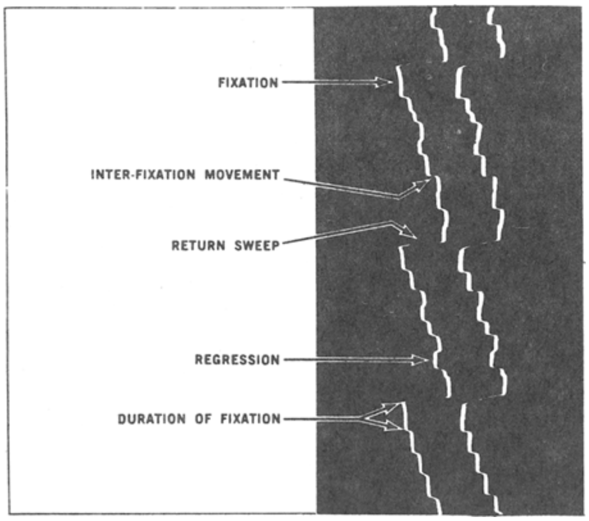


Figure 5. Continuous moving film record of corneal reflections (Taylor, 1971)(Courtesy of Educational Development Laboratories, A Division of McGraw-Hill Book Company).

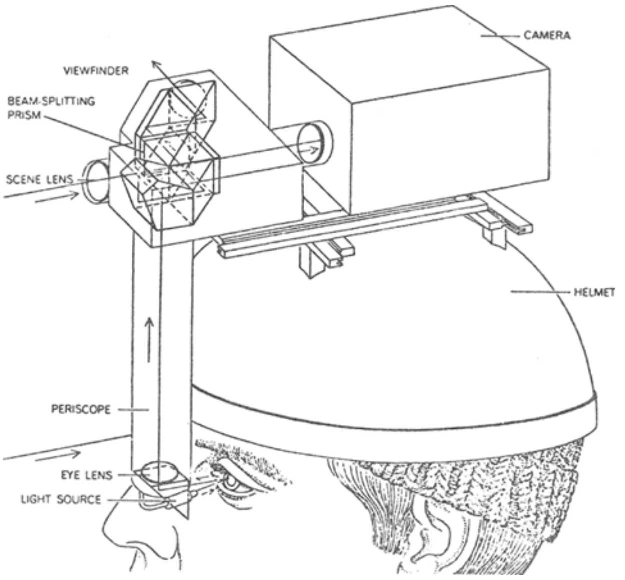


Figure 6. Eye-marker camera tracks and records the eye's glance. The image of a spot of light, reflected from the cornea, is transmitted by an optical system in the periscope through a series of prisms. This serves to superimpose the eye-marker image on the scene image. The combined image can be monitored through the viewfinder as it is photographed by the motion-picture camera (Thomas, 1968) (Copyright [1968] by Scientific American, Inc. All rights reserved).

output of the system is graphic, but a 15 by 15 resolving digital unit is available to extract the spot position from a television picture.

Head-mounted corneal reflex camera. An important extension of the basic corneal reflex technique, in which the light source for the corneal reflex is still attached to the head, is the head-mounted eye monitor camera. In this free head system, developed by Mackworth and Mackworth (1958), a film or television camera that is aligned with the head during free head movements continuously records the field of view. The corneal reflex, measured as a reflected light spot from a peripheral lamp, as in the head-fixed system, is combined with the visual field scene through a beam splitter and appears in the film or video display as a white spot placed over the portion of the scene which is being fixated. The system is shown schematically in Figure 6. The accuracy is poorer than that with a fixed head system, approximately ±2 deg, since it is subject to greater error from the relative movements of the light source with respect to the eye associated with head movements. Several commercial verions of the head-mounted Mackworth camera are available. When the camera is mounted directly on the head, as in the early Mackworth helmet-mounted camera system, the interference with head movements associated with the weight of the instrument may be considerable.

Recent advances have been aimed chiefly at reducing the weight and moment of inertia of the portion of the eye movement recorder which must be worn on the head. Some improvement was made through miniature cameras and miniature TV systems. The largest advance, however, has been the mounting of the camera separately and carrying the visual information, including corneal reflex, and the field of view from the head to the TV or motion picture camera via coherent fiber optics cables. An illustration of one such system is given in Figure 7 in which the headpiece weight is reduced to 2 lbs. Note that a bite board and headband are used for stabilization.

A similar fiber optics version of the Mackworth camera, manufactured by NAC, has a body which weighs less than 1 lb, with another 5.3 oz for the fiber optics and 9.9 oz for a camera adapter–not carried on the head. This version is pictured in Figure 8.

An alternative approach to fiber optics for dropping the weight is the use of a miniature TV camera on the head, combining the corneal reflex as before. A picture of such a device and a diagram showing its principles of operation are shown in Figures 9 and 10. This system, manufactured by NAC of Japan, in conjunction with a TV system from Rees Instruments, Ltd. of England, requires a combining mirror in the field of view. Its weight is 3 lbs 13 oz with the camera shown, reduceable to 15 oz on the head, including cable, with a lighter camera according to specification sheets.

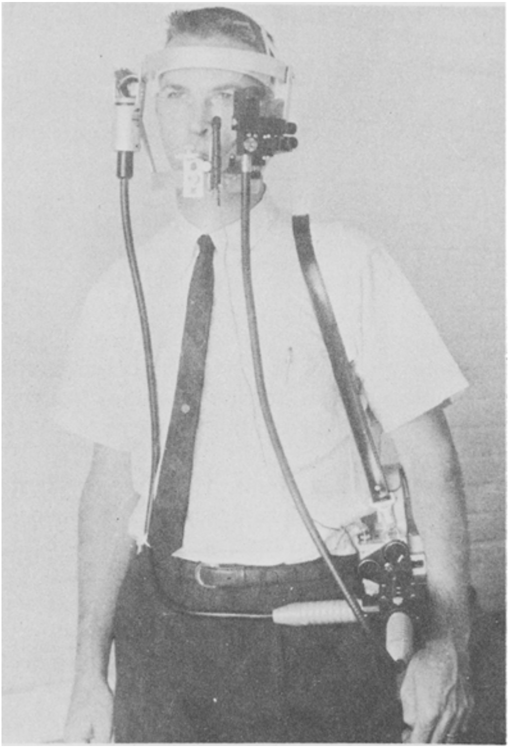


Figure 7. Mobile corneal reflex eye movement camera (Courtesy of Polymetric Company).

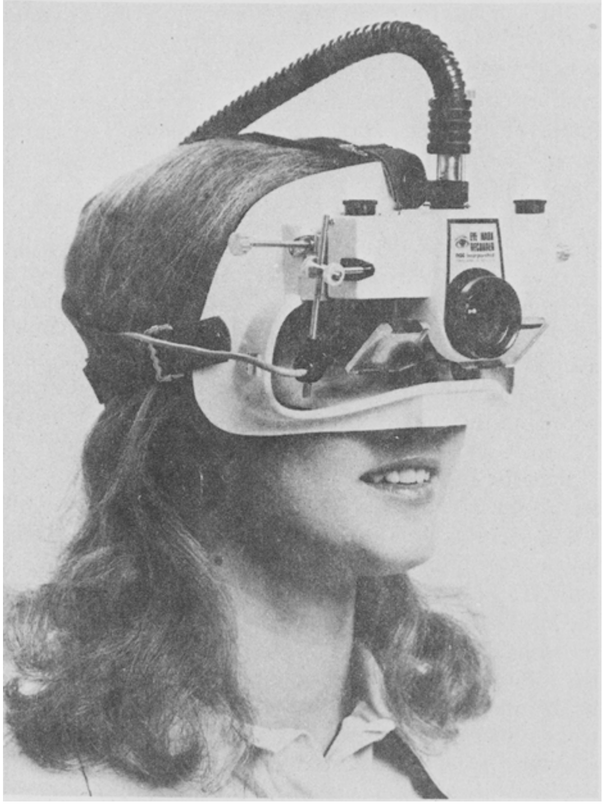


Figure 8. Head-mounted corneal reflex illumination, viewing, and combining optics (Courtesy of Instrumentation Marketing Corporation).

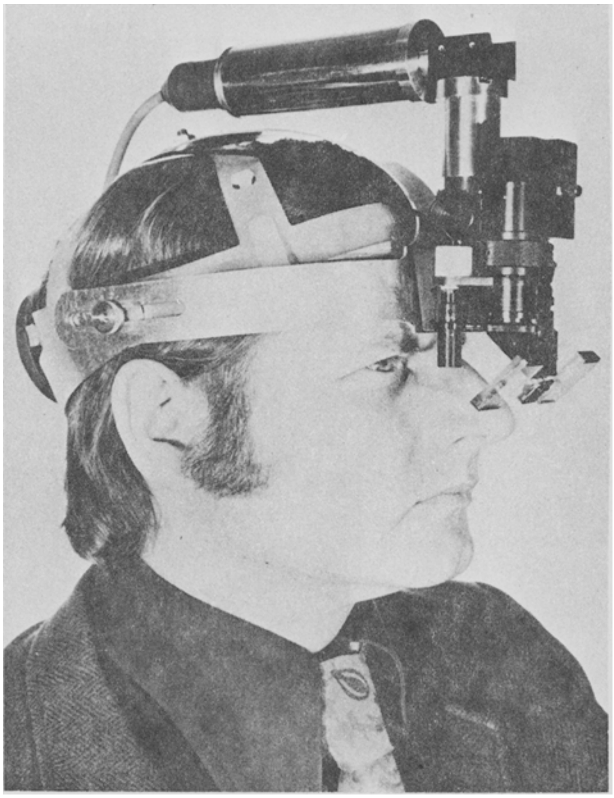


Figure 9. Head-mounted corneal reflex illumination, viewing and combining optics (courtesy of Instrumentation Marketing Corporation).

Evaluation of corneal reflex methods. The uncorrected linear range of all corneal reflex systems which employ a *single* light source for the reflex is limited to eye excursions of ±12-15 deg vertical or horizontal. Larger excursions place the reflex in the nonspherical and rougher peripheral portion of the cornea and require a complex (usually computer-generated) calibration and linearization technique. The reflex range is ultimately limited by the size of the cornea and its partial disappearance behind the lids. In addition to head movements, other factors which limit the accuracy of corneal reflection methods to .5-1 deg are variations in cornea shape and thickness of tear fluid, corneal astigmatism, and the production of other reflections by eyeglasses (Hall, Note 4).

The output of most of these systems is usually graphic and therefore requires manual measurement and/or recording. But any of the systems which produce a single bright spot on film or directly on a video signal can be used to provide conversion to the x-y coordinates of that spot. The most common of these converters detects the brightest (or darkest) spot on the video signal and determines its x and y coordinates by the time of its occurrence, relative to the horizontal and vertical scan sequences. Resolution is about equal to two video lines, or about 1 part in 250, for conventional TV scans. This information can then be digitized for further processing of the part of the field being fixated. Polymetric Company makes a low-resolution digitizer (15 by 15 matrix) for use with their instrument. No other commercial quantitative devices exist for the simple corneal reflex method.

Limbus, Pupil, and Eyelid Tracking

Basic techniques. The sharp boundary between the iris and the sclera (the limbus) is an easily identifiable edge which can be detected optically and tracked by a

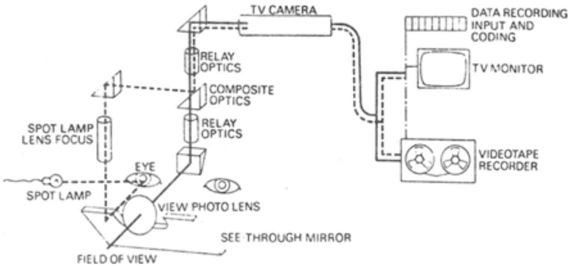


Figure 10. Schematic diagram for head-mounted TV corneal reflex system (Courtesy of Rees Instruments, Ltd.).

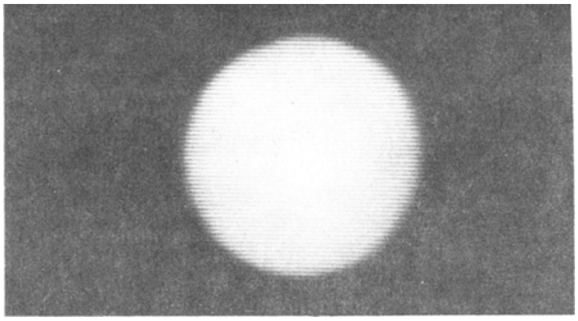


Figure 11. TV picture of a bright pupil (Merchant & Morrissette, 1974).

variety of means; a human observer looking at the eye can do surprisingly well in determining where the subject is looking. If the entire iris were always visible, and not partially hidden by the lids, it would be a simple matter to trace its circumference and determine its center. However, because only part of the iris is normally visible, other optical methods, including pupil tracking, are necessary to find its center.

When only horizontal eye movements are of concern, then the left and right extremes of the iris can be tracked, either by measuring the gross difference in reflected illumination from fixed areas of the eye on either side of the central gaze position or by tracking the limbus with a video scan system. When vertical measurement is also required, one may track either the eyelid level, the pupil position, or the vertical motion of a visible part of the limbus. Nearly all limbus tracking systems use invisible, usually infrared, illumination. They all measure the position of the limbus relative to the photodetectors. For head-fixed photodetectors and illuminators, free head movement is possible and the measurement is of eye relative to the head.

The pupil offers a number of distinct advantages over the limbus. First, it is smaller and therefore unobscured by the eyelid for a much greater range of eye motion. For large eye motion, it presents to the observer or the observing instrument a greater portion of the round or slightly elliptical shape. The center of the pupil virtually coincides with the foveal optical axis of the eye. There is a 5-6-deg deviation between the two, but with most measurement techniques, this can generally be calibrated out. The edge of the pupil is usually a crisper, sharper boundary than that between the sclera and the iris. This makes for a higher resolution measurement.

On the other hand, the pupil, when viewed under normal illumination, appears black and therefore presents a lower contrast with its surrounding iris than the iris does with respect to the sclera. This makes it a more difficult problem to automatically discriminate the pupil. If collimated illumination is used, however, the light is reflected from the interior of the eye and to an observer looking along the illumination axis, the pupil appears bright. This effect is often seen as "pink eyes" in flash photographs where the flash lamp is close to the camera lens. This phenomenon is employed in the Honeywell oculometer and other similar devices (Merchant & Morrissette, 1974) (see Figure 11).

Another characteristic of the pupil which provides both an advantage and a disadvantage is the fact that its diameter varies as a result of both psychological and physiological influences. This makes measuring the center of the pupil somewhat more difficult but it does provide, in many techniques, the pupil diameter as a collateral output of the measurement which may be of interest to the experimenter in correlating with the position of the eye at any point in time.

Specific implementations: Scanning methods. One technique involves scanning of the eye with a normal TV camera, which has sufficient sensitivity in the near infrared region (700-900 millimicrons) to be effective with IR lighting. Horizontal sweeps which intersect the iris and the pupil have a video signal as shown schematically in Figure 12. The horizontal position of the limbus or the pupil is determined by the horizontal sweep of the line crossing the center of the iris with video contrast very high.The time from the start of the sweep to the drop in intensity at the first iris boundary is a measure of the eye horizontal position relative to the camera. Since the total sweep time is 62 microsec, resolution of 1/500 of the line length (comparable to vertical resolution) requires circuitry to give time resolution of .1 microsec, which is now within the state of the art. The choice of which line is to be measured can be done in two ways. One way is to measure the left iris boundary every sweep

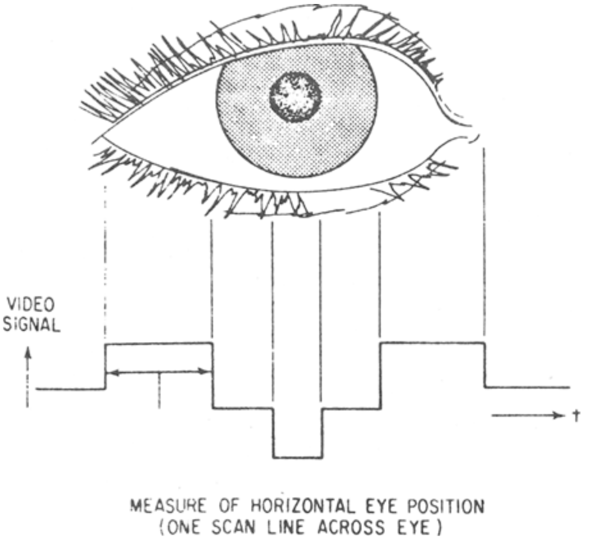


Figure 12. Scanning method for tracking limbus. From Young (1970) (Copyright 1970, McGraw-Hill Book Company. Used with permission of McGraw-Hill Book Company.).

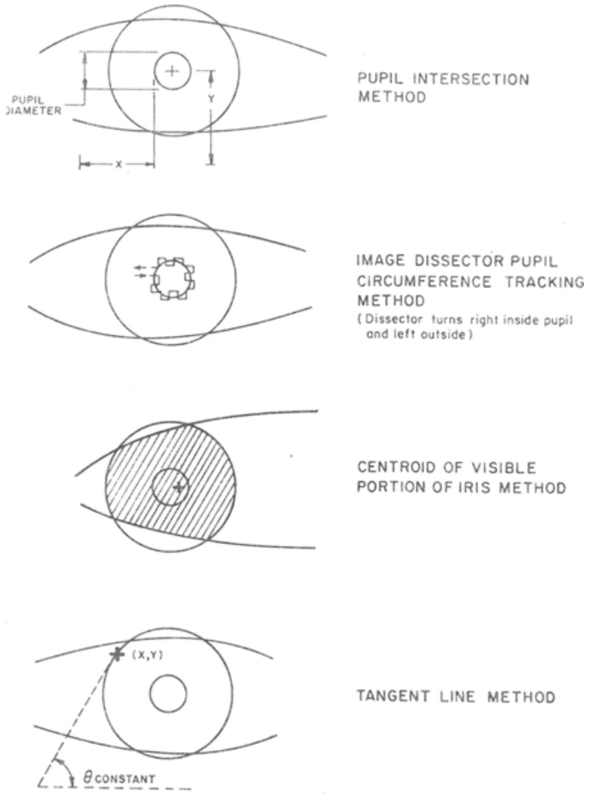


Figure 13. Various scan methods applied to tracking the limbus and pupil.

and select the one which is furthest to the left as the midline. The other method is to rely upon the vertical eye position measurement to select that horizontal sweep which crosses the center. For example, measuring the top and bottom sweeps which intersect the pupil yields pupil diameter as well as vertical pupil position. That line which is midway between the pupil top and bottom can be selected as the midline and its intersection with the pupil or iris measured (Sheena, 1973) (see Figure 30). Vertical resolution is limited by scan line density. For standard US systems, this yields, at best, 1 part in 212 per field (two fields/frame) at a 30-Hz rate, or 1 part in 525 at a 60-Hz rate. Horizontal measurement of the pupil boundary has to take into account the varying pupil diameter.

Other methods of scanning have been applied to tracking the limbus or the pupil. A programmable video scan, or image dissector, can be used to trace the circumference of the pupil for determination of the center (Merchant, Note 5) or to trace only the visible portion of the curve of the limbus, and from that information calculate the coordinates of its centroid (Sheena, 1969). This latter method permits large eye excursions. Instead of illuminating the eye uniformly and tracking with a wide scan, one can scan a small spot of light across the eye and measure the returned reflected light at every instant. Cornsweet (1958) used such a flying spot scanner to track the limbus. Rashbass (1960) used it to maintain a small sweep tangent to the limbus at a fixed angular orientation, thus measuring the vertical and horizontal eye position from tracking a single part of the limbus (see Figure 13).

A TV camera with an image dissector has been applied to precise tracking of the corneal reflex (Ishikawa, Yamakazi, Inabi, & Naito, 1971). The main horizontal sweep is a normal full-picture left-to-right scan, which is used for approximate location of the bright reflex, whereas every second sweep is a short (high resolution) line centered in the part of the field containing the reflex. This combination scan of coarse slow and fine rapid sweeps was used to track vertical and horizontal eye movements over the range of ±15 deg with a resolution of .01 deg and frequency up to 15 KHz.

Specific implementations: Differential reflection methods. Scanning methods either require head fixation or the attachment of a scanning mechanism to the head, directly or using fiber optics. Similar results can be obtained by measuring limbus position with two or more small photocells viewing appropriate parts of the eye, either directly or examining its image. Just as with the scanning systems, there are basically two choices—either broad illumination and tightly constrained fields for photodetection or the use of

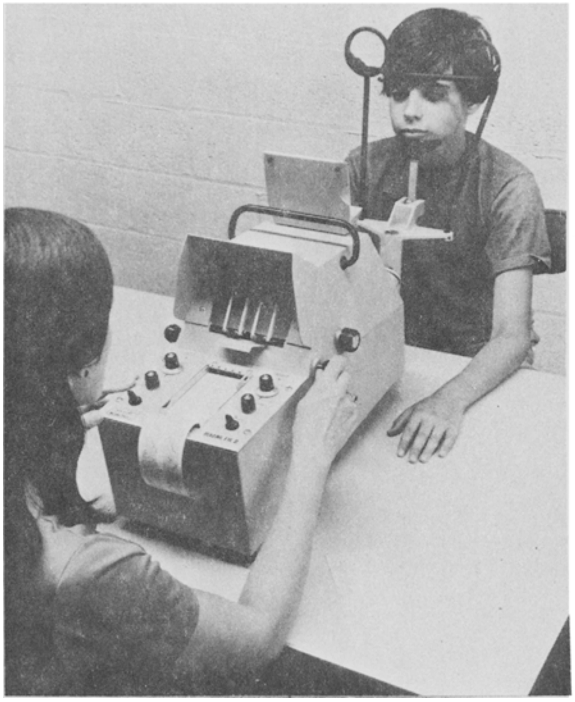
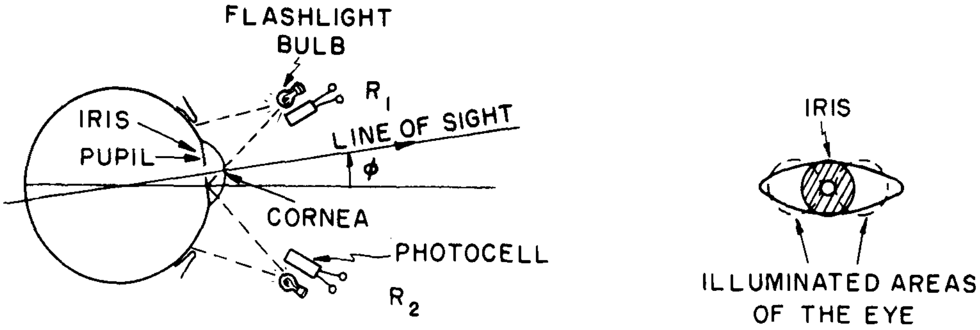


Figure 14. Differential reflection reading eye movement measurement device (Courtesy of Biometrics Division, Narco Bio-Systems, Inc.).



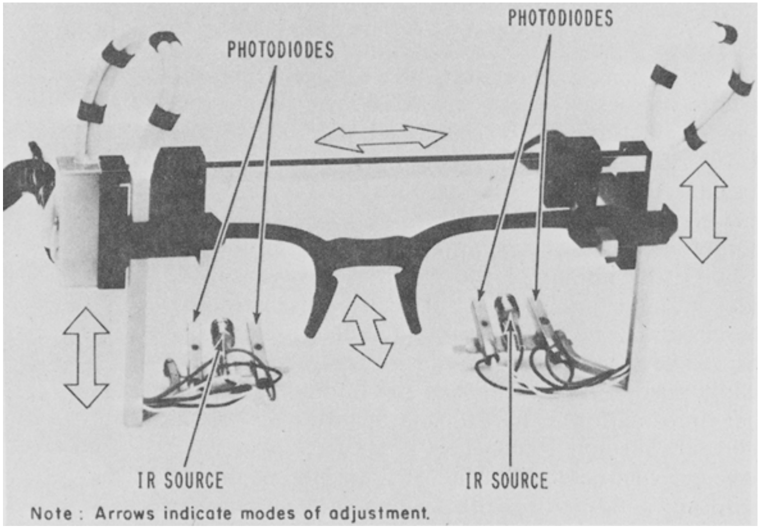
(a) (b)

Figure 15. Light and photocell arrangement for limbus tracking (Stark, Vossius, & Young, 1962).

focused slits or circles of light on the eye with relatively large detection regions. Each of these methods is used, although the most common method uses broad field illumination so that only one source, and no mask, is required.

In the earliest versions of this device, Torok, Guillemin, and Barnothy (1951) and Smith and Warter (1960) imaged one side of the eye on a small horizontal slit placed in front of a photomultiplier. As the eye moved horizontally, the image on the slit contained more or less bright sclera, depending on the direction of eye movements, and thus the photocell output varied. Accuracies of 15 arc min over several degrees were obtained with careful head restraint. A current commercial version of this technique is shown in Figure 14. This tracks the horizontal movement of each eye by recording differences in output of two photocells on opposite sides of the iris image. All of these methods require a fixed head and a fixed place for viewed material. Richter (1956) placed the light and photocells on goggles worn by the subject, and relied on diffuse reflected light from the sclera rather than an image. Stark and Sandberg (1961) used two small lamps illuminating small discs on the two sides of the iris and recorded the difference in reflected light from two photocells viewing these areas (see Figure 15). The two cells permit a larger range of horizontal eye movement (to ±15 deg), a more linear relationship than a single sensor, and relative insensitivity to vertical movements because of the push-pull sensor arrangement. With photodiodes attached to a spectacle frame, accuracy is over the order of 15-30 arc min. When the head is rigidly held in place with a bite board, and narrow beam photodiodes used with a range of a few degrees, resolution of 10 arc sec is possible (Zuber, 1965). The interference of any changes in ambient illumination is now overcome in most systems by illuminating the eye with chopped light and then demodulating at the same frequency. Chopper wheels in the light path are useful in immobile systems (Wheeless, Boynton, & Cohen, 1966), but infrared light-emitting diodes (GaAs) are small and preferable for monitors that are

Figure 16. Spectacle mounted differential reflectivity device (Courtesy of Biometrics Division, Narco Bio-Systems, Inc.).



Note : Arrows indicate modes of adjustment.

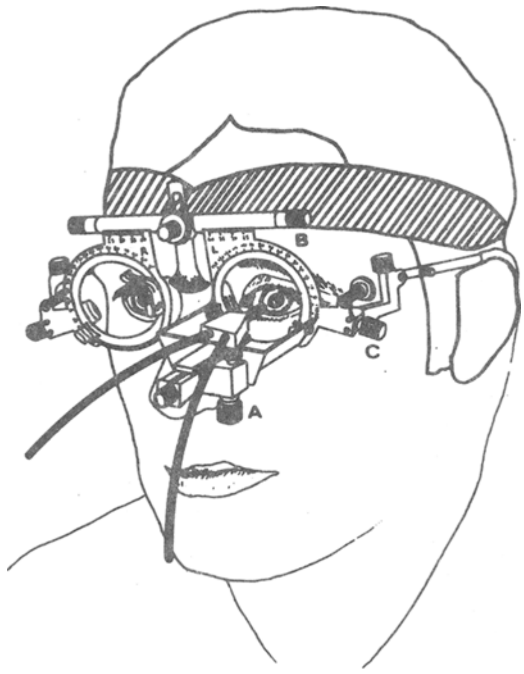


Figure 17. Limbus tracking with bifurcated fiber optics (Findlay, 1974).

built on spectacle frames to allow free head movement (Young, 1970), as seen in Figure 16. Findlay (1974) used a bifurcated fiber optic bundle to both illuminate the limbus and to collect the reflected light as shown in Figure 17. In this manner, both light source and detector are effectively placed closer to the eye resulting in a smaller illuminated area sensed by the detector.

Measurement of the vertical position with the differential reflection methods is difficult, for the same reasons as with scanning techniques. For this purpose, Young tracked the upper lid position with the output of two photodiodes arranged to be relatively insensitive to horizontal motion. A new variation on this method by Mitrani, Yakimoff, and Mateeff (1972) uses a third photocell and a separate light source to measure the vertical eye movements by tracking the related lower lid height. As seen in Figure 18, the light from this source falls directly on the additional photocell, partially shadowed by the lower lid. Although linearity is a problem for large eye movements, resolution of 15 arc min, comparable to the horizontal, is reported.

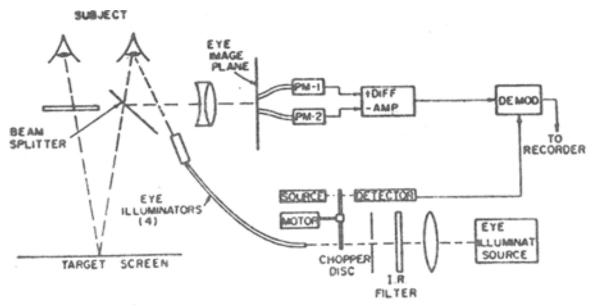


Figure 19. Tracking of limbus image (Wheeless et al., 1966).

Finally, the differential reflection technique can be extended to measurement of vertical eye movement by the proper positioning of the viewing areas or the use of additional areas. Wheeless et al. (1966), in an immobile system with the head fixed using a bite board, brought an image of the eye onto two detectors which could be arranged for horizontal or vertical recording. The eye illumination, coming from a chopped source, was brought to the eye with four fiber optic bundles and their projection lenses, as shown in Figure 19. The eye viewed through a beam splitter with visible illumination is imaged on a frosted screen. The four fiber bundles are then manipulated to yield the pattern of four slits on the eye seen in Figure 20, and the infrared filter is replaced for recording. The difference between the Iris-Pupil Detectors 3 and 4 is a measure of vertical eye position, independent of

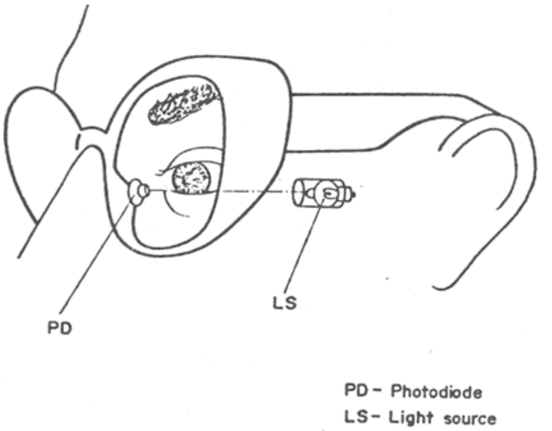


Figure 18. Tracking of the lower lid (Mitrani et al., 1972).

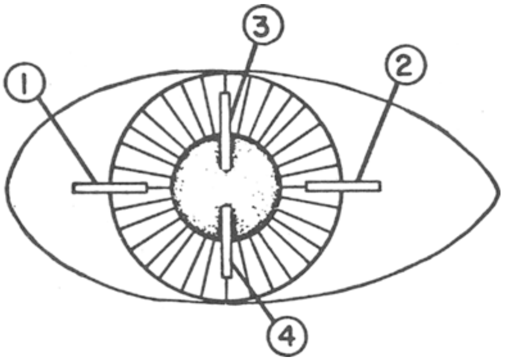


Figure 20. Position of detector fiber bundles on eye image (Wheeless et al., 1966). Areas 1 and 2 are used for horizontal-motion detection, 3 and 4 for vertical-motion detection.

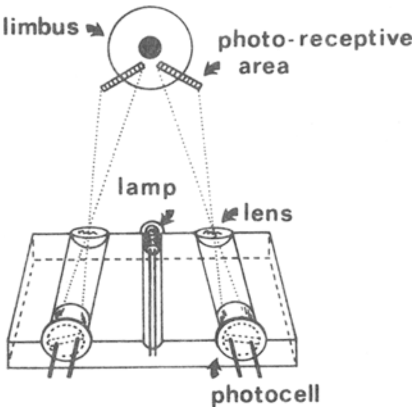


Figure 21. Illumination pattern for two-dimensional limbus tracking (Jones, 1973).

pupil diameter to first order. Another variation described by Jones (1973) uses only two photocells. Using very short focal length lenses (12 mm) and rectangular masks in front of each photocell, he projects 3.8 x .5 mm strips of photocell fields onto the lower limbus in the orientation shown in Figure 21. Horizontal eye motion effects the light sensed by the two photocells differentially, while vertical motion changes them similarly. By separately adding and subtracting the two photocell outputs, a monotonic, though nonlinear measure of vertical and horizontal eye position is achieved with a simple light spectacle mounted device.

Evaluation of limbus and pupil tracking techniques. Many implementations of these techniques yield good results with good accuracies for a reasonable range. The output is an electrical record which can have a good frequency response.

As noted, however, vertical eye movements are a problem. The technique also requires head fixing or a head-mounted device. The latter can be quite light but precludes eyeglasses. Iris coloration can also be a factor in its utilization.

Contact Lens Method

Basic techniques. The most precise measurements of eye movement are made with one of the techniques employing some device tightly attached to the eye with a contact lens (Ditchburn & Ginsborg, 1953; Riggs, Ratliff, Cornsweet, & Cornsweet, 1953; Yarbus, 1967). Conventional corneal lenses are too mobile to be of use, and all measurement systems use special lenses consisting of two individually ground spherical surfaces to fit snugly over the cornea and sclera. For accurate recording, it is essential for the lens to move with the eye—both in steady displacement and during the high acceleration associated with voluntary saccades. Tight fit and lack of slip is achieved by close grinding tolerances and by the suction effect of 20 mm Hg, or more negative pressure, between the contact lens and the eye. Fender (1964) pointed out one way of developing the negative pressure by filling the cavity with a 2% sodium bicarbonate solution which osmoses out through the tissue. Yarbus (1967) achieved the accurate tracking required for image stabilization work by withdrawing a small amount of fluid through a valve after applying the lens. Withdrawing air from under the contact lens is also effective for stabilization but of limited time use because of the lack of corneal irrigation. All of the contact lens systems cause discomfort, and the very tight ones usally required the application of a topical anesthetic. Fender (1964) estimates that even with the best current stabilization, the lens slips behind the eye about 1 arc min during a 1-deg saccade and 6 arc min during a 9-deg saccade. The contact lens and its associated attached material should not be of a size or mass to interfere with normal eye movements. Those which include a protruding stalk preclude normal blinking.

Specific implementations. The most commonly used contact lens system is the "optical lever," in which one or more plane mirror surfaces ground on the lens reflect light from a light source to a photographic plate or photocell or quadrant detector array. (The latter is a solid state photodetector arrangement which produces a pair of voltages proportional to the x and y coordinates of a spot of light falling on the sensitive area. It is used in the double Purkinje image method discussed below.) The reflection from a plane mirror has a number of accuracy advantages over the corneal reflection techniques. First, and least important of all, for the plane contact lens mirror, the change in reflection angle is twice the eye rotation angle rather than 1.3 times as large. Second, the imperfections related to the cornea are eliminated. Most important, however, is the fact that the angle of reflection depends only on eye rotation and is independent of pure linear displacement, as long as the incident beam still illuminates the mirror. This fact makes the system largely unaffected by the inevitable small head movements which interfere with corneal reflection methods. Collimated light is reflected from such a plane mirror and focused with a lens on an image plane. When the eye moves, lateral motion of a plane mirror in a collimated beam does not cause a shift in image position. Only rotation of the eye and the mirror will produce deflections of the projected image (Ratliff & Riggs, 1950). Nevertheless, because of the high inherent accuracy of the system, very careful head stabilization relative to the recording device is usually used.

One early version of the optical lever principle, by Ditchburn and Ginsborg (1953), used a 3-mm-diam optical plate on the lens, 35 deg off the visual axis, to reflect a slit of light through a cylindrical lens camera to moving film for a record. The orientation of the slit

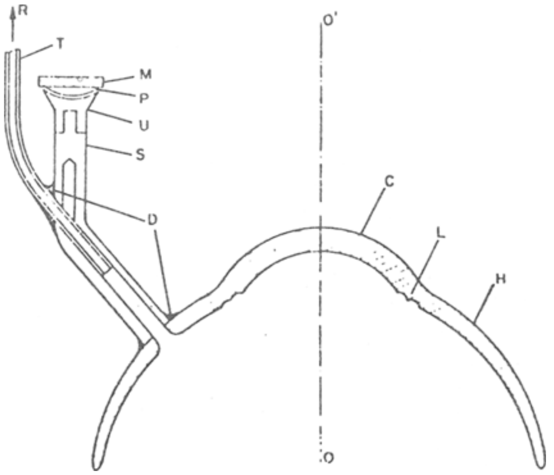


Figure 22. Plane mirror attached to scleral lens (Boyce & West, 1968). Haptic contact lens with stalk/mirror unit attached. 0-0′ optical axis; R to suction reservoir; T polyethylene tube 1/16 in. o.d.; M flat front surface mirror; P grease pad (M may be moved laterally on P for collimation purposes); S stalk 1/8 in. o.d., drilled bore 1/16 in. i.d., to allow entry of suction tube T; C corneal section of lens; L transcurves over limbus; H haptic section; D Durofix seals; U cup.

and of the camera determined whether horizontal or vertical eye movements were recorded. Movements as small as 5 arc sec can be recorded with the optical lever, over a range of ±5 deg. The frequency response of the system is generally determined by the stability of the lens in following the eye and by the recorder response. When the plane of the mirror is not normal to the visual axis, torsional movements of the eye also effect the reflected beam angle. Matin and Pearce (1964) used this fact to advantage. He embedded two mirrors into the contact lens, one temporal and one nasal, so that the reflected beams move in opposite directions during ocular torsion. By resolving the beam deflections from an eye movement into orthogonal rotations about the original axes with an analog computer, they were able to measure three axis rotations to within 2 arc sec.

Those techniques using flush embedded mirrors suffer from changes in mirror properties with tear film, especially when the output is measured photoelectrically rather than photographically. For that reason, several contact lens optical mirror systems employ mirrors or lights mounted on stalks projecting from the lens. Fender (1964), in one version, attached a single mirror to the end of a stalk for two-axis recording and at other times used orthogonal mirrors for three-axis measurement. Construction details of one haptic contact lens unit with a stalk/mirror are shown in Figure 22. A small light, weighing less than 50 mg has also been mounted at the end of a contact lens stalk, parallel to the visual axis, to throw a moving shadow across a photomultiplier face for accurate recording of horizontal or vertical miniature eye movements (Byford, 1962). Byford showed that his aluminum stalk and lamp assembly had mechanical resonance peaks at greater than 200 Hz (the one chosen was at 350 Hz) and were adequate for the calculated 150-Hz bandwidth required for miniature saccade displacement recording. Further tests using a 1/8-in. o.d. hollow Perspec stalk showed it to have a high enough resonance peak for satisfactory use for retinal image stabilization. One way of creating a small light source on the contact lens without a lamp and its associated power leads, and thereby permitting lid closure, is by using a small radiating source. Nayrac, Milbled, Parquet, Leclerq, & Dhedin (1969) placed a small bit of the luminescent phosphor containing radioactive tritium on the contact lens. The 1-mm^2 surface glowed brightly under ultraviolet illumination. The position of the spot, and thus the eye, was monitored in two axes by use of two optical density wedges, placed in front of separate photomultipliers for recording horizontal and vertical motions. They report a resolution of 20 arc min, which is poor for a contact lens system, but a useful range of .3 to 30 deg.

A recent addition to the repertoire of optical contact lens methods is one in which a multiple line pattern, fixed to the contact lens stalk, is imaged through a slit on moving film, as shown in Figure 23. The film pattern of one thick and several thin lines, shown schematically in Figure 24, contains all the information needed for measurement of vertical, horizontal, and torsional eye movements as a function of time.

The principal nonoptical contact lens measuring method is the search coil technique introduced by Robinson (1963). Two small wire coils, oriented perpendicularly to each other and embedded in the contact lens, pick up an induced voltage from two large perpendicular electromagnetic coils surrounding

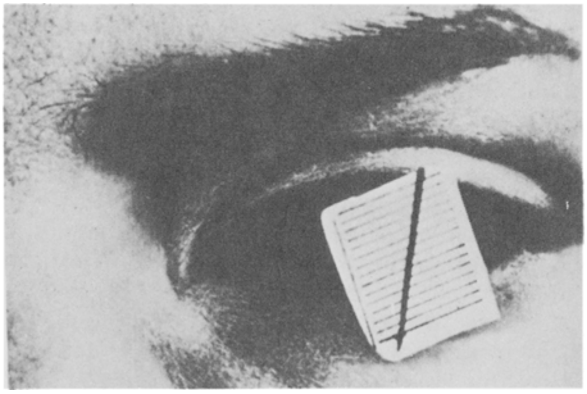


Figure 23. Line diagram fixed to the eyeball by means of the scleral contact lens (Forgacs, Jarfas, & Kun, 1973).

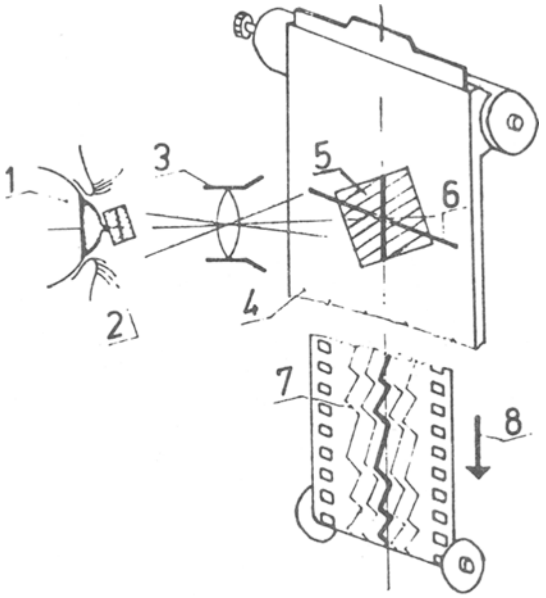


Figure 24. The modified photonystagmographic method of Forgacs (Forgacs et al., 1973). When properly set, on the surface of the film cassette facing the lens (4) of a special camera (3) provided with .1-mm-wide transversal slit (6) the magnified sharp picture (5) of the line diagram fixed to the eyeball (1) by means of the scleral contact lens (2) is obtained. This picture is crossed by the transversal slit (6). The thick line of the line drawing is perpendicular to the slit, while the thin lines intersect it at an angle of 30°. On the film moving downwards (8) in the cassette behind the transversal slit at a constant speed of 10 mm/sec, curves in a number corresponding to the number of points of intersection between the lines of the diagram and the transversal slit are depicted as the eye moves. This set of curves makes up the photonystagmogram (7).

the subject. The induced voltage in each coil varies only with the sine of the eye angle relative to the magnetic field and is independent of head position within the uniform portion of the field. Use of different frequencies or quadrature phases in the two large coils permits the detection of the angle between each search coil and each driving plane and, therefore, stable three-dimensional angular localization to the order of 1 arc min over large angular excursions. Voltages are read out through light flexible wires extending from the lens. Extension of this technique to implanting the coils on the globe for chronic animal experiments permit the precise repeatable localization of eye position.

Evaluation of contact lens methods. Although the contact lens systems offer the best resolution of any system down to 5-10 arc sec, they do so in general at the sacrifice of range. They are normally applicable for the study of miniature eye movements and, with the exception of the magnetic search coil method, are inappropriate for movements of greater than 5 deg. The expense and discomfort of the contact lens makes it a technique more suitable for use on a few subjects for physiological studies of fixation than for widespread investigation on the normal population.

The dangers of fitting a contact lens with negative pressure are also considerable. There is the possibility of deforming the cornea and the worse hazard of damaging the accommodation muscles as a result of the pressure stress placed upon them.

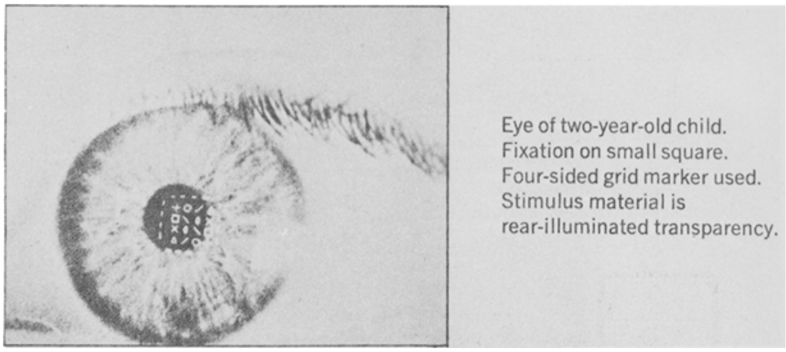
Point of Regard Measurement: Tracking of Corneal Reflection Center with Respect to the Pupil Center

General principle. It is often of interest to the investigator to know the fixation point of the subject as it falls in space rather than the position of the eye with respect to the head. In other words, one wants to determine where a subject is looking regardless of whether his eye got there through eye rotation or head motion. Clearly, the two measurements are equivalent if the head is fixed; or the position of the head may be measured by any of a number of techniques and the position of the eye in space deduced by summing the relative position of the eye to the position of the head. Various head-position measurement techniques are discussed in a later section of this paper.

One of the main problems of measuring eye direction optically is that of separating lateral motion of the eye relative to the observer or the sensor and rotary motion of the eye relative to the scene. For example, eye rotation can be measured by tracking the corneal reflection of a suitable source; however, it is not possible to distinguish this from motion of the corneal reflection which results from translation. Unless the corneal reflection tracker is the head-mounted variety described in a previous section, lateral motion of the head will introduce large errors--approximately 1 deg of error for every 5×10^{-3} in. of lateral head motion. It is difficult to eliminate this head motion completely by any fixing methods.

A desirable method is one which would allow relatively free, natural head motion and measure the position of some parameters of the eye in such a manner that they would indicate eye rotation only and consequently point of gaze in space. This may be done by measuring features of the eye that only change with rotation, or by measuring the positions of various details on the eye which move differently as a function of head motion and eye rotation, such that pure eye rotation can be deduced from them. Two features which satisfy this requirement are the corneal reflection and the center of the pupil. Each has been independently used for eye-position determination, but, differentially, they provide a powerful tool.

Specific implementations. The corneal reflex was discussed at length in a previous section. It possesses a very useful property. If a subject is looking directly at a light source, and an observer is looking at the subject's eye from a position at or very near the



Eye of two-year-old child.
Fixation on small square.
Four-sided grid marker used.
Stimulus material is
rear-illuminated transparency.

Figure 25. Photograph from wide angle Mackworth camera (Courtesy Polymetric Co.).

light source, then, from the obvious considerations of symmetry, the corneal reflex will appear to the observer to be in the center of the subject's pupil. This result may be used in either of two ways. First, the image of the point on which the subject is fixating will be found in the center of the pupil. Second, the subject's angle of gaze with respect to the light source is approximately proportional to the distance between the image of the light source and the center of his pupil. These two properties are equivalent to each other. In the first, multiple light sources are used,and point of regard is determined by which light source is imaged in the center of the pupil. In the second, a single light source is used, and the error between its image and the center of the pupil is measured. Both results are monotonically related to the point of regard. Measurement of the center of the corneal reflection from the limbus is also possible but poses practical problems.

Both these approaches are applied to methods of eye point-of-regard measurement. The first is effectively the inverse of the conventional corneal reflex method where the reflections were superimposed on the scene being viewed by the subject, and the eye position is determined by where the corneal reflection falls on the scene. In the wide angle Mackworth camera, the illuminated scene is itself used as the light source for the reflection. By photographing the eye at high magnification, the corneal curvature produces a superimposed image of the field being viewed, with the position "being" fixated lying directly in the center of the pupil (See Figure 25). Since the entire field is being imaged over the small area of the cornea, resolution is lost relative to the simple corneal reflex method. This method is therefore not very amenable to high resolution analysis. Also, in order to photograph a scene reflected from the cornea, the field must contain bright light sources against dark backgrounds. It does, however, provide a method of obtaining eye fixation points without excessive head restraint requirements. All that is required is that the pupil center be visible to the observer or the observing instrument.

A commercial instrument which performs this type of measurement is the Polymetric Company wide angle eye movement recorder. This instrument outputs a photograph (Figure 25) from which fixation may be determined, or a 4 x 4 digital position output provided with a television system. It offers a 40-deg maximum field of view, ±2.5 recording accuracy, when manual determination is made, and a 1 part in 4 electronic accuracy. The sampling rate is 12 photographic frames/second, or 60 TV fields/second. The system requires no bite board. The subject looks at the scene through a viewing aperture.

In another application of the wide angle corneal reflex technique using multiple light sources, Salapatek and Kessen (1966), and later, Haith (1969), developed a wide angle corneal reflex technique for use with the human infant. The arrangement of fixed infrared illuminators over the infant's head is shown in Figure 26. The TV picture of the eye contains the corneal reflex of some or all of the six infrared illuminators; scoring is done using video tape on a frame-by-frame basis.

The x-y coordinates of the pupil center, and of a particular infrared reflection, are measured with a

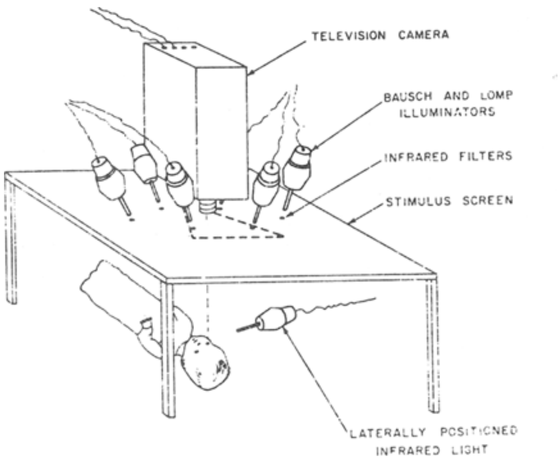
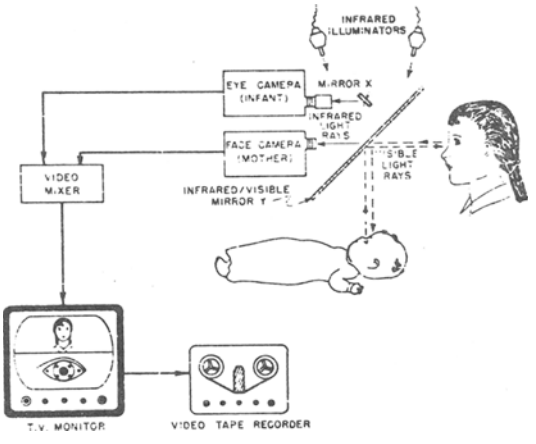


Figure 26. Illustration of a system for recording eye behavior in infants ([Haith, 1969] Copyright [1969] by the American Psychological Association. Reprinted by Permission.).



An illustration of a procedure for recording eye-to-eye contact between mother and child. (A mirror at a 45-degree angle to the visual axes of the mother and the baby reflects visible light thus producing an apparent natural vis-à-vis image to both. The infrared image of the infant's eye is transmitted through Mirror Y, reflected by Mirror X, and then recorded by the top television eye camera. The infrared image of the mother's face is transmitted by Mirror Y and recorded by the lower television face camera. The outputs from these two cameras are mixed into one picture and then recorded onto video tape.)

Figure 27. An illustration of a procedure for recording eye-to-eye contact between mother and child (Haith, 1969) (Copyright [1969] by the American Psychological Association. Reprinted by permission).

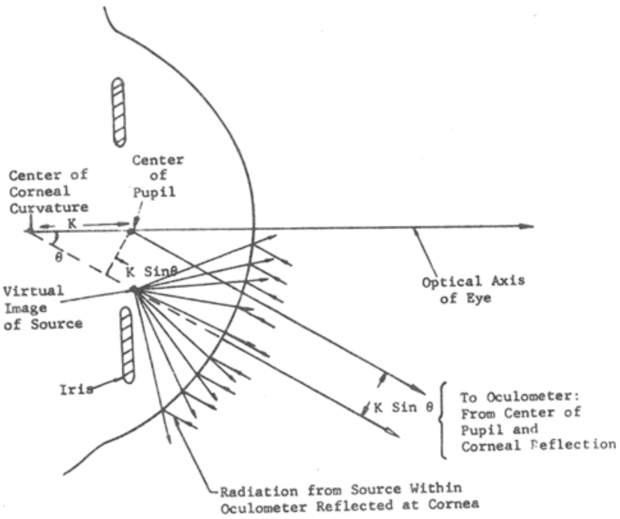


Figure 28. Displacement of corneal reflection from center of pupil, K sin θ, is proportional to the angular direction, θ, of the eye and is independent of the position of the eye (Merchant & Morrissette, 1974).

cursor whose position is outlined by a superimposed cross on the video monitor. By use of a video mixing system, a second TV picture can be added to the first so that each frame contains both eye position and a picture of the field being scanned, as shown in Figure 27.

The wide angle Mackworth camera uses what effectively is a wide field corneal reflex and determines which part of it appears in the center of the pupil. A second version of this method is to use a single point corneal reflex and to find how far it lies from the center of the pupil. This principle was put into practice by the oculometer, developed by Merchant (Note 5) at Honeywell. In the oculometer, a single light source is used to produce a corneal reflex on the pupil. The problem of obtaining net eye motion with respect to the scene is overcome through the tracking of two elements of the eye that move differently with eye position and head position. As discussed above, the pupil is viewed by observing optics that are coaxial with the illumination optics in the oculometer. The corneal reflection appears always in line with the center of corneal curvature. The apparent displacement of corneal reflection from the center of the pupil is thus equivalent to the apparent displacement of the center of corneal curvature from the center of the pupil, which is obviously a function of eye rotation only. See Figure 28 (Merchant & Morrissette, 1974). This phenomenon may be graphically seen from Figure 29, which shows that the corneal reflection with respect to the center of pupil position remains unchanged as a result of lateral head motion and changes for eye rotation only.

A number of versions of this instrument exist which automatically find the pupil center and corneal highlight in the x-y plane and calculate eye position from the relative vector. These include the Honeywell

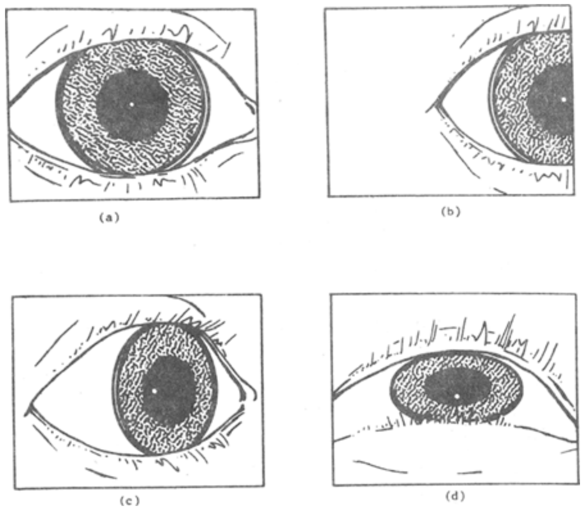


Figure 29. Effects of eye translation and rotation on corneal reflection–pupil center (Merchant & Morrissette, 1974): (a) Eye looking straight ahead–note corneal reflection is at center of pupil. (b) Eye looking straight ahead but laterally displaced–note corneal reflection still at center of pupil. (c) Eye looking to side–corneal reflection displaced horizontally from pupil center. (d) Eye looking up–corneal reflection displaced vertically from pupil center.

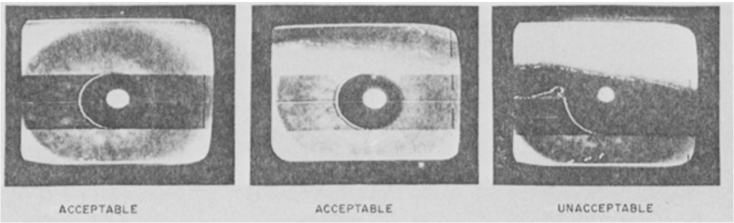


Figure 30. Operator indicators superimposed on TV image of eye as a function of threshold setting showing status of measurement. Measurement is good when pupil is properly delimited (Courtesy Whittaker Corporation).

oculometer (Merchant & Morrissette, 1974), a portable oculometer for transportation studies developed at the Department of Transportation (Davis, Note 6), the EG&G/Human Engineering Laboratory facility (Monty, 1975; Hall, Rosenberg, & Monty, Note 7); a laboratory oculometer developed by the University of Alberta (Petruk, Note 8); and the Whittaker Corporation eye view monitor (Sheena, 1973).

Several techniques are available to present a nonvisible light source to develop the corneal reflection and to locate the pupil center and corneal reflex on the image. Honeywell and Whittaker use an invisible infrared light source for the corneal reflection and use a TV camera with sufficient sensitivity in the infrared region to detect this highlight easily. EG&G, in their original version, used visible light. By having all of the light source in the room polarized, except for a small portion and by passing all returned light through another polarizing filter to a low light level TV camera, the corneal highlight was sharply defined.

With the Honeywell oculometer, and others, the pupil is backlighted; and the resulting image is the bright pupil and even brighter corneal reflex as in Figure 11. In some Whittaker units, and the EG&G/Human Engineering Laboratories system, the pupil is black as in Figure 30.

The center of the pupil was determined in Merchant's original design by an image dissector which traced the circumference of the pupil and tracked it as it moved. As with any image dissector tracking system, this required some time for reacquisition of the pupil whenever it was lost, as, for example, during a blink. However, currently, all of the systems appear to use a conventional TV raster system in which the geometrical coordinates of the pupil center and of the highlight are determined by timing signals on the video scan. For example, if the corneal reflex corresponds to the brightest point in the picture, and it was located in the upper left-hand portion of the picture a quarter of the way down from the top and a quarter of the way in from the left, the highest voltage on the video scan would occur 25% of the time from the beginning of a new field following the vertical sync and 25% of the time across a horizontal scan line. A variety of processing and pattern recognition aids in determining the center of the pupil and corneal reflection correctly have been developed in connection with video systems. Indicators are also superimposed on the video as operator aids; see Figure 30 (Sheena, Note 9). A silicon vidicon television system is also generally used for its high sensitivity, especially in the IR region.

The most advanced Honeywell oculometer can follow large head motion by maintaining a field of view which covers the subject's eye by driving a two-axis mirror which compensates for gross head motion. The position of the head when the eye is lost is detected through a search pattern (See Figure 31).

With the EG&G/HEL system, the subject sits in a chair and views a projection screen without even knowing that his eye is being observed with a camera located underneath the screen. This camera leads to a video processing system also attached to a PDP-11 computer. Eye movement and fixation information is extracted and recorded in any of a number of formats, including video tape recording and others (See Figure 32).

A variant of the basic single corneal reflection-pupil center vector method is used by Hochberg (Note 10). He employs two corneal reflection spots to eliminate the effect of distance variation from the optics to the subject or overall optical system magnification. The separation between the two spots becomes the basic length around which all the other measurements are normalized. This therefore eliminates the need for absolute calibration. The pupil center position is then measured with respect to a point equidistant between the two corneal reflection spots.

Most of these systems use a digital computer. Sophisticated processing is therefore possible and correction and linearization for various limitations of this measurement principle can be overcome. In particular, the corneal reflection method is generally limited by the curvature of the corneal bulge to less ±15 deg. Beyond that, the cornea flattens out and the measurement becomes nonlinear, although still monotonic. There may also be imperfections and asymmetries in any individual cornea that makes the measurement nonlinear; changes in the tear film also cause a problem. As the pupil constricts and dilates, it does not normally maintain a fixed center with respect to the eyeball. All of these problems can be eliminated to a large extent by the processing which is incorporated in the computer and circuitry of the systems.

Any system which determines the pupil center for eye movement measurement also can make pupil area or pupil diameter available as an additional output

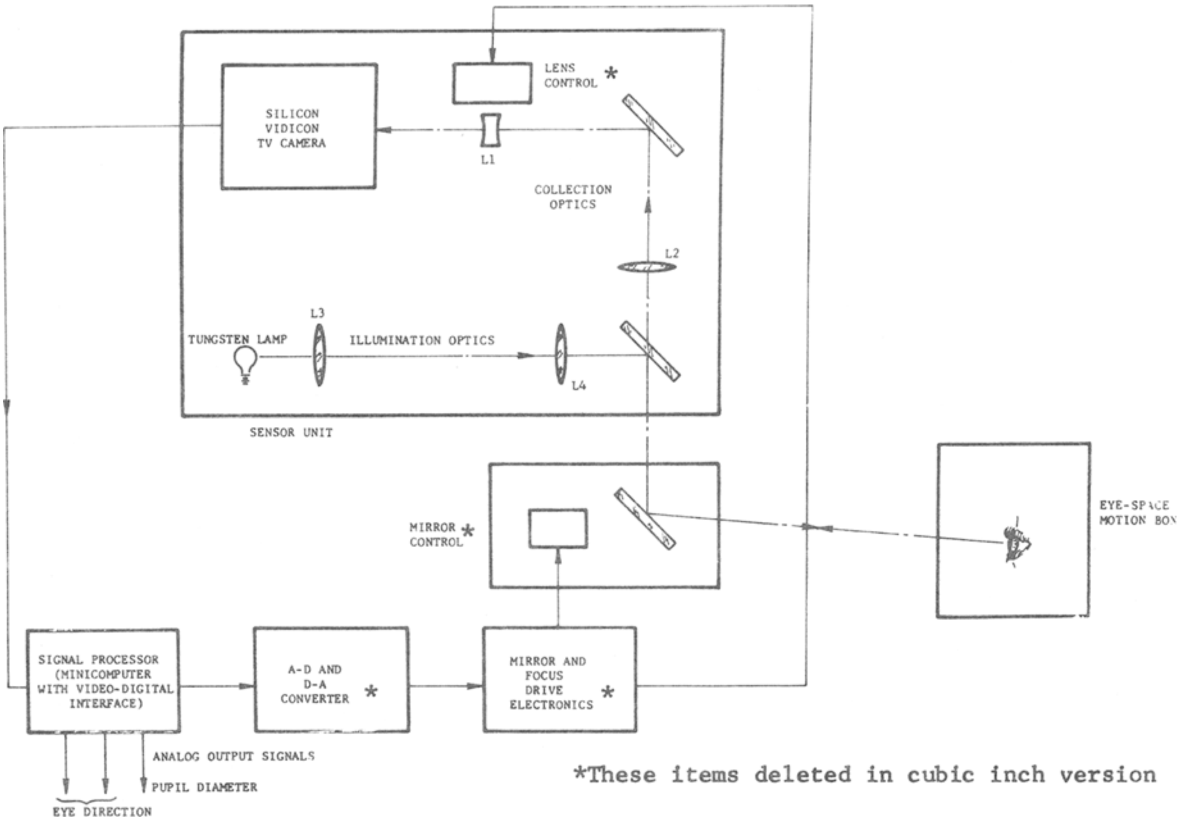


Figure 31. Schematic of the cubic foot remote oculometer (Merchant & Morrissette, 1974).

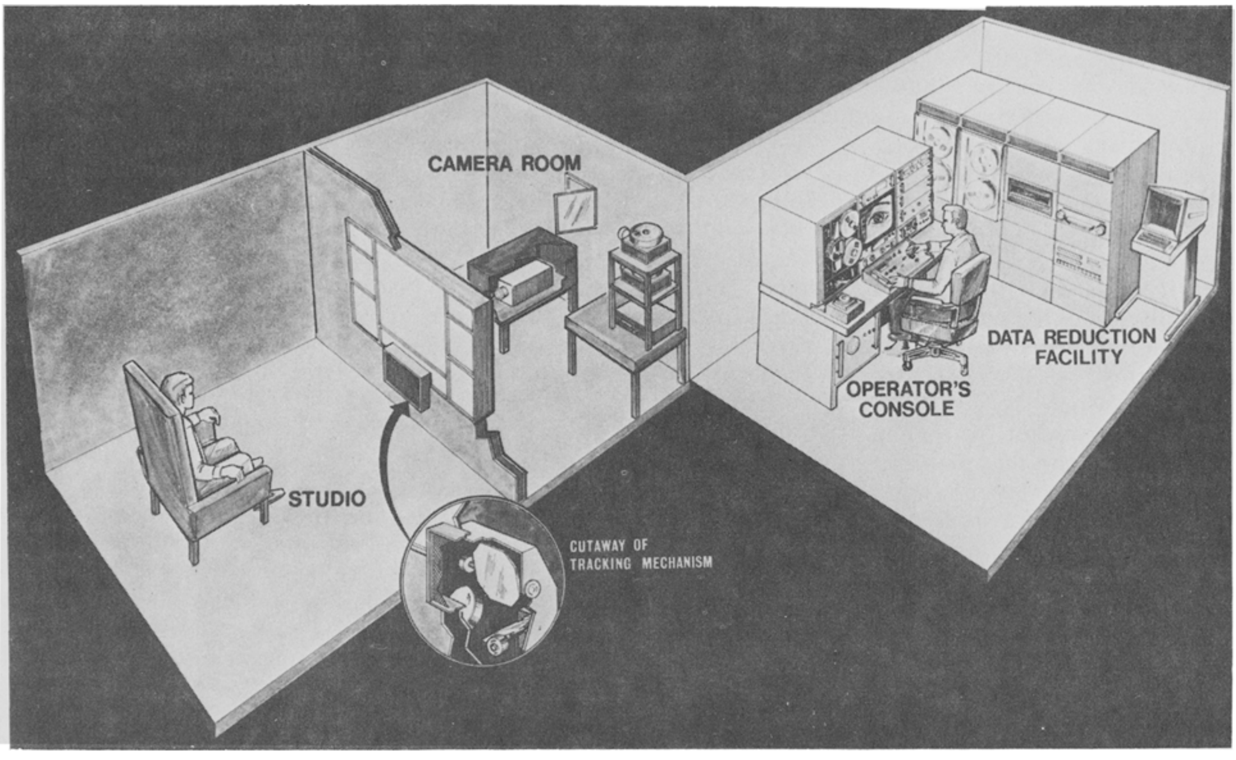


Figure 32. EG&G-HEL oculometer system (Monty, 1975).

with virtually no additional electronics processing. With continued interest in pupil diameter as a measurement of tension or arousal, this technique offers the ability to monitor the effect on pupil diameter of different portions of the scene being scanned.

At the present time, there are two known systems commercially available: (1) The Honeywell Oculometer Mark II, which allows a cubic inch of motion, and the Mark III, which allows a cubic foot of motion; (2) the Whittaker Corporation eye movement monitor is also commercially available and allows up to a foot of head motion. The Honeywell unit provides an accuracy of 1 deg, for a maximum range of 60 deg horizontal and 40 deg vertical, with time constant of .1 sec. The Whittaker unit provides an accuracy of 1 deg, for a range of 40 deg horizontal and 30 deg vertical, with a sampling rate of 60/sec. Both systems also provide instantaneous pupil diameter.

Evaluation of the corneal reflection-pupil center measurement. There is no question that maintenance of a fixed head or attachments to the head are difficult, uncomfortable, unsuitable for many subjects, and may require long setup time. Therefore, the methods that measure eye point of gaze relative to space without requiring any head position measurement or stabilization, offer considerable advantage. They are comfortable; the data is generally in a form very amenable for processing; and the illumination is usually infrared and, therefore, not annoying or disturbing. Many of the units also incorporate a great deal of information and signal processing, which allows broadening the limitation of eye movement measurement to a greater range of eye motion and even larger head movement allowances, with signal improvements by averaging, linearization, and various other corrections.

This advanced and sophisticated instrumentation is more expensive than the various other simpler, more direct methods of eye movement measurement. It is also generally bulkier and more involved to learn to use, although easier once learned.

What these methods may lack is speed; the television systems can operate only as fast as 60 samples/second. The basic speed limitation comes from the lag of the TV camera tube. Also, precisions and accuracies are not as good as those that can be obtained with head-fixed contact lens, limbus tracking, or corneal reflex methods.

Measurement of Eye Rotation by the Double Purkinje Image Method

Principle. As light passes through the eye, reflections occur at the various interface surfaces. At the surface of the cornea, there is the well-known corneal reflection or the first Purkinje image, a second one occurs at the rear surface of the cornea, a third one occurs at the front surface of the lens, and a fourth occurs at the rear surface of the lens where it interfaces with the vitreous humor. The second Purkinje image is relatively dim, the third Purkinje image is formed in a plane far from the others, and these two are not used in this measurement method.

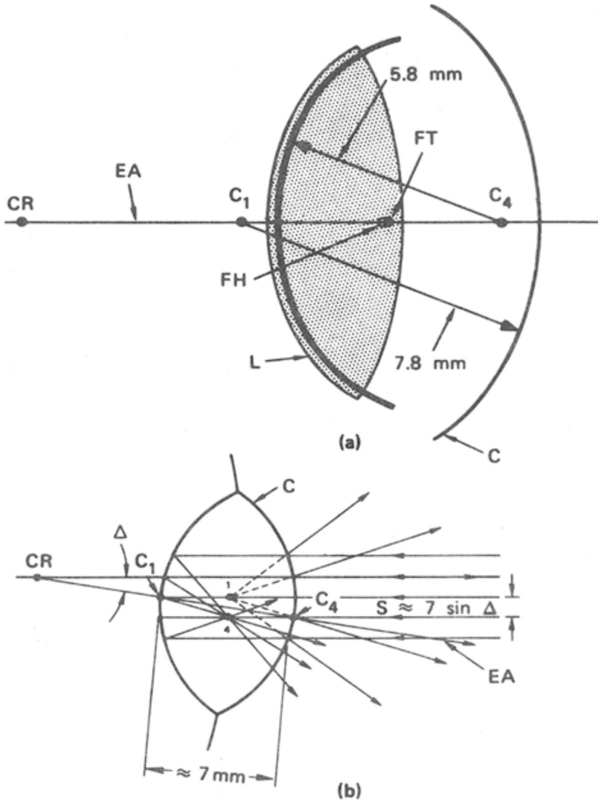


Figure 33. Simple field representation of cornea and rear surface of lens (Cornsweet & Crane, Note 11). Location of the first and fourth Purkinje images for (a) collimated light on the eye axis and (b) collimated light at angle Δ from optic axis of the eye; EA, eye axis; FT, first Purkinje image; FH, fourth Purkinje image; L, lens; C, cornea. The dark section of arc is the equivalent mirror for the fourth Purkinje reflection.

Cornsweet and Crane (1973) used the first and fourth Purkinje reflections as the two features of the eye which they track. Like the relationship between the corneal reflection and the pupil center, these two marks move together under eye translation but differentially under eye rotation.

For purposes of simplicity, the two surfaces in question–the front of the cornea and the rear of the lens–are assumed to resemble a clam shell arrangement (shown in Figure 33) where both surfaces have the same radius of curvature and have a separation equal to their radius of curvature. C_1 is the center of curvature for the cornea, and C_4 is the center of curvature of the rear of the lens. If these two surfaces are assumed to be spherical, the effect of collimated incident light is to produce

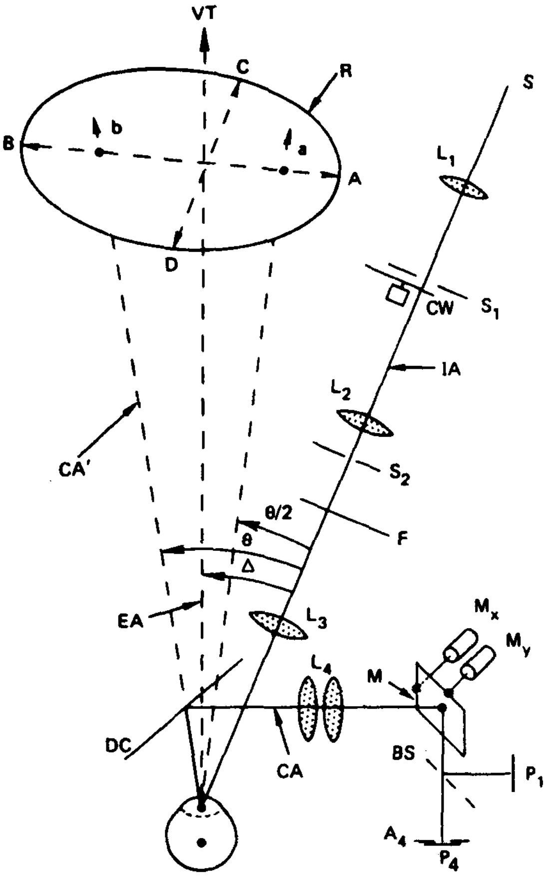


Figure 34. Schematic layout of the double Purkinje image eye tracker (Cornsweet & Crane, 1973). Schematic of the eye-tracker optical system: VT, visual target; R, allowed range of eye movements; IA, input axis; CA, collection axis; CA', extension of collecting axis; S, light source; S_1, artificial pupil image at pupil of eye; CW, chopper wheel; S_2, source of Purkinje pattern, imaged at infinity; DC, dichroic mirror; M, front surface mirror; M_x and M_y, motors that drive M in x and y direction, respectively; BS, beam splitter; P_1 and P_4, quadrant photocells, A_4, aperture in front of P_4. Focal lengths of lenses L_2, L_3, and L_4 are 60, 150, and 90 mm.

the two images roughly in the center, equidistant between the two surfaces. The distance that each image moves as a result of eye rotation is related to the distance from the center of rotation CR to the center of curvature for the surface that forms it. The separation of the two images as a function of eye rotation Δ is approximately given by $S = 7 \sin \Delta$, where S is in millimeters.

Change in separation between these two images therefore is directly related to the angular rotation of the eye and independent of head translation.

Implementation. Figure 34 shows the optics employed for this kind of measurement. From a light source S, Circular Aperture S_2 forms two Purkinje images on the eye. Collection Optics L_4 view the eye and image the two Purkinje reflections on the two photodetectors, P_1 and P_4. These are four-quadrant photodetectors which yield a signal proportional to the position of the image off center. They control servomotors to drive each image continuously to center. The final output is the difference in the electrical signals that are generated in the servomechanisms required to maintain a centered null condition. As the eye translates, both images move in the same manner, and the difference is effectively zero. This is performed in both axes. The two Purkinje images are separated by the optics so that they can be tracked independently.

This instrument has been developing through a number of stages. The recent units have allowable head motion of ±.5 cm in all three axes. Automatic focusing has been included to allow head movements along the optic axis. The field of view allows a coverage of ±15 deg vertically and horizontally. Although very precise alignments are necessary to obtain the proper image position; the illumination optics have themselves been controlled to track the motion of the eye and place the illumination on the pupil.

The bandwidth of the system, which is limited by the servomotors which drive the photodetectors, is quite high–up to 300 Hz. The instrument also boasts an accuracy of 2 min of arc in response to 1 deg of step.

Evaluation of the double Purkinje image eye tracker. This technique represents a new and promising way of monitoring eye movements. It is the only head-movement–independent eye-tracking method which can measure eye position with such accuracies. It has a higher frequency response than the television systems. In these ways it is superior to the pupil center-corneal reflection center method.

It is planned to integrate accommodation measurement using the Stanford Research Institute optometer (Cornsweet & Crane, Note 11), into this system so that the power to the eye is also measured along with eye rotation for what is effectively a three-dimensional eye position determination.

The eye tracker falls slightly short of other techniques in the field of view (±15 deg) which is pupil-diameter dependent. It also requires higher illumination than the other techniques in order to bring the fourth Purkinje image above the noise. The allowable head movement is, still, not very large; but this may also be further increased. It appears also that the optics need to be fairly close to the eye. What the system cannot provide is pupil diameter, but this may also be later incorporated.

Normally for high-precision measurement using this instrument, the head is stabilized with a bite board. Some experiments usually requiring contact lenses have been performed with this device.

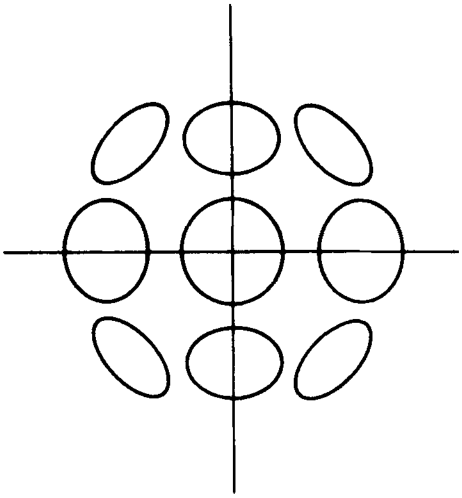


Figure 35. Apparent ellipticity of pupil as eye rotates.

Measurement of Fixation Point by Determining the Rotation of a Plane Attached to the Eye

General principles. In this section are grouped the methods which measure some parameter of the eye that varies with eye rotation but is for the most part independent of head translation.

These methods include measurement of the orientation but not translation of some imaginary or real "plane" attached to the front of the eye relative to a fixed observer. One way is to determine the apparent ellipticity of the pupil to an observer. Other ways are to attach just such a plane to the eye, a plane mirror with a contact lens or the plane of a search coil imbedded in a contact lens (Robinson, 1963).

Another method invariant to head motion is the tracking of an image focused on the retina. If an eye is fixating a particular point in space, then that point will always fall on the fovea regardless of head translation or eye rotation. This principle was put into practice by a retinal image tracker developed by Cornsweet (1958). Again, the principle here is the measurement of rotation of a plane attached to the retina.

Specific implementations: Ellipticity of the pupil. When the pupil is viewed head on, it appears circular. If the eye rotates, the pupil will have an apparent ellipticity. The apparent shape of the pupil to a fixed observer will not vary as the head of the subject moves but only as the subject's eye rotates. If the eccentricity of the pupil is measured, therefore, it would indicate the rotation of the eye only. One problem, however, is that the measure is an even function of eye position, and some other course determinants would have to be used to differentiate between up and down and right and left. A second problem is that a rather involved geometrical computation would be required. See Figure 35. There have, therefore, been no successful implementations of this method (Hall, Note 4).

Specific implementations: Contact lens method. A plane mirror or a search coil attached to the eye provides a geometrical "plane" whose orientation may be determined independent of translation. These two approaches were discussed in detail in the section concerning specific implementations of the contact lens methods.

Specific implementations: Tracking of a retinal image. The retina is usually observed under wide field illumination, but if the field is focused to a small spot on the retina and the subject is fixating it, then the image of the illumination spot clearly remains on the same point on the retina. Clearly, also, the retinal image of a second point near the first, and in the same plane, would be fixed to the retinal image of the first.

Another way of viewing this concept is to consider a subject looking at a very distant object, say a star; the image will not shift on his retina if he translates his head, but will obviously move if he rotates his eye. A collimated light source is equivalent to a very distant object.

Cornsweet (1958) had a subject fixate on one point, and he projected a small rectangle of light on the optic disk as shown in Figure 36. If the relation between the fixation point and the spot is constant, the spot position on the disk shifts only with fixation changes. A pronounced blood vessel was selected on the disk, and the relative shift of the imaged spot was measured by the distance the spot had to be moved to be repositioned on the blood vessel. In other words, whenever fixation changed, the spot went off the blood vessel and was repositioned there. This was actually accomplished by a flying spot scanner which scans this vessel. The instantaneous reflected light was viewed with a photomultiplier (See Figure 37). The time from the beginning of the scan to arrive to the reference and vessel was directly related to shifts in fixation.

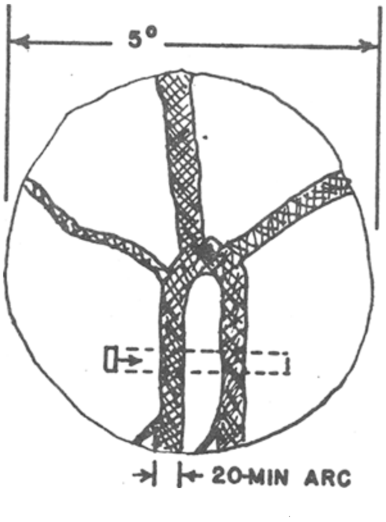


Figure 36. Scanning of retinal vessel (Cornsweet, 1958). Drawing of the optic disk, right eye. The small rectangle is the scanning spot. The dashed lines indicate the locus of its path of movement.

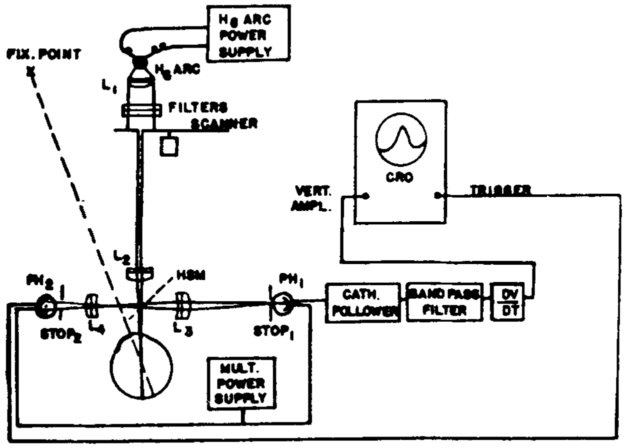


Figure 37. Fundus tracking system (Cornsweet, 1958).

Resolution of 10 sec of arc was possible with this method. Resolution was limited primarily by instrument noise. Also, blood vessel diameter changes and cross-talk from vertical eye motion were problems. Large eye motion would move the spot off the disk and lose the measurement.

This is a very precise method not requiring a fixed head. It seems to be limited only by the practical problems associated with viewing the retina. Technological advances in this area are certainly possible.

Head Movement Measurement to Obtain Point of Regard

All eye movement monitoring techniques fall broadly into two categories–those that measure the position of the eye relative to the head and those that measure the orientation of the eye in space. For studies of the eye movement control system, per se, the first category techniques normally suffice. When the concern is with identifying the elements in a visual scene that are being fixated or scanned, however, the orientation of the eye in space, or the "point of regard," is required. Any of the first category methods can be adapted for use in the free head fixation pattern application by measurement of head angle and position (See Figure 43). Whether or not head linear position is required in addition to angular orientation depends, of course, on the freedom of head linear displacement permitted, the distance to the material being viewed, and the desired system accuracy. For this consideration, we also review some common techniques for measurement of head position, all of which can be combined with eye position recording to yield the point of regard.

The only eye movement methods which give the angle of gaze relative to a reference point in the visual field are those with a camera mounted to the head, those that track two separate points in different planes on the eye, or those that measure retinal plane rotation. Any of the methods which track a feature on the front of the eye or EOG must be corrected for head position to give the point of regard.

Current and advanced methods of monitoring head angle (head line of sight, LOS), suitable for combination with eye measurement techniques to yield eye point of regard, are given below.

All of the head measurement techniques, with the exception of the eye-tracking video method discussed in conjunction with the corneal reflex-pupil vector systems, require some attachment to the head. The attachments may be as unobtrusive as reflecting surfaces or distinctive optical targets taped to the head, spectacles, or bite board; or they may involve a helmet to carry the transducers. Basically, five methods have been utilized: optical, ultrasonic, electromagnetic, inertial, and mechanical. All but the last can be free of any mechanical connection between the subject's head and his surround.

Optical head position sensors. Optical x-y tracking techniques that have been developed for tracking rockets or small variations in thickness in industrial processes can be used to locate the x-y coordinates of a small point attached to the head. The basic scanning methods discussed under the corneal reflex implementation are applied to locate the brightest or darkest spot in a scene servo-drive the camera or mirrors to keep it centered. One common variation is the use of a circular scan pattern which uses phase-sensitive detection of the video signal to determine the required direction to draw the circle center for alignment over the target, as shown in Figure 38. These devices can be stabilized to resolve angular motions of a few seconds of arc with appropriate optics. By using three such targets, all translations and rotations of the head could be calculated.

The most common optical head tracking devices employ a helmet of some sort with an array of light sources (or photodetectors) on it, and the compli-

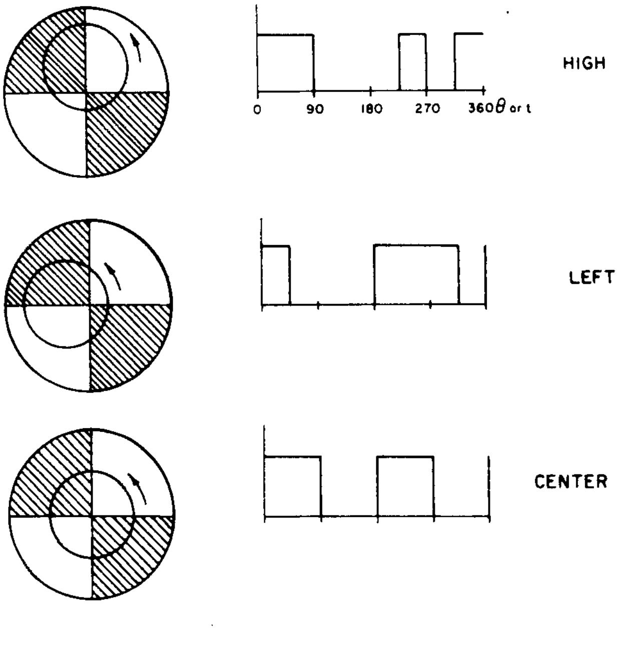


Figure 38. Circular scan x-y tracker.

mentary devices fixed to the surround. One such system, built with the idea of measurement of astronaut head angles relative to a large visor or a fixed outer shell, is shown in Figure 39. It uses three miniature pulsed infrared LEDs on the helmet liner and an array of eight photodiodes as receivers (Chouet & Young, 1974). The cross-coupling between head angle measurements in various axes is minimized with a small computer and compensation circuit.

The need for accurate knowledge of head position for a variety of "visually coupled systems" for hands-off localization and aiming has led to the development of accurate and reliable head line of sight sensing systems. One such system, shown in Figure 40, was developed for tracking the pilot's line of sight within the restricted confines of a cockpit (Ferrin, Note 12). The sensor surveying unit (SSU), fixed to the laboratory or cockpit, emits two thin fan-shaped beams of IR which sweep across the photodetectors in the helmet, triggering each one at the moment of intersection. Use of the IR fans and detectors on each side of the helmet increases the range of head motion allowed while still tracking the line of sight. Although this and related systems appear bulky because of the helmet and related display equipment, the actual hardware which must be worn on the head for head tracking is merely two or four miniature photodetectors.

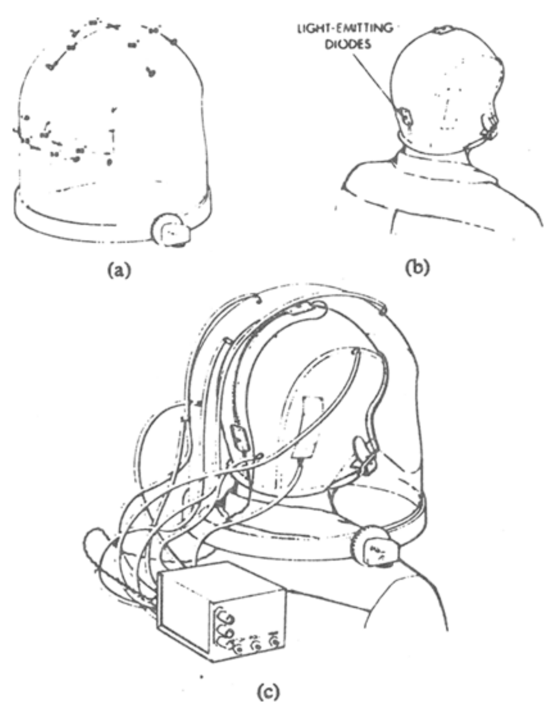


Figure 39. Optical head position sensor (Chouet & Young, 1974). (a) Helmet and disposition of eight photodetectors. (b) Helmet liner with two LEDs. (c) Monitoring equipment.

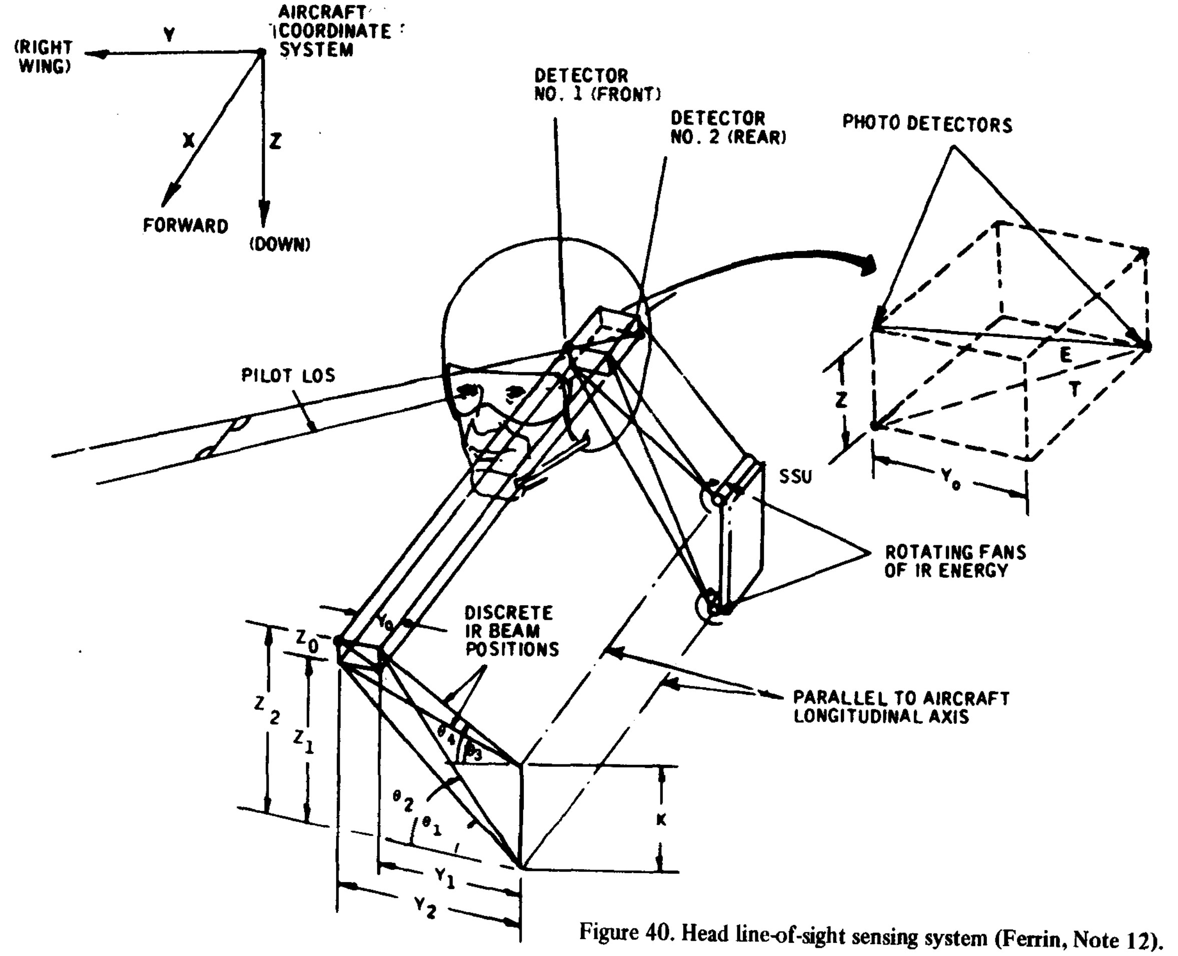


Figure 40. Head line-of-sight sensing system (Ferrin, Note 12).

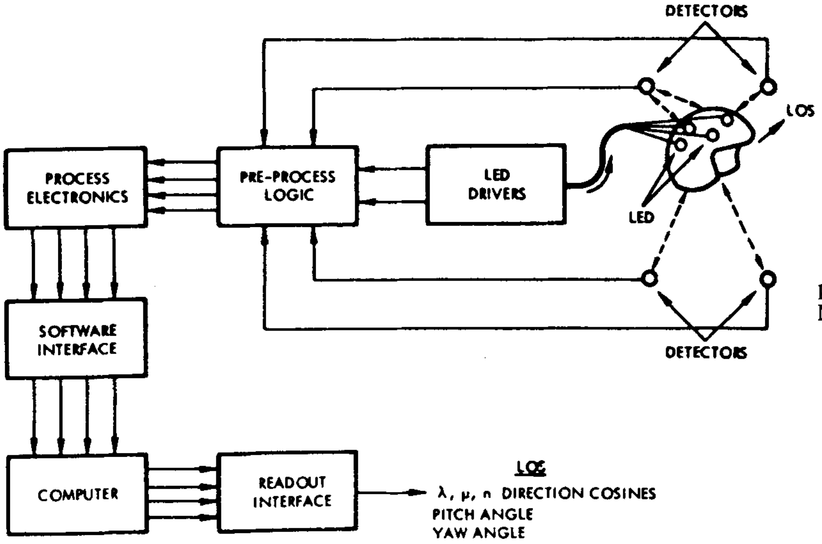


Figure 41. LED line-of-sight head position measurement system (Haywood, Note 13).

A newer design proposed for the helmet line of sight measurement uses four LEDs mounted on a helmet, each one pulsed at a different frequency (Haywood, Note 13)(see Figure 41). Up to four optical linear position proportional detectors are positioned in the laboratory fixed frame. Each detector measures the x-y coordinates of the *image* of each source in its field of view and thereby provides the computer with the information required for the resolution of the line of sight angles of the helmet. The goal for such a system is ±1 deg static accuracy in head pitch and yaw, over a range of ±75 deg about each axis.

Ultrasonic head position sensors. The use of multiple ultrasonic transmitters and detectors on the helmet and in the laboratory permits head position to be sensed by measurement of the distance from each source to each receiver by means of the sonic delay time. Practical implementation of a multiple source system to measure head position and orientation was demonstrated at MIT's Lincoln Laboratory for computer graphics applications. One possible arrangement of ultrasonic transmitters and receivers, shown in Figure 42, is especially useful for pitch and lateral rotation head movement sensing (Sawamura, Note 14). The weight of the helmet-mounted portion can be reduced by mounting the transmitter, rather than the receivers, on the helmet. Tests of a similar system showed static errors of less than 1 deg rms, with range of up to 360 deg possible. The ultrasonic sensing systems inherently provide head position as well as orientation information.

Mechanical head position sensors. Head position can be measured by mechanical linkages to the target field. Perhaps the simplest is the attachment of flexible shafts, one for each axis of rotation to be measured, from a hel-

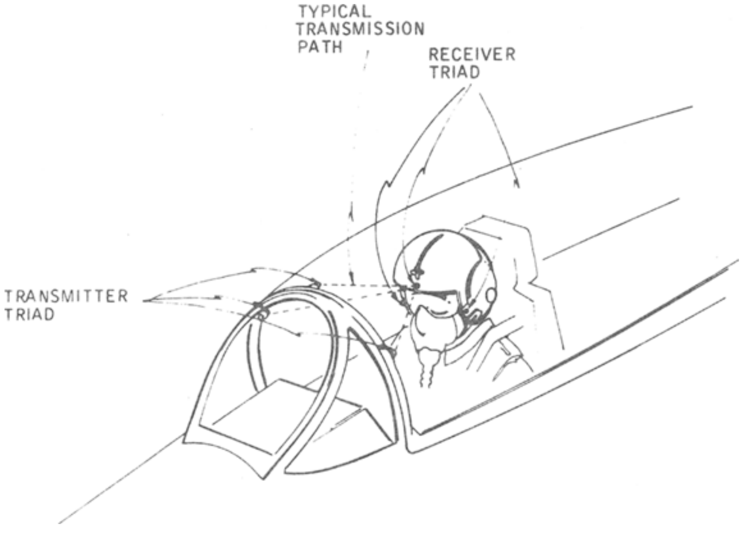


Figure 42. Ultrasonic head position measurement system (Sawamura, Note 14).

met to the laboratory bench. Head freedom of motion is restricted somewhat by the cables, depending on their number and length.

The next step in mechanical measurement is a form of goniometer for measuring angles of one body relative to another. These typically consist of rigid or telescoping rods with potentiometers at each linkage to measure head angles. Sperry developed such a rigid linkage system with a magnetic quick disconnect for pilot helmet orientation measurement. A two gimbal system with a vertical and a horizontal potentiometer was combined with a limbus reflection eye movement monitor to yield a practical eye point-of-regard system. One end of the mechanical linkage is attached to a point in the target field, and the other is held between the subject's molar teeth, with a "pipestem" bite board (Klein & Jex, Note 15). The device permits head movements of up to 20 cm and eye point-of-regard measurements of better than 1 deg of accuracy over a range of 20 deg vertical and 40 deg horizontal (see Figure 43). The same technique can be applied to measurement of the head position and orientation in all 6 deg of freedom by measuring all linkage angles and lengths. The 6 deg of freedom system allows accurate head-position measurement within a volume approximately 2 ft high and 6 ft in diam, allowing full freedom in yaw, and pitch of 30 deg upward and 80 deg downward.

An additional high-accuracy mechanical head-position sensor was developed by Vickers (Note 16) using a telescoping tube with one end attached to the ceiling and the other to the subject's headset via a universal joint. The weight of the apparatus was supported by constant-tension springs. Six rotary pulse generators at the headset measured the 6 deg of freedom changes in position with resolution of hundredths of an inch in translation and .3 arc min in rotation within a volume approximately 2 ft high and 5 ft in diam.

Inertial head position sensors. Inertial measurements of head motion can be made with miniature gyroscopes and accelerometers mounted on the helmets. The size and expense of systems to measure position accurately enough for eye fixation work is currently not justified. However, for gross measures of subject angular velocity or acceleration, as for studies of vestibular nystagmus, such systems are practical (Howland, 1961). When linear accelerometers are used, care must be taken to separate the effects of rotations of the sensitive axis into the gravity vector from pure linear accelerations, including the tangential and centripetal accelerations associated with rotation. Simultaneous telemetry of eye movements (EOG) and head linear acceleration during ballet rotation is useful in a qualitative assessment of head and eye movements (Tokita, Fokuda, & Watanabe, 1973).

Electromagnetic head position sensors. Steinman (Note 17) described the use of Robinson's (1963) search coil placed on a subject's eyeglass frames to detect the angular position of his head. The subject was seated with sensing magnets around him, and the measurement was made of the relative orientation of the search coil with respect to the magnetic field produced by the surrounding system.

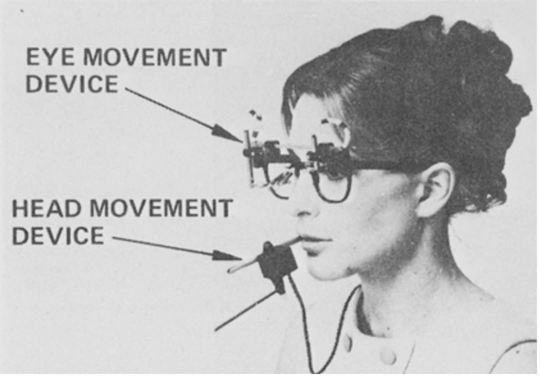


Figure 43. "Pipestem" bite board device for head-position measurement incorporated with an eye movement device (Courtesy Systems Technology, Inc.).

Eyeball Geometry

A schematic diagram of the eyeball is given in Figure 44 for reference.

TRADE-OFFS AND GENERAL CONSIDERATIONS IN INSTRUMENTATION SELECTION FOR EYE MOVEMENT RESEARCH

Trade-offs

Fortunately, for a particular eye movement instrumentation requirement, not all of the highest performance criteria of the various measurement conditions are needed to produce useful results. Clearly some parameters are more important than others, and the best possible system that meets the minimum requirements should be chosen and employed (See Table 1).

As an example, a researcher may not be interested in or need to detect fine eye movement; he may not need to look at the high-frequency details of a saccade; or his range requirements may be small. He may therefore be satisfied with a simpler, less powerful instrument.

One of the first and most important trade-offs is that of subject comfort and setup time as opposed to accuracy and precision. One is invariably at the expense of the other. Very high maximum accuracy of about .01 deg may be obtained with tight-fitting contact lenses, but setup and discomfort shortcomings are obvious. Another trade-off is that of range and accuracy. A very high range of greater than ±50 deg can be obtained with electro-oculography. That, however, is at the expense of poor dc accuracy, a high percentage of lost data, considerable setup time, and artifact problems. Another trade-off is that

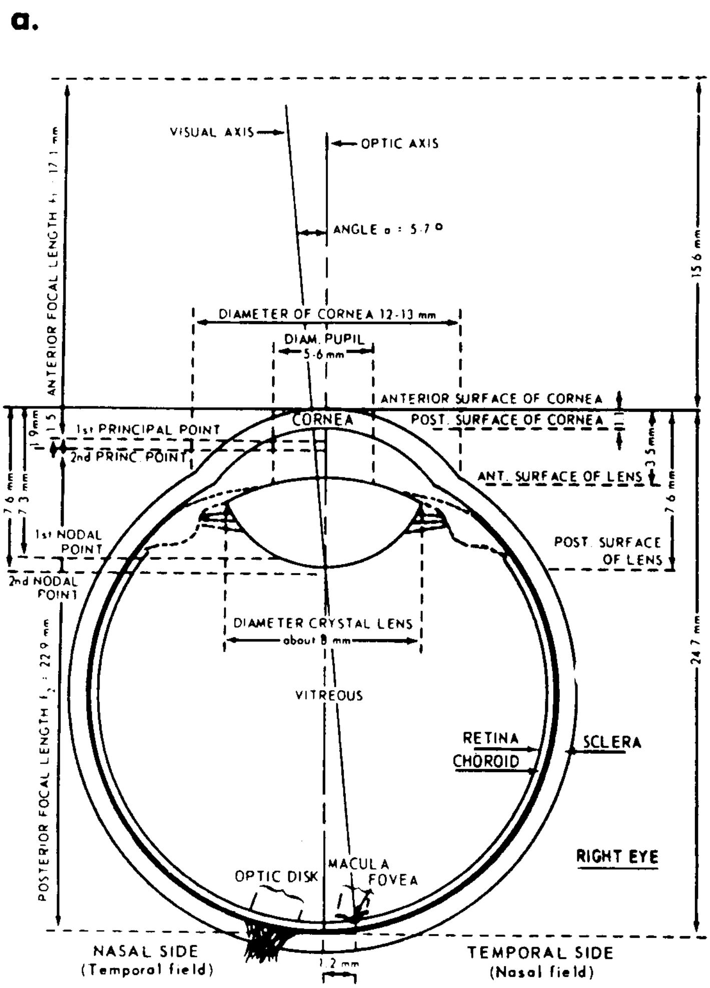
Table 1
Comparison of Eye-Movement Measuring Techniques

Method	Measurement Range (deg)		Accuracy		Speed or Frequency Response	Interference With Normal Vision	Glasses Acceptable	Contact Lens Acceptable	Subject Variation Problems, Eye Color, Etc.	Subject Cooperation Required	Subject Training Required	Usable With Young Children
	Vertical	Horizontal	Vertical	Horizontal								
1. Corneal reflex (Mackworth Camera)												
Polymetric Lab VII64	±9	±9	.5 deg	.5 deg	Photographic rate: 12-64 frames/sec **Television: 60 fields/sec**	Medium	?	Possible source of error	None	High	Low	?
Polymetric **Mobile VO165**	±10	±10	1 deg	1 deg	**Same as above**	High: Weight on head; optics near eye	No	Possible source of error	None	High	Low	No
NAC-REES	±10-20	±10-20	2 deg	2 deg	Same as above	High: Weight on head	No	Possible source of error	None	High	Low	No
2. Contact lens with						High		No	Eye must accept contact lens	High	High	No
lamp or radiant spot	Both ±10-30	±10-30	Precision 3 sec	3 sec	High		No					
coil	Larger than others		15 sec	15 sec	High		Yes					
mirror	±10	±10	2 sec	2 sec	High		No					
3. EOG	±50	±50-80	2 deg	1.5 deg	dc or .01-15 Hz limited by filtering	None	Yes	Yes	Medium: placement of electrodes and calibration is variable	Medium	Low	Yes
4. Limbus boundary												
Narco Eye Trac		±10	4 deg	2 deg	**2 msec; 30 msec with recorder**	Medium	Yes	Yes	Iris coloration a factor	High	Low	Yes
Narco Model 200	+10 −20	±20	2 deg	1 deg	**4 msec; 26 msec with filtering**	Medium	No	Yes	Iris coloration a factor	High	Low	Yes
5. Wide-Angle Mackworth Camera												
Polymetric VII66	40	40	2.5 deg	2.5 deg	Same as Method 1	Medium: Subject looks through apertures; special lighted stimuli are required	?	Possible source of error	None	High	Low	Yes
6. Pupil-center-corneal-reflection distance												
Honeywell Oculometer	+30 −10	±30	1 deg	1 deg	.1 sec time constant	Low	Yes	Possible source of error	Low	Low	Low	Yes
Whittaker Eye View Monitor	±15 Higher possible	±22	1 deg	1 deg	30-60 samples/sec	Low	Yes	Same as above	Low	Low	Low	Yes
U.S. Army Human Engineering Lab	30	40	2 deg	2 deg	60 samples/sec filtered	Low	No	Same as above	Low	Low	Low	Yes
7. Double Purkinje **image eye tracker**	25 deg diam	25 deg diam	Noise of 1 min		300 Hz	Low	Autocorrection possible		Low	Low	Low	Yes

Table 1 Continued

Calibration and Setup Time	Head Attachments Required	Head Stabilization Requirement*	Subject Discomfort	Subject Awareness	Pupil Diam Output Also	Form of Output	Status	Cost of Operation	Remarks	Source of Further Information
Low	Chinrest or biteboard	High head restraint or biteboard	Medium	High	No	Photographic or videotape; low-resolution digital output	Commercially available	High for film		Polymetric Co. P.O. Box D Roseland, NJ 07068
High: biteboard	Biteboard	None	High	High	No	Same as above		High for film	Higher resolution digital output is possible with other instruments	
Medium: fit headband, set light source	Head-mounted optics	None	Medium	High	No	Same as above		High for film	Head-mounted TV camera	Instrumentation Marketing Corp. 820 South Mariposa Burbank, CA 91506 **REES Inst. Ltd.** **Westminister House, Old Woking, Surrey, United Kingdom**
High: lens must be filtered	Contact lens	High Low Low	**High**	High	No	Photographic or electrical	Some commercial devices available	Lens grinding may costly	Negative pressure application may be hazardous	
High: requires electrode stabilization and light adaptation	Yes, 2-6 electrodes	Low	Low	High	No	Electrical record	Commercially available	Low	More suitable for eye motion than eye position	**LT Instruments** **4004 Osage** Houston, TX 77036 Grass, Inst. Quincy, MA 02169 ICS, 129 Laura Dr. Addison, IL 60101
Low	Head bracket and chinrest	High	Low	High	No	Analog and digital	Commercially available	Low	**Vertical position of eyelid is used to** approximate vertical eye position	**Narco BioSystems, Inc., Biometrics Div.** **7651 Airport Blvd.** **Houston, TX 77017**
Low	Spectacles	None	Low	High	No	Analog and digital	Commercially available	Low		Narco (also see ICS)
Low	Viewing through aperture	Medium, head must be kept still	Low	High	No	Photographic or videotape; low-resolution digitizer available	Commercially available	High for film	Point of regard output without head motion artifact	Polymetric Co. (see above)
Low: higher for maximum linearization	None	Mark II: head free, 1 in.^{3} Mark III: head free, 1 ft.^{3}	Low	Low	Yes	Digital, analog, and fixation pointer on TV image of scene	Commercially available	Low	Computer-based system Mark III tracks head motion and has auto focus	Honeywell Radiation 2 Forbes Rd. Lexington, MA 02172
Low	None	**Head free up to 1 ft^3**	Low	Medium	Yes	Same as above	Commercially available	Low	Tracks head motion and has auto focus available	**Whittaker, Space Sci. Div., 335 Bear Hill Rd.** **Waltham, MA** **02154**
Low	None	1 ft.^{3}	Low	Low	Yes	Digital, analog, videotape, and graphic	Research laboratory	NA		U.S. Army/HEL Aberdeen Proving Ground, MD
Low	Chinrest or biteboard	**None** **Head free 1 cm^3** **Biteboard for high precision**	Low	Medium	No	Analog output	Small production	Low	Has auto focus; field and operation are dependent on pupil size suitable for image stabilization	Stanford Research Institute Menlo Park, CA 94025

**To make measurement, not to obtain fixation point.*



b.

Constant	Eye Area or Measurement	
Refractive index	Cornea	1.37
	Aqueous humor	1.33
	Lens capsule	1.38*
	Outer cortex, lens	
	Anterior cortex, lens	
	Posterior cortex, lens	
	Center, lens	1.41
	Calculated total index	1.41
	Vitreous body	1.33
Radius of curvature, mm	Cornea	7.7
	Anterior surface, lens	9.2-12.2
	Posterior surface, lens	5.4-7.1
Distance from cornea, mm	Post. surface, cornea	1.2
	Ant. surface, lens	3.5
	Post. surface, lens	7.6
	Retina	24.8
Focal distance, mm	Anterior focal length	17.1 [14.2]**
	Posterior focal length	22.8 [18.9]
Position of cardinal points measured from corneal surface, mm	1. Focus	-15.7 [-12.4]
	2. Focus	24.4 [21.0]
	1. Principal point	1.5 [1.8]
	2. Principal point	1.9 [2.1]
	1. Nodal point	7.3 [6.5]
	2. Nodal point	7.6 [6.8]
Diameter, mm	Optic disk	2-5
	Macula	1-3
	Fovea	1.5
Depth, mm	Anterior chamber	2.7-4.2

*Cortex of lens and its capsule

**Values in brackets refer to state of maximum accommodation

The diagram and table give dimensions and optical constants of the human eye. Values in brackets shown in the table refer to state of maximum accommodation. The drawing is a cross section of the right eye from above.

The horizontal and vertical diameters of the eyeball are 24.0 and 23.5 mm, respectively. The optic disk, or blind spot, is about 15 degrees to the nasal side of the center of the retina and about 1.5 degrees below the horizontal meridian.

Figure 44. Schematic and optical constants of the eyeball (Roth, Note 19; after White, Note 20; and Spector, Note 21).

between speed and noise. When video signal data or other measuring systems that inherently generate noise are used, averaging and filtering may be used to reduce noise, but the price paid here is a lowered frequency response.

One very important trade-off against most of the parameters is cost. One can almost always pay more and get higher performance. This is especially apparent in the newer devices and systems that employ sophisticated optics and electronics to yield eye-position measurement.

In reading research, for example, it may be eye movements in themselves, the saccades, regressions, fixations, blinks, etc., that are of interest. It may often not be necessary to relate this information to actual points in the scene. In this case, a method like EOG or a spectacle-mounted limbus tracker may be the most suitable since a virtually free head is tolerated and satisfactory data is obtained. If point of fixation is needed, however, some head fixing or measuring method is needed or a point-of-regard system must be especially built or purchased. Performance may also be reduced in some aspects.

If testing of children is considered, then a system must be chosen which requires minimal subject training or cooperation. This may preclude the use of contact lens methods or even EOG under some experimental conditions. In these cases, an instrument that can be set up quickly with minimum calibration would be needed.

Considerable thought should also be given to handling the data coming out of the eye movement measurement instrumentation. Again, there is a trade-off. The simpler and cheaper the form of the output, the harder it is to process. A photograph or a video tape is a simple output but is hard to handle. An analog signal output is the next step up. It is easier to handle and to view but may still pose some difficulties in large data analysis. A digital recordable output that goes on digital tape or into a computer is most amenable to sophisticated analysis but is the most costly and difficult to interface. Also time and expense is required for the programming to extract the desired information.

Simultaneous Psychophysiological Measurement

In addition to eye movement and position, there are two human eye functions from which psychological inferences can be drawn, and there is a great deal of literature available in the field. The first is blinking. Almost all of the eye movement measurement methods will have blinks as an output artifact. It can clearly be picked out in a photograph, in an EOG record, or in all the systems that track the limbus, the pupil, or the corneal reflection. In methods providing an electronic output, it can clearly be seen as a pulse with a characteristic blink duration. The second parameter is pupil diameter. There is considerable controversy in the scientific community as to whether pupil diameter is an indicator of positive and negative emotion, with dilation indicating the former and constriction the latter. But there is general agreement, however, that pupil dilation is an indicator of emotional activity, whatever the sign. It is therefore very convenient to record pupil diameter, especially if it is part of the eye movement measurement output, and to correlate that with the part of the scene the subject is viewing. Some of the existing commercial eye movement monitor systems give pupil diameter as an output. Koff, Elman, and Wong (Note 18) compiled a comprehensive bibliography on pupillary response.

For other psychophysiological measures, some consideration must be given to their compatibility with eye movement measurements. For example, if the required test will encumber the subject and keep him stationary, there is no value in obtaining an expensive eye movement system that would allow free head motion. If electroencephalography is being performed and electrodes are attached to the subject's head, then EOG may be a reasonable measurement method since the electrodes are similar and the procedure is being done anyway. This is, of course, assuming that it fulfills the other experiment requirements.

It is also important to be able to simultaneously record the eye position measurement output along with the measures being taken in a compatible format where the time element is either recorded or may be deduced. Some marker or indication of stimuli presentation should also be recorded. In this way only can the various parameters being recorded be correlated to the stimuli. Unless the effects of the inputs are strikingly apparent, statistics might be needed to relate cause and effect where the latencies are not known. This is one reason why digitized outputs amenable to computer handling are desirable.

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NOTES

1. From Young, 1970.

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