1 THEORY OF OPERATION

1.1 Physiological Basis for Eyetracking

Even though the eye has wide peripheral vision, people control their gaze direction quite precisely. Eye pointing is precise because there is a centralized region in the retina, the macular region, where there is increasing image resolution toward its center. At the center of the macular region is the foveola. "The foveola (0.17 mm or 0.6^o in radius) is the small central region in which the thickness of the retina is reduced so as to contain only photoreceptors, glial cells, and Mueller's cells" (Bishop, 1981, p. 578). When people fixate on an object, they align their eye such that the image of the object lands precisely on the foveola. Due to this physiological phenomenon, humans have natural and precise control of eye motions.

1.2 Some Properties of the Human Eye

The eye is visually observable, and if a camera is configured appropriately, there is sufficient information in the camera's image of the eye to determine the eye's gaze direction. Figure 1 illustrates several key characteristics of the eye that make its gaze direction measurable from a video camera image.

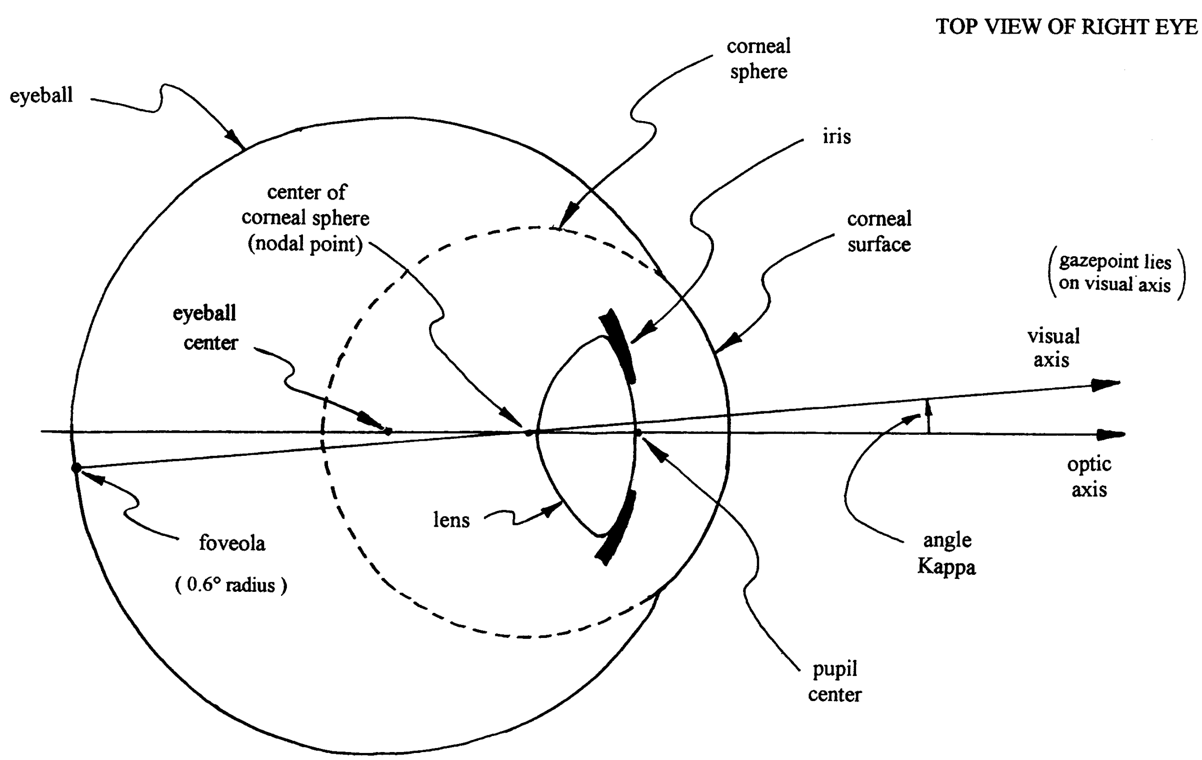


Figure 1: Schematic of the Eye

The "visual axis" of the eye is the line from the center of the foveola through the center of the corneal sphere, also known as the optical nodal point of the eye. By definition, the eye's gazepoint lies on the visual axis.

The eye's "optic axis" is defined as the axis of symmetry for the eye's optical system. The location of the foveola is generally offset from the eye's optic axis, so the optic axis is distinct from the visual axis. The foveola of the eye is usually located to the temporal side of the eye, causing the visual axis of the eye to point to the nasal side of the optic axis. The angle between the optical and visual axes of the eye is called Kappa. Kappa is typically about 5^o and has a standard deviation of about 2^o over the human population.

The surface of the cornea is approximately spherical, flattening somewhat toward the outer edges. The "corneal sphere" is smaller than the eyeball, and it's surface protrudes out of the eyeball sphere by approximately 1.5 mm. The typical radius of curvature for the cornea is 7.7 +- 2.0 mm.

1.3 Eyegaze Edge Equipment Configuration

Machines designed to measure eye movements, gaze direction and/or gazepoints are called eyetrackers. This manual describes the LC Technologies Eyegaze Edge, a remote eyetracker that measures the subject's gazepoint on a computer monitor screen.

The Eyegaze Edge observes the eye remotely with a video camera. Nothing is attached to the subject's head. A schematic of the Eyegaze Edge equipment is shown in Figure 2. The video camera is located below the computer screen, and it continually observes the subject's eye. A small, low power, infrared light emitting diode (LED) located at the center of the camera lens (US Patent 4,836,670) illuminates the eye.[1]

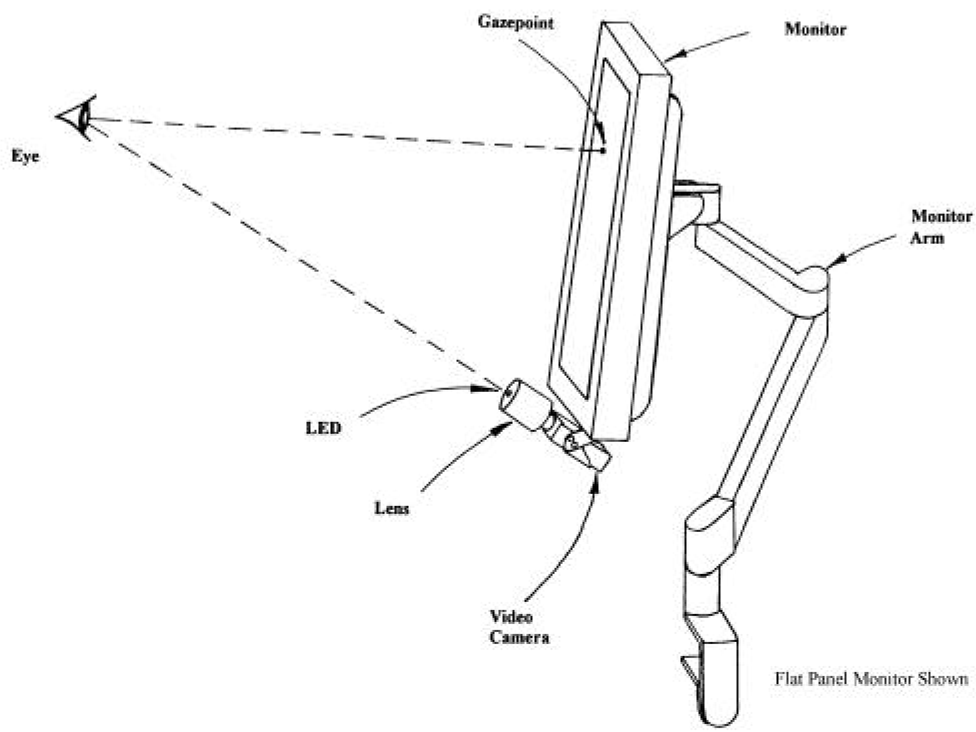


Figure 2: Eyegaze Edge Configuration

[1] The LED illumination of the eye is safe. At a range of 15 inches, the illumination is approximately 20% of the HEW maximum permissible exposure (LaMarre, 1977).

1.4 Processing the Camera's Image of the Eye

A typical image of the eye as seen by the Eyegaze Edge camera is shown in Figure 3. The corneal-reflection image results from the LED light reflecting directly off the corneal surface of the eye. The corneal reflection is often referred to as the glint spot.

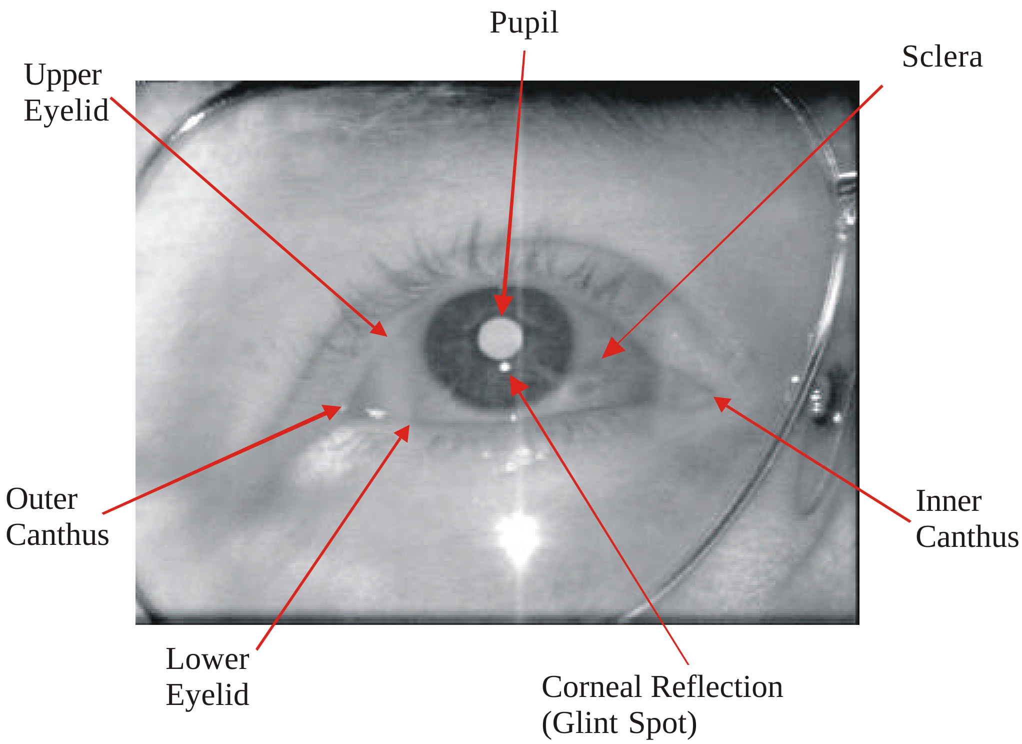


Figure 3: Video Eye Image with Bright Pupil and Corneal Reflection

The bright pupil, which is the same as the red-eye effect in flash photography, is caused by light from the LED entering the eye, reflecting off the retina, re-emerging from the pupil, and returning toward the LED. The camera sees the light returning from the pupil toward the LED because the LED is located at the center of the camera lens. (If the illuminator were not located coaxially along the camera axis, the pupil would appear dark, as we are normally accustomed to seeing it.) The Eyegaze Edge uses the bright-pupil effect to increase the accuracy of the image processing.

As the video camera acquires images of the eye, specialized image-processing software analyzes each eye image. The image processing software first identifies the pupil and corneal-reflection objects within the overall camera image. It then precisely measures the center locations of both the pupil and corneal reflection.

Once the locations of the pupil center and corneal reflection have been measured within the camera image, the Eyegaze Edge projects the coordinates of the eye's gazepoint on the computer screen.

1.5 Pupil Center Corneal Reflection (PCCR) Method

The Eyegaze Edge uses the Pupil Center Corneal Reflection (PCCR) method to measure the direction of the eye's gaze (Mason, Merchant, Young). The theory underlying the PCCR method states that the direction of the eye's gaze is directly related to the vector from the corneal reflection to the center of the pupil within the camera image. This vector, often called the glint-pupil vector, is illustrated in Figure 4.

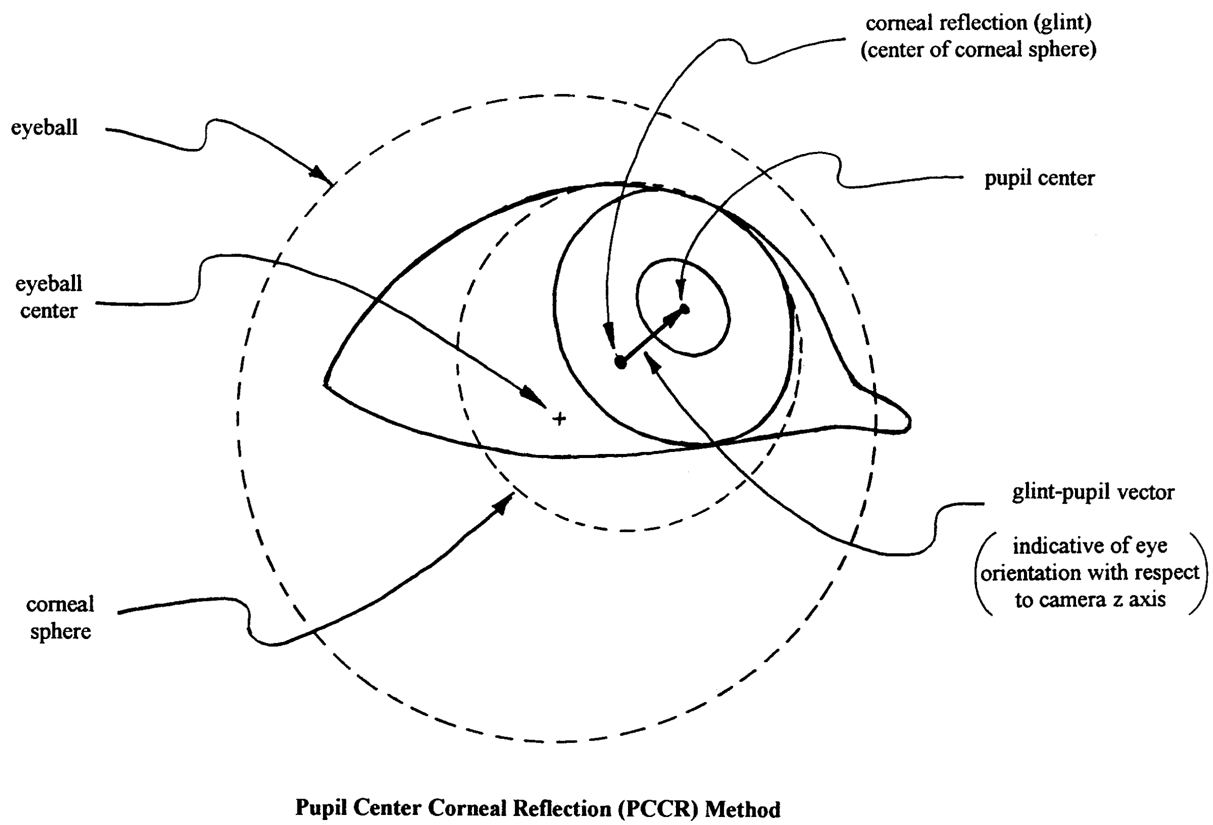


Figure 4: The Glint-Pupil Vector and Direction of Gaze

When a person looks directly at the camera, the image of the corneal reflection appears near the center of the pupil image. (Even with the LED mounted at the center to the camera lens, the corneal reflection generally does not appear precisely at the center of the pupil because the foveola typically lies off the optic axis of the eye. See the discussion of Kappa in Section 1.2.) As the person rotates his gaze upward away from the camera, the pupil center moves upward and away from the corneal reflection, and the glint-pupil vector points higher. Similarly, as the person rotates his gaze to the camera's right (which is his left), the pupil image moves to the right of the corneal reflection, and the glint-pupil vector points further right.

(The PCCR Method applies equally whether using the bright or dark pupil effects.)

The PCCR theory is based on the following assumptions:

a) The eye's optic axis passes through two fixed points within the eye: the center of the corneal sphere and the center of the pupil.
b) The orientation of the eye can be inferred from the measurement of these two points.
c) The locations of these two points can be determined from the camera's image of the eye.

d) The center of the corneal sphere can be determined from the location of the corneal reflection, i.e. the reflection of the LED off the corneal surface of the eye.

The pupil center can be calculated from the observable edges of the pupil image.

Figure 5 illustrates the geometric optics of the PCCR method. The horizontal and vertical components of the eye's orientation angle, measured with respect to the line between the center of the camera lens and the center of the corneal sphere, can thus be measured from the vector distance between the corneal reflection and the pupil center within the camera image.

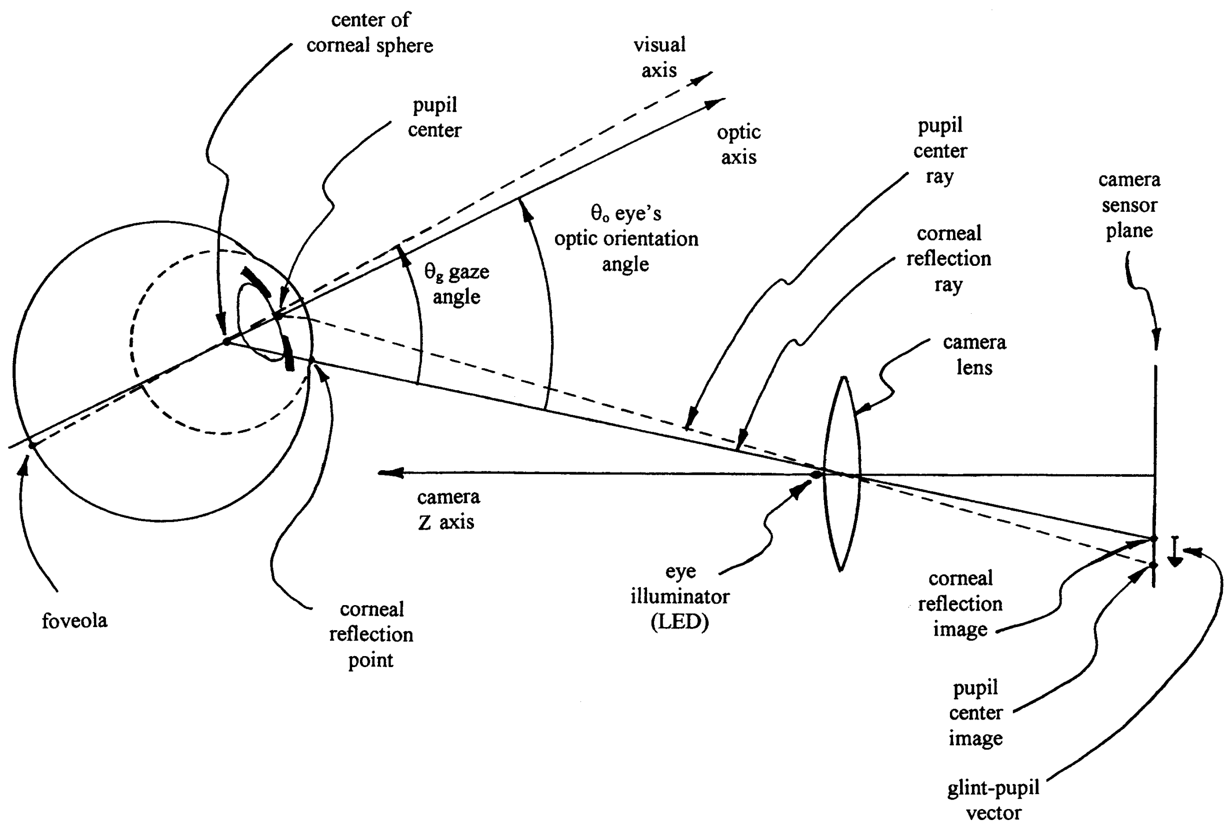


Figure 5: Geometric Optics of the PCCR Method

1.6 Classic PCCR Gazepoint Tracking Equations

For nomenclature purposes, pixel coordinates within the camera image are designated i and j. The horizontal pixel index i is defined positive to the right, and the vertical pixel index j is defined positive downward. The (0,0) coordinate is the upper left corner of the image.

The vector from the corneal reflection to the pupil center, often called the "glint-pupil vector" is denoted (di,dj), where:

$$di = i_{pupil\text{-}cent} - i_{glint}$$
$$dj = j_{pupil\text{-}cent} - j_{glint}$$

As a first approximation, the gazepoint may be modeled as a pair of simple linear equations:

$$x_{gaze} = A_0 + A_i * di \qquad \text{(mm)} \qquad \text{(classic PCCR equations,}$$
$$y_{gaze} = B_0 + B_j * dj \qquad \text{(mm)} \qquad \underline{\text{Not}} \text{ used in the Eyegaze Edge)}$$

These are the classic forms of the PCCR equations. The As and Bs are constants which depend on the fixed geometric constants of the camera lens, the camera sensor, the location of the viewing plane with respect to the camera, and the physiological constants of the eye. di and dj are time varying variables which represent the eye's orientation. The gazepoint equations are computed for each camera field.

The constant terms A_0 and B_0 account, in part, for fixed x and y offsets between the gaze plane and the camera's X and Y axes. The constant terms also account for the angular offsets Kappa between the eye's optic and visual axes. The glint-pupil vector measurement (di,dj) made from the camera's image of the eye provides information about the orientation of the eye's optic axis, not the focal axis. To find the gazepoint, the optic vector needs to be rotated by the angle Kappa to find the gaze vector. If the eye remains a fixed distance from the gaze plane, the fixed angular offset Kappa may be approximated by a constant distance offset.

The linear terms A_i and B_j in the above equations account for the time-varying rotations of the eye. For gaze angles within about 20 degrees of the camera, variations in the gazepoint vary approximately linearly with the glint-pupil vector (di,dj).

1.7 Eyegaze Edge's Gazepoint Tracking Equations

In the Eyegaze Edge, where the gaze surface is a computer monitor screen and the camera is mounted below the monitor, the above linearized equations for measuring the gazepoint are typically inadequate. A significant nonlinearity is introduced by the screen being tilted with respect to the camera Z axis. Additionally, the corneal surface of the eye flattens out toward the edges, and many computer screens have significant curvature. To accommodate these nonlinearities, the gazepoint equations in the Eyegaze Edge are expanded from the classic forms as follows:

$$x_{gaze} = A_0 + A_i * di + A_j * dj + A_{ij} * di * dj \qquad \text{(mm)} \qquad \text{(Nonlinear equations used in}$$

$$y_{gaze} = B_0 + B_i * di + B_j * dj + B_{jj} * dj^2 \qquad \text{(mm)} \qquad \text{the Eyegaze Edge)}$$

The "cross" terms ($A_j * dj$) in x_{gaze} and ($B_i * di$) in y_{gaze} allow for roll angle misalignment between the camera's and monitor's horizontal axes. Thus purely horizontal eye motion in the camera image may yield some vertical variation in the calculated gazepoint and vice versa.

The ($A_{ij} * di * dj$) term in x_{gaze} and the ($B_{jj} * dj^2$) term in y_{gaze} amount to scale factors on di and dj such that the gains of di on x_{gaze} and dj on y_{gaze} vary as a function of how high (dj) on the screen the user is looking. Within the range of the computer screen, these two nonlinear terms accommodate most of the nonlinearity associated with the tilt of the screen. The ($B_{jj} * dj^2$) term in y_{gaze} also accommodates flattening of the corneal surface toward the edges, which is typical in the human eye.

The coefficients A_0, A_i, A_j, A_{ij}, and B_0, B_i, B_j, B_{jj} are computed during the calibration procedure, discussed in Section 3. During calibration, the subject visually follows a dot as it is displayed at several locations on the computer screen. A least-squares regression procedure is used to find the coefficient values that optimally map the measured glint-pupil vectors to the known gazepoints.

1.8 Eyetracking Sensitivity to Focus Range

A key to accurate prediction of the subject's gazepoint is knowledge of variations in the range from the camera to the eye. To see the effects of range variation on the calculation of the gazepoint, assume that a person keeps his gaze fixed on a point in the middle of the screen while he moves his head back and forth along the camera Z axis.

Figure 6 illustrates the effects of range on gazepoint measurement. When the user moves his head backward away from the camera, two things cause the glint-pupil vector in the camera image to change. First, the eye rotates downward to maintain the same fixation point. Second, the image of the eye gets smaller as the eye gets farther from the camera. Both effects cause a decrease in the magnitude of the measured glint-pupil vector and, if uncorrected, result in a downward motion of the predicted gazepoint.

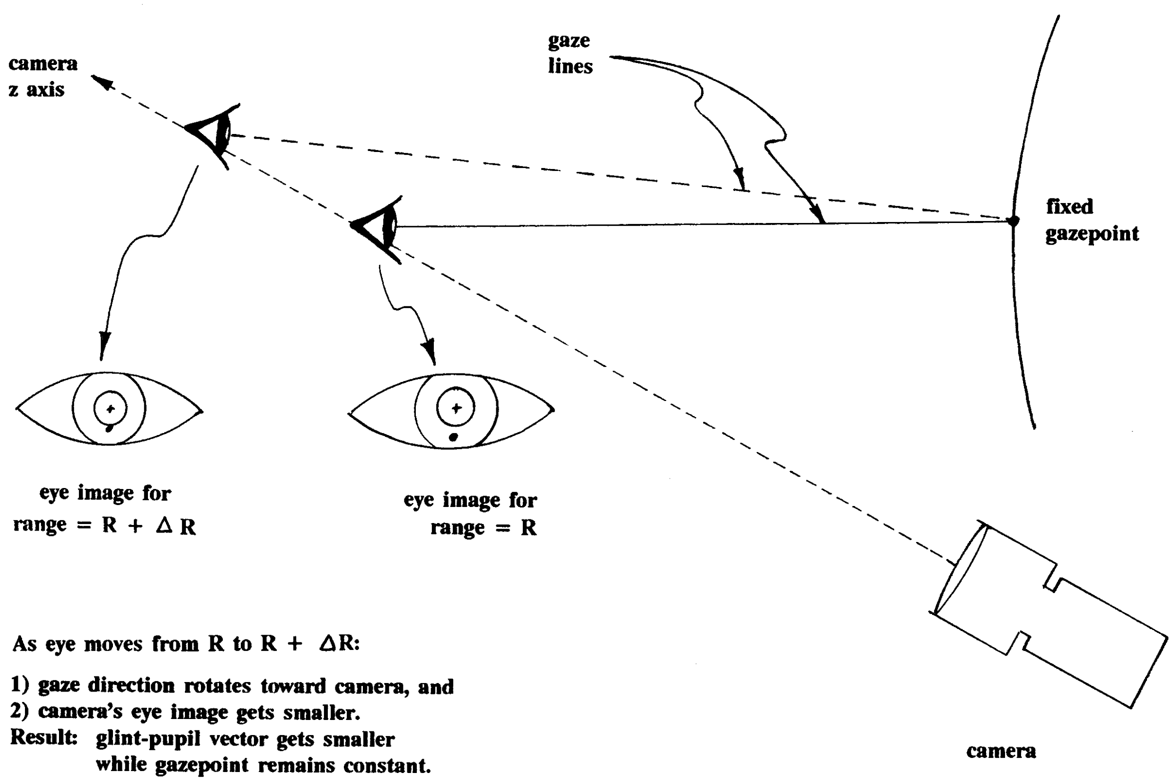


Figure 6: Effects of Range on Gazepoint Tracking

Typically, when a person is sitting about 24 inches from the camera, and looking at a point toward the top of the computer screen, head motions of 1.0 inch along the camera Z axis result in predicted gazepoint variations of about 0.75 inch. Range sensitivity is proportionately reduced as the true gazepoint approaches the camera. As the head moves toward the camera, the predicted gazepoint (if uncorrected for range) moves radially away from the camera, and as the head moves backward, the predicted gazepoint moves radially in toward the camera.

1.9 Focus Range Compensation with the Triangular Camera Aperture

The triangular aperture on the Eyegaze Edge camera (US Patent 4,974,010) allows the image processing software to measure variations in the range from the camera to the corneal surface of the eye. As the eye moves back and forth along the camera Z axis, the camera's image of the corneal reflection, as shaped by the triangular aperture, changes size and orientation. See Figure 7. The magnitude of the blur indicates how far the eye is from the camera's focus plane. The orientation of the glint image, an inverted or uninverted triangle, indicates whether the eye is in front of or behind the ideal focus plane. The algorithm produces a range offset DeltaR, which indicates how far the cornea is from the ideal focus plane.

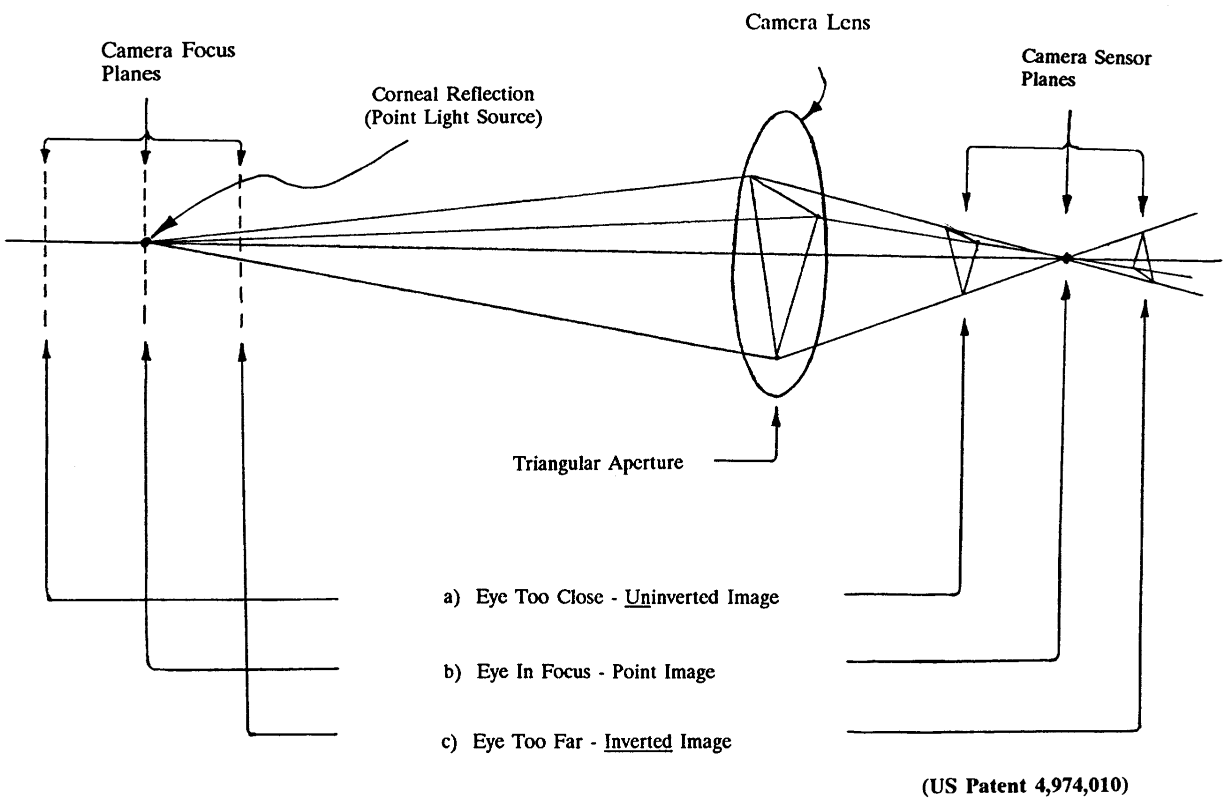


Figure 7: Focus Offset Measurement with Triangular Aperture

Prior to computing the gazepoint equations, the Eyegaze Edge provides a first order correction to the raw magnitudes of glint-pupil vector (di,dj) by multiplying the glint-pupil vector by the term (1 + DeltaR / R)2. R is the nominal focus range of the camera. When the eye is in good focus, DeltaR is zero and the corrected glint-pupil vector is equal to its raw value. If the head drifts backward away from the camera (DeltaR positive), the correction term amplifies the raw glint-pupil vector. If the head drifts forward of the focus plane, the term attenuates the glint-pupil vector.

The Focus Range Compensation on the Eyegaze Edge works over a range of approximately 2.5 inches (64 mm), from 1.25 inches (32 mm) in front of the camera focus plane to 1.25 inches (32 mm) behind. A display on the right side of the Eye Image Display (see Section 2.6, Figure 6) indicates the instantaneous focus range error. The center tick mark indicates zero focus range offset and the upper and lower tick marks indicate 0.75 (20mm) inch offsets.

1.10 The Eyegaze Tracking Cone

The Eyegaze Edge can track the subject's gaze as long as he is looking within about 40^o of the camera Z axis. This conical tracking region, illustrated in Figure 8, is a result of the Pupil Center Corneal Reflection (PCCR) method which the Eyegaze Edge uses to measure the direction of gaze (see Section 1.5). As the eye's gaze moves away from the camera, the corneal reflection moves from the center of the pupil out toward the edge of the cornea. As the corneal reflection nears the edge of the cornea, it begins to merge with a reflection off the sclera (the white of the eye). When the corneal reflection is no longer distinct from the scleral reflection, the Eyegaze Edge can no longer measure the eye's orientation.

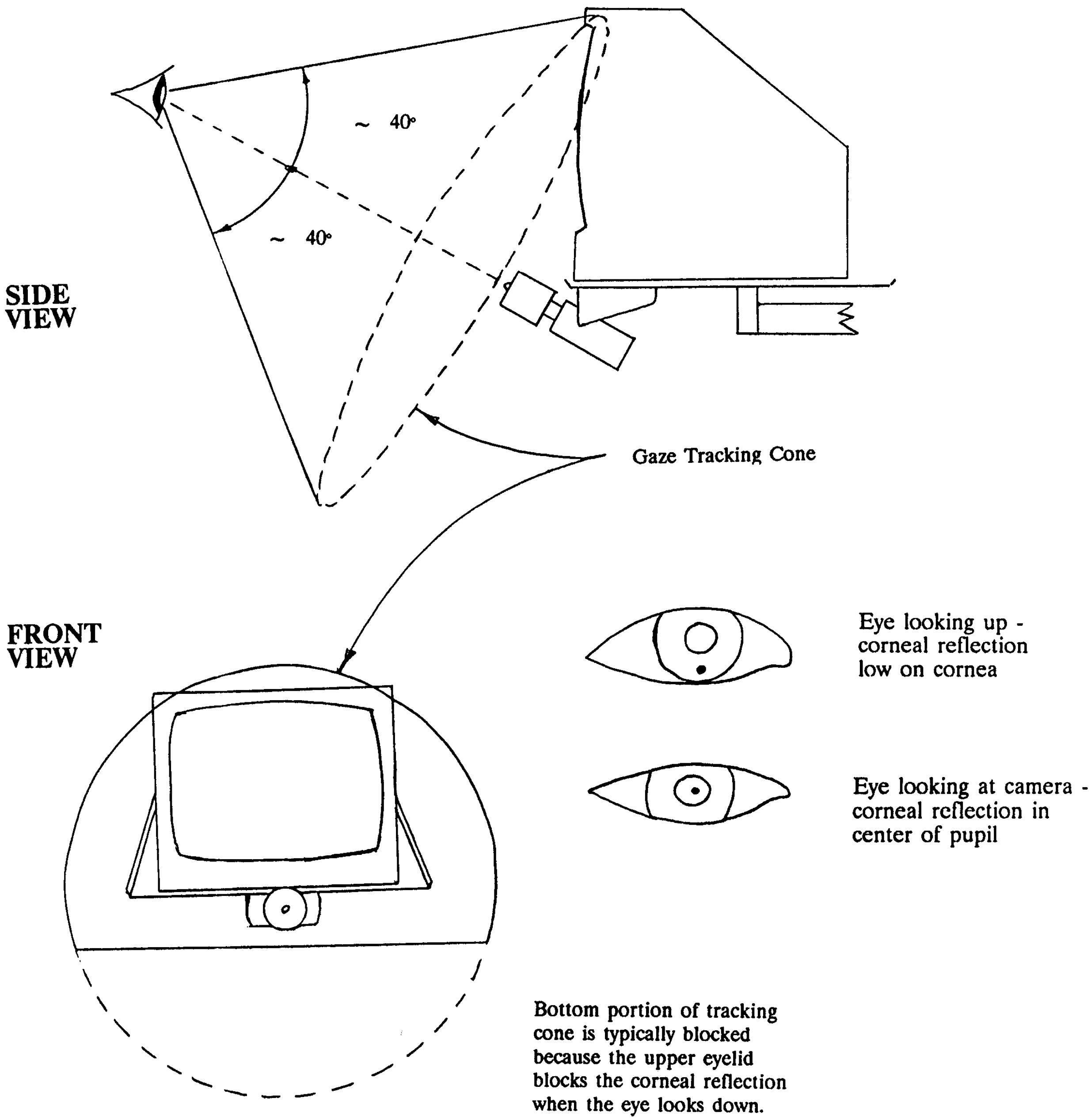


Figure 8: Conical Gaze Tracking Region

1.11 Keeping the Monitor Display in the Tracking Cone

When tracking the gazepoint on a computer screen, it is important that the display screen be fully within the gaze tracking cone.

1.12 Droopy Eyelid Compensation

If a subject has particularly droopy eyelids or a particularly large pupil, the eyelid may come down over the top edge of the pupil and induce a gazetracking error. Figure 9 illustrates a droopy upper eyelid. When the eyelid occludes the upper edge of the pupil, the top edge of the pupil appears to be lower than it really is, resulting in a series of subsequent errors. A low measurement of the pupil upper edge results in a low value for the pupil center, which in turn results in a low predicted value for the gazepoint. Thus the calculated gazepoint systematically "droops" as the eyelid droops down over the pupil.

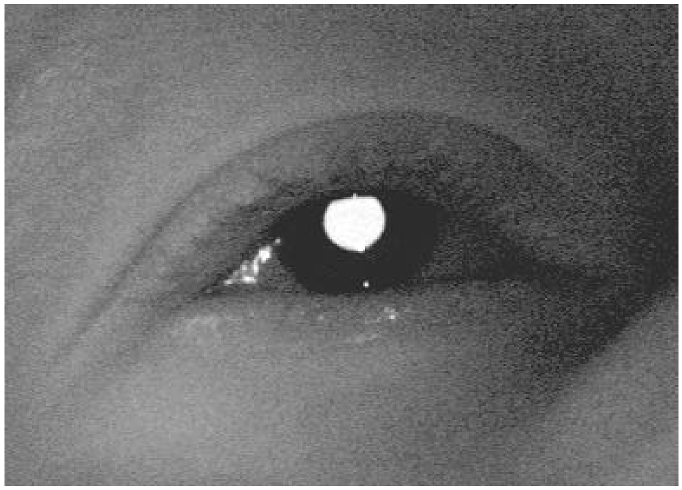


Figure 9: Droopy Eyelid Occluding Upper Pupil Edge

To compensate for gazetracking errors nominally induced by droopy eyelids, the Eyegaze Edge has specialized "pupil-occlusion-detection" software that detects segments of the pupil perimeter that are occluded by an eyelid. When fitting an ellipse to the pupil perimeter, the algorithm leaves out the occluded portions of the true pupil perimeter. Though the loss of the full pupil perimeter data increases the frame-to-frame noise in the pupil center measurements, systematic errors introduced by the eyelid impinging on the pupil are eliminated.

1.13 Eyegaze Edge Outputs

Monocular versions of the Eyegaze Edge (which have one eyetracking camera) track one of the subject's eyes. Binocular versions (with two eyetracking cameras) track both eyes. Each camera generates data at 60 Hz. In binocular systems, the frame capture of the two cameras is temporally interleaved, so the two cameras take pictures alternately, providing an overall frame rate of 120 Hz

After processing each camera field, the Eyegaze Edge software provides the following basic data about the eye being tracked:

The eye-found flag indicates whether or not the image processing functions identified and successfully processed an eye in the camera image. The eye-found flag goes false, for example, when a person blinks, squints excessively (occluding the pupil and/or corneal reflection), looks outside the gaze cone (see Section 1.10), or moves his eye out of the camera field of view.

The following data is valid if the eye-found flag is true, and is not valid when the eye-found flag is false:

The gazepoint coordinates (x_{gaze}, y_{gaze}) indicate the computed location of the gazepoint on the computer monitor screen. The gazepoint coordinates are expressed in terms of both millimeters and screen pixel coordinates.

The pupil diameter is measured from the camera's image of the pupil. Pupil diameter is expressed both in terms of camera pixels and in terms of millimeters as measured at the eye.

The camera field count is a form of time stamp. It indicates the sequence number of the camera image, i.e. the sequence number of the camera field.

Location of the eyeball center within the camera image -- Location of the eyeball is useful because it indicates motion of the head within the camera image. Recall from Figure 1 that the center of the corneal sphere is offset from the center of the eyeball sphere. As the eyeball rotates, the location of the corneal sphere moves within the head, so location of the corneal sphere is not solely dependent on head location. Eyeball location, on the other hand, is solely dependent on head location, and is independent of the eye's orientation.

See Section 4, the "Eyegaze Edge Programmer's Manual," for programming details on how to access the image processing data.

1.14 Gazepoint Reference Frames

At its lowest level, i.e. at the EgWin program-interface level, the Eyegaze Edge computes the user's gazepoint in terms of *full-screen* coordinates, not in terms of the *client-window* coordinates. The origin of the gazepoint coordinate frame (iIGaze = 0 and iJGaze = 0) is the upper left corner of the full screen display. (See the Programmer's Manual for a more complete description of the EgWin program interface and the variable iIGaze and iJGaze.)

Since EgWin reports gazepoint coordinates within the full-screen frame of reference, Eyegaze application programs are responsible for converting the gazepoint from full-screen to client-window coordinates, thus accommodating gazepoints within their own frames of reference.

For example, the Eyegaze **Trace** program, a typical Eyegaze application program, performs the full-screen to window transformation and records gazepoints within the *client-window* coordinate frame, not in terms of the full screen display. Thus in trace.dat, a gazepoint of 0, 0 means that the user is looking at the upper left corner of the *displayed image*, not the upper left corner of the *full screen*.

1.15 Salient Eyetracking Features of the Eyegaze Edge

The following is a summary of some of the key eyetracking features of the Eyegaze Edge.

CALIBRATION

The procedure to calibrate the Eyegaze Edge is robust yet fast and easy to perform. The calibration procedure takes approximately 15 seconds to perform. (See Section 3 for a detailed discussion of the calibration procedure.)

Fully Automatic Operation: The calibration procedure is fully automatic; no assistance from another person is required. The procedure adapts to the user speed by waiting for the user to fixate clearly on each calibration point before accepting it and moving on to the next point. The procedure accommodates interruptions from the user blinking or looking away from the computer screen. The procedure simply waits for a good fixation before moving to the next calibration point.

Consistency Checking: After the original pass through the calibration points, the procedure tests that the eye was properly fixated on each point by checking that each gazepoint prediction is consistent with all the other calibration points. It retakes any calibration points that are inconsistent with other points. The procedure does not accept the full calibration until the overall gaze prediction accuracy and consistency exceed desired thresholds.

ACCURACY

To achieve high gazepoint tracking accuracy, the image processing algorithms in the Eyegaze Edge explicitly accommodate several common sources of gazepoint tracking error.

Nonlinear Gazepoint Tracking Equations: As discussed in Section 1.7, the Eyegaze Edge uses nonlinear equations to predict the gazepoint accurately from the measured glint-pupil vector. The nonlinear terms account for a) the camera axis being tilted with respect to the computer screen, b) curved computer display screens, and c) flattening of the corneal surface toward the edges. With the Eyefollower, full 6-degree-of-freedom coordinate transformations are used to accurately account for variable gimbal angles and camera focus ranges.

Accommodating Head Range Variation: As discussed in Section 1.8, the accuracy of video eyetrackers is typically sensitive to head motion along the camera axis. The Eyegaze Edge uses the patented Asymmetric Aperture Method (see Section 1.9) to measure variations in the range between the camera and the cornea of the eye, and it uses the range information to minimize gazepoint-tracking errors resulting from longitudinal head motions.

Accommodating Pupil Diameter Variation: With video eyetrackers, the center of the pupil is not directly measurable from the camera's image of the eye. The pupil center is estimated by observing the edges of the pupil and calculating the center location from the edge measurements. Due to the fact that the pupil lies behind the corneal surface of the eye, however, a ray from the center of the physical pupil does not arrive precisely at the center of the pupil image. When the eye is looking away from the camera, the curved cornea refracts the rays from the various pupil edge points differently. Thus as pupil diameter varies concentrically about its true center, the edges in the pupil image move non-concentrically around the true pupil center point, even if the true pupil center is stationary.

If varying pupil diameter is not explicitly accommodated, gazepoint calculations can vary up to 0.5 inch as the pupil diameter varies between 3.5 and 7 mm. The Eyegaze Edge has corneal refraction compensation logic to minimize gazepoint calculation errors resulting from varying pupil diameter.

Accommodating Glint Straddling Pupil Edge: Many PCCR eyetrackers are prone to errors when the corneal reflection is near or straddles the edge of the pupil. Figure 10 illustrates a case where the corneal reflection straddles the pupil edge. Pupil edge measurements in the region of the corneal reflection are unreliable, and image intensity gradients from the pupil-iris boundary distort the corneal reflection image and result in imprecise measurement of the true corneal reflection location. The Eyegaze Edge has sophisticated image processing software to locate the corneal reflection accurately when the corneal reflection straddles the pupil-iris boundary.

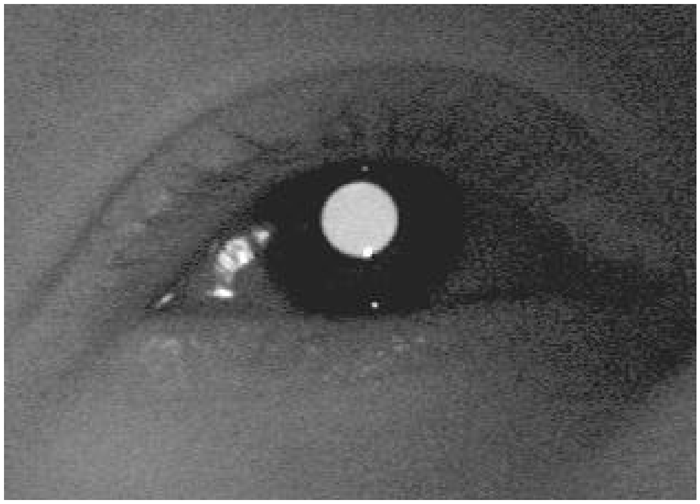


Figure 10: Corneal Reflection Straddling Pupil Edge

Eyelid Occlusion ("Droopy Eyelids"): See the discussion in Section 1.12.

RELIABILITY

Reliability refers to the range of operational conditions under which the Eyegaze Edge is able to measure gazepoint data.

Robust Eye Recognition: Rather than using simple brightness thresholding methods to detect the pupil and corneal reflection, the Eyegaze Edge uses sophisticated pattern recognition and hypothesis testing logic to detect the eye reliably in cluttered images. The system does not get confused by reflections off glasses, or by bright or dark facial features. The system cannot measure gaze direction if reflection from glasses is directly superimposed on the pupil and/or corneal reflection, but it is not confused by these spurious reflections. It simply reports that a "measurable eye" was not detected.

Accommodating Human Eye Variations: The system accommodates a wide variation in the eye image, such as pupil size and pupil and iris brightness. The system typically tracks 90 to 95% of the human population.

Tolerance to Head Motion: For the full specifications on the Eyegaze Edge tolerance to head motion, see Chapter 1, Section 6.4. If the subject moves his eye outside the camera's field of view, the system does not detect a pupil and the associated corneal reflection, and it reports the eye-found flag to be false.

Tolerance to Ambient Infrared Light: The Eyegaze Edge can tolerate moderate levels of ambient infrared light, such as those encountered in most indoor environments or outdoors on a cloudy day, but the system does not operate well in bright sunlight. Stray IR sources obscure the lighting from the Eyegaze Edge's light emitting diode and degrade the image of the eye. The sun and incandescent lamps contain high levels of infrared light. The environment may be brightly illuminated with lights such as fluorescent or mercury-vapor which emit low levels of infrared light. The Eyegaze Edge also works well in the dark.

Tolerance to Glasses and Contact Lenses: In most cases, the Eyegaze Edge works with glasses and contact lenses. The calibration procedure accommodates the refractive properties of the lenses. When wearing glasses, the glasses may not be tilted significantly downward, or the reflection of the LED off the surface of the glass is reflected back into the camera and obscures the image of the eye. The lens boundary in hard line bifocal glasses often splits the camera's image of the eye, and the discontinuity in the image invalidates the image measurements.

Soft contact lenses that cover all or most of the cornea generally work well with the Eyegaze Edge. The corneal reflection is obtained from the contact lens surface rather than the cornea itself. Small, hard contacts can cause problems, however, if the lenses move around considerably on the cornea, and the corneal reflection moves across the discontinuity between the contact lens and the cornea.

The IR light source penetrates normally tinted glasses, but does not penetrate reflective glasses.

Tolerance to Vibration: The Eyegaze Edge is intended for use on a desk or table in an office, laboratory or home environment. There is little tolerance for vibration, which could come, for example, from a wheelchair or moving vehicle.

2 PREPARING A SUBJECT FOR EYETRACKER OPERATION

Fixed-camera versions of the Eyegaze Edge, (i.e. non-Eyefollower versions) require some setup to prepare a person for eyetracking. Generally, the subject, i.e. the person whose gaze is being tracked during an experiment, must be positioned in front of the computer monitor in such a way that a) he can comfortably see the entire screen and b) the camera can clearly "see" the subject's eyes.

With the Eyefollower, the positioning functions required by the fixed-camera systems are accommodated automatically by the Eyefollower's gimbal. Sections 2.1 through 2.3 do not apply to Eyefollower systems.

2.1 Positioning the Subject (applicable only for fixed-camera, non-Eyefollower systems)

The subject sits in a chair in front of the computer monitor. He should sit back in the chair and be relaxed so he can remain still comfortably. To minimize head motion, the chair should be of a fixed type, i.e. not a swivel or tilting chair. Typically a bite bar is not required to hold the subject's head still, though one may be used if desired.

Position the monitor so that the subject is comfortable when viewing the computer screen. People are typically comfortable between 22 and 28 inches from the screen, with the height of the monitor set so that the top of the screen is approximately at eye level.

2.2 Selecting an Eye to Track (applicable only for monocular, single-camera Edge Systems)

The monocular (single-camera) Eyegaze Edge tracks one eye. Select which eye you desire to track. If the subject is known to have a dominant eye, the dominant eye should be chosen for eyetracking. If the subject does not have a clearly dominant eye, either eye may be chosen. However, once the Eyegaze Edge has been calibrated to a given eye, it must continue to be aimed at that eye.

You can easily determine which eye the camera is aimed at by looking at the image of the eye on the Eye Monitor. If the nose is on the right side of the eye image, the camera is viewing the subject's right eye. If the nose is to the left of the eye, the camera is viewing the subject's left eye.

With binocular Edge systems (with two fixed cameras), the head must be positioned (or conversely the monitor must be positioned) such that each camera sees its respective eye.

2.3 Adjusting the Camera (applicable only for fixed-camera, non-Eyefollower systems)

First, make sure that the f-stop ring is turned fully to the right – opening the lens aperture to its largest area. The f-stop is adjusted by rotating the appropriate ring on the camera. (Note, on most lenses, the f-stop ring may be locked down to the proper setting.)

Next, point the camera at the eye you have selected to track. Adjust the camera pointing angle and the lens focus ring so that a clear, i.e. well focused, image of the eye appears in the center of the Eye Image (see Figure 11 on next page).

The camera elevation angle is adjusted by loosening the brass nut on the side of the camera bracket, rotating the camera to the desired elevation angle, and retightening the nut. The horizontal angle of the camera is adjusted by swiveling the monitor from side to side.

The focus range can be adjusted by turning the focus ring on the camera lens. Typically, however, the best eyetracker operation is obtained when the subject is sitting at or near the camera's maximum focus distance (focus ring turned fully to the right, to the infinity symbol). It is generally recommended that the focus ring be set to the maximum value, and that the camera image clarity be adjusted by moving the monitor forward and backward, rather than by adjusting the focus ring. If a subject wishes to sit closer to the screen however, the focus ring may be adjusted off maximum with only minor loss in eyetracker performance.

All adjustments to the camera should be made prior to beginning the calibration procedure, i.e. prior to the subject "looking at the camera to begin" (see Section 3, "Calibrating the Eyegaze Edge"). Once a calibration procedure has been started, varying the camera geometry with respect to the computer monitor invalidates that calibration. The monitor, with the camera fixed to it, may be moved around without affecting the calibration, but no further adjustments should be made to the camera bracket or the focus ring. Adjusting the camera necessitates a recalibration.

2.4 Eye Image Displays

Generally, the camera is adjusted properly when the eye is in good focus.

During calibration, an Eye Image Display, shown in Figure 11, provides the user with a view of the camera's eye image. This display contains:

a) A display of the full camera image (right panel of the display)
b) a magnified display of the eye's pupil and corneal reflection (left panel of display)
c) a focus offset indicator (between the image panels)
a) a pupil intensity indicator (left of the left image panel)

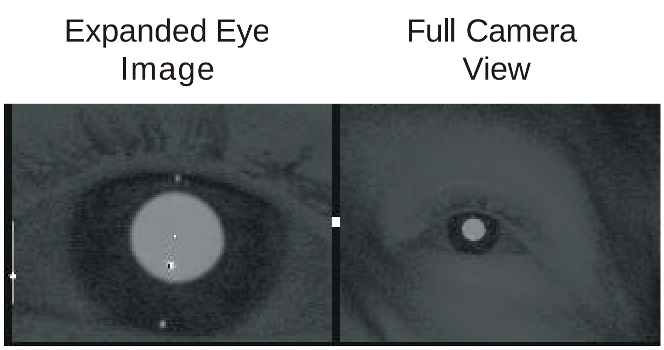


Figure 11: Eye Image Displays

The display of the full camera image provides information about whether the subject's eye is within the camera field of view. The expanded eye image shows a magnified view of the portion of the full camera view that contains the eye image.

The F12 key controls the eye display on the Eyegaze Edge's computer monitor. Pressing F12 toggles the display among two states:

1) no eye display
2) display of Full Camera View and Expanded Eye Image

2.5 Eyetracking Indicators

The magnified eye display shows whether the Eyegaze Edge is presently tracking the subject's eye. If the eye is being tracked, a bright tracking indicator is placed in the center of the pupil and a dark tracking indicator is placed in the center of the corneal reflection (See Figure 11). You should look for these tracking indicators during the process of positioning the subject. The subject is in good position when the image of the eye is in clear focus and the Eyegaze Edge is tracking.

2.6 Focus Range Indicator

As shown in Figure 12, the focus-offset indicator is a dot (located between the Expanded Eye Image and the Full Camera View) that moves up or down showing whether the subject is too close or too far from the camera. If the focus indicator is centered on the reference tick mark, the eye is in perfect focus. If the focus indicator reaches either end of the scale, the eye is approximately 0.75 inch (2 cm) out of focus. As an additional indicator, the video images of the eye turn red or green if the eye moves significantly out of focus. Green ("go forward") indicates that the subject should move forward to restore good focus, and red ("retreat") indicates that he should move backward.

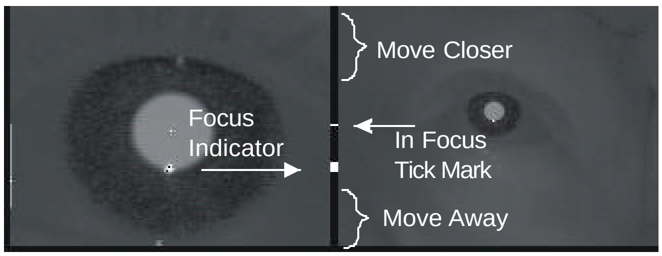


Figure 12: Focus Range Indicator

2.7 Pupil Brightness Indicator

A Pulser circuit in the Eyegaze Edge automatically controls the intensity of LED illumination on the eye. To help verify that the Pulser is illuminating the pupil properly, a Pupil Intensity Indicator, shown in Figure 13, displays a dot that moves vertically along the left edge of the expanded eye image. The dot varies from zero brightness at the bottom of the eye image to full-scale brightness at the top of the image. The vertical bar in the display shows an "acceptance range" of good pupil intensities. Note that the top of the acceptance range is 50% of full-scale intensity.

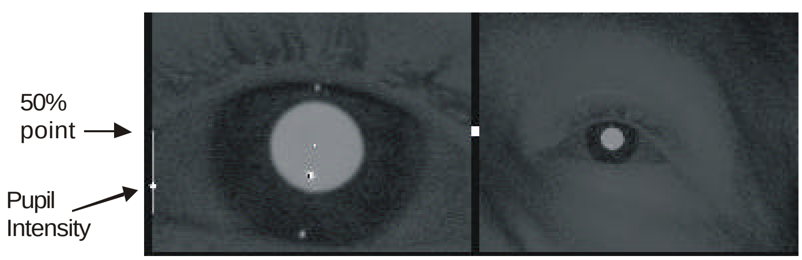


Figure 13: Pupil Intensity Indicator

3 CALIBRATING THE EYEGAZE EDGE

Before the Eyegaze Edge can track the subject's eye movements accurately, it must "learn" several of the optical characteristics of his particular eye.

3.1 Following the Dots

The calibration program calibrates to the subject's eye by placing a sequence of small circles on the computer monitor and having the subject look directly at the center of each circle. By analyzing the different images of the subject's eye when the subject is gazing at these known points, the calibration program determines how to predict the subject's gazepoint anywhere on the screen.

At the beginning of the calibration procedure, the screen displays the message "Look at Camera to Begin Calibration." The subject directs the Eyegaze Edge to begin the procedure by looking directly at the light-emitting-diode (LED) at the center of the camera lens. The system then sounds a beep and places the first calibration point on the screen. If the subject has difficulty looking at the camera to start the calibration procedure, you may bring up the first calibration point by pressing the F2 function key on the manual keyboard. Once the first calibration point is on the screen, the camera angle and focus range may no longer be adjusted.

The calibration points are small circles displayed on an otherwise blank screen. The subject looks at the calibration point by looking at the center of the circle and holding his gaze still for a period of about a second. He may relax and take his time. The computer will not move to the next calibration point until he has settled his gaze on the point for the full second. It waits for him if his eyes are moving or if he blinks. After the computer gets a calibration point, it moves the circle to the next position. The subject moves his eye to that next location and repeats the process until all calibration points are done.

Note: As discussed in Section 3.12, the number and location of the calibration points may be adjusted.

3.2 Maintaining Focus During Calibration

With fixed-camera Eyegaze systems, (i.e. systems without an Eyefollower gimbal), it is desirable for the user to keep his eye in good focus during the calibration procedure. If the user is significantly out of focus during calibration, a circle appears around the calibration dot to alert the user to move into focus. If the circle is green, move forward toward the camera. If the circle is red, move backward. The color code is a little like a traffic light:

Green	"go forward"
Red	"retreat", "reverse" or "back up"

If the eye is out of focus, the calibration procedure waits for the user to restore focus before accepting the calibration point and moving on to the next point. Generally, forward and backward motions of only a fraction of an inch are required to restore good focus. The out-of-focus indicator disappears when the eye is in good focus.

It is often helpful to the use the Eye Image Displays during calibration. See Section 2.4, "Eye Image Displays and Tracking Indicators".

With Eyefollower versions of the Eyegaze Edge, the gimbal automatically keeps the eyes in focus, so the user need not pay attention to camera focus conditions during calibration.

3.3 Skipping Calibration Points

Pressing the F2 function key during the calibration procedure causes the calibration program to skip the present point. Pressing F2 is particularly useful if the computer does not respond when the user looks down at the camera to begin the calibration procedure.

3.4 Accuracy Display

At the end of the calibration procedure, the Eyegaze Edge displays the accuracy of the calibration that it just performed. As illustrated in Figure 14, it redisplays, in one picture, the locations of all the predicted gazepoints in relation to the actual calibration points. The circles show the locations of the original calibration points, and the crosses show where the Eyegaze Edge projected the subject's gazepoints. The number displayed at the top of the screen shows the average accuracy of the gazepoint predictions. The horizontal and vertical components of the average error are shown in the upper right.

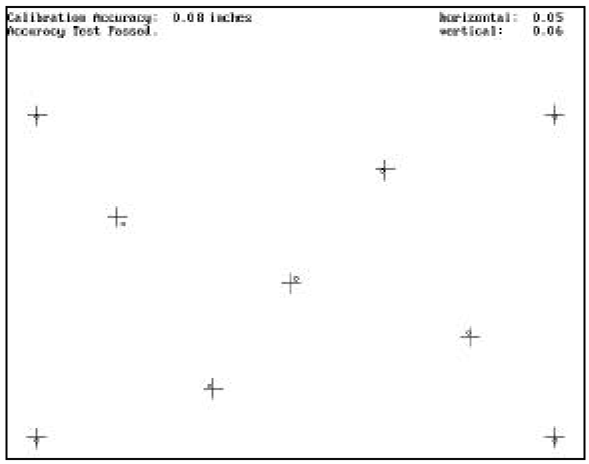


Figure 14: Calibration Accuracy Display

3.5 Retaking Calibration Points

If the subject does not get a sufficiently accurate calibration, i.e. if the average error is more than about a quarter of an inch, the calibration program assumes that it did not get good readings on one or more of the calibration points, and it automatically repeats the data collection for the worst-case points. The system indicates a point that it will "retake" by highlighting it in purple on the accuracy display. After each calibration point retake, the program readjusts the calibration parameters and re-computes the calibration accuracy. If the accuracy is still not good enough, it retakes points up to five additional times, before automatically beginning the calibration procedure again. When the accuracy is good enough, the calibration procedure is complete.

If a worse performance results from a calibration point retake, the system ignores the retake and keeps the best-to-date performance. The shift back to the previous better point can be seen in the accuracy display. The display first shows the result of the new retake, but if the resulting performance is worse, the prior better performance is subsequently redisplayed.

3.6 Accepting Calibrations

If the subject has limited eye control that prevents obtaining a calibration with an accuracy of better than a quarter of an inch after continued retakes, you may override the retakes and make the system accept the best-to-date accuracy by pressing the F3 function key on the manual keyboard. You may accept a calibration any time after the subject completes the original calibration points, i.e. either during the retakes or while the screen displays its message to start the calibration by looking at the camera. Alternatively, the subject may initiate a new calibration by looking at the camera.

3.7 Restarting the Calibration Procedure

You may, if the calibration procedure is not going well, restart the procedure at any time by pressing the F1 function key on the Manual Keyboard.

3.8 Escaping from the Calibration Procedure

The calibration process may be terminated at any time by pressing the Escape key on the manual keyboard. If the calibration process is terminated with an Escape, the Eyegaze Edge completely ignores any results from the calibration session and leaves the previous copy of CALIBRATION.DAT unchanged. Escaping from the calibration procedure is useful if you do not want to repeat the calibration procedure when your re-enter an Eyegaze Edge program.

3.9 Retention of the Calibration Results

Once the Eyegaze Edge is calibrated for a given subject, the system retains the calibration data, in the CALIBRATION.DAT file, until another calibration process is completed. The subject may close his eyes, move his head, and move away from the Eyegaze Edge. On returning to his position in front of the computer monitor, the Eyegaze Edge resumes operation without need for recalibration. Different Eyegaze programs may be run with the same calibration data. The computer may even be turned off and back on without losing the calibration. Note, however, that when the subject gets back in front of the system, the camera must be aimed at the same eye that was calibrated! Recall: the camera should not have been readjusted since calibration.

3.10 Saving Calibrations for Later Retrieval

Saving someone's calibration may be useful if it is desired to allow another person to use the Eyegaze Edge and then for the original person to return to the system without having to recalibrate. In Eyegaze applications programs that call the control_eyegaze() function (see the Programmer's Manual), calibration results can be copied to a special file called CalibrationSaved.dat by pressing the F5 function key on the manual keyboard. Note: You save a calibration during an Eyegaze application program <u>after</u> completing the calibration session. (Saving a calibration during a calibration session saves the calibration data that existed prior to the session; it does not save the results of the on-going session. If you want to save the results of the present session, first complete the calibration session and then press the F5 key.)

To verify that the calibration data is being saved when you push the F5 key, the control_eyegaze() function displays a "Saving Calibration" message in the upper right corner of the computer display. When saving a subject's calibration data, it is necessary to note the camera angle and the focus range settings, because these settings must be the same when the calibration data is retrieved.

To retrieve a saved calibration, enter the calibration program (by pressing F1) and press the F4 function key on the manual keyboard. It is important, if the camera angle or focus range have been changed since the calibration being retrieved, to restore the camera angle and focus range settings.

3.11 The Calibration Data File

The calibration coefficients (A_0, A_i, A_j, A_{ij}, and B_0, B_i, B_j, B_{jj}) are stored in a file called CALIBRATION.DAT. Eyetracking programs read the CALIBRATION.DAT file and use these coefficient values for converting the glint-pupil vector to the predicted gazepoint, in accordance with the calibration equations. If the user bypasses or aborts the calibration procedure by "Escaping" out of it, the CALIBRATION.DAT file is unchanged, and the Eyegaze Edge uses the last set of calibration parameters that was generated. The date and time of the calibration session are also recorded in the CALIBRATION.DAT file for reference purposes.

3.12 Modifying the Calibration Parameters

Many characteristics of the Eyegaze calibration procedure can be modified via the EGSettings.exe program. See Section 6.3, “Setting Calibration Parameters”.

4 MAINTAINING EYETRACKING ACCURACY

To maintain accurate Eyegaze operation with a fixed-camera Edge system, the user must keep his head positioned such that the camera(s) are aimed at the ***same eye*** on which the calibration was performed, and the eye(s) must be kept in relatively ***good focus***.

With Eyefollower versions of the Eyegaze Edge, the Eyefollower's gimbal automatically accommodates user head motions, keeps the eyetracking cameras pointed at the correct eyes, and keeps the eyes in good focus.

The subject should ***not put on or take off glasses*** or contacts without recalibrating.

<u>For fixed-camera Eyegaze Edge systems</u>:

After calibration, do ***not modify the camera***; i.e. do not modify the camera pointing angle, the focus ring, or the monitor position on the tray. Such modifications prevent the Eyegaze Edge from accurately predicting where the subject is looking and necessitate recalibration. If the system is not tracking the subject's gaze accurately and it is suspected that such changes may have occurred, recalibrate so as not to frustrate the subject with inaccurate responses.

If the subject gets out of focus or out of the field of view of the camera, the focus may be recaptured by moving either the subject and/or the camera/tray/monitor complex as a unit. Do not adjust the camera pointing angle or focus ring.

5 CONTROLLING EYEGAZE OPERATION

5.1 On-line Calibration Controls

F1 – In the Eyegaze Communication program for people with disabilities, the calibration procedure may be restarted at any time by pressing F1. F1 has no Eyegaze function in most other Eyegaze application programs.

F2 - During the calibration procedure, the user may skip any calibration point (including the "0^{th}" point where the subject looks at the camera) by pressing the F2 function key. The calibration procedure then ignores that point when calculating the calibration parameters.

F3 - If the subject did not get a sufficiently accurate calibration to be accepted automatically, the calibration may be accepted manually by pressing F3 during the calibration point retakes or while the screen displays its message to restart the calibration. The Eyegaze Edge then accepts a less-than-perfect calibration and returns.

Escape - The calibration procedure may be exited at any time by pressing the Escape key.

5.2 Runtime Controls

F12 - The F12 function key toggles the state of the Eye Image Display in the upper right corner of the Eyegaze Computer screen. (See Section 2.4 "Eye Image Displays and Tracking Indicators".)

(The Escape and Function keys perform specific Eyegaze control functions while Eyegaze programs for people with disabilities are running. These function control keys are described in the Appendix.)

5.3 No Support for Simultaneous Eyegaze Applications

If you attempt to load an Eyegaze application program when another Eyegaze application program is already running, Eyegaze beeps and terminates the second application.

6 EYEGAZE SETTINGS PROGRAM

The **EGSettings.exe** program allows the user to modify several of the Eyegaze Edge's eyetracker settings.

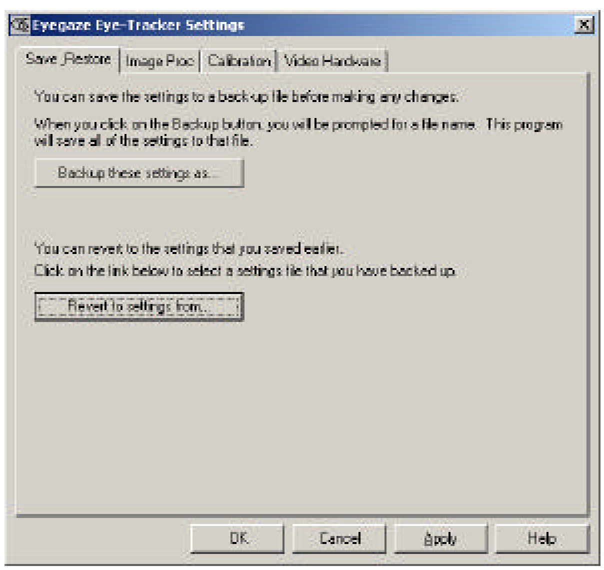
Each parameter in the EGSettings program has a default value considered most useful for most people. To see which parameters are set to non-default values, click the button entitled "Highlight Non-Default Values". Any non-default values are then highlighted in red for easy recognition. All the values on a page may be set to their defaults by clicking the "Set Values to Defaults on this Page" button.

The values of the Eyegaze settings parameters are stored in a file called **c:\eyegaze\CurrentConfig.eg**.

<u>Note on Disability Demonstration Software</u>: Eyegaze Analysis Systems have Eyegaze Communication software loaded on them for demonstration purposes. The disability program, **ecs.exe**, uses many of the same eyetracker controls used by other application programs, such as the example Analysis System programs provided by LC Technologies and your own development programs. To allow different sets of eyetracker control parameter values to be used in disability versus development applications, the Eyegaze Edge maintains separate settings files for these two categories of applications, and it has separate settings programs for modifying the two parameter sets. Thus you may modify the settings for your applications programs (e.g. the calibration type or calibration screen color) without also modifying them for the disability demonstration software. The settings program for the disability software is called ***ECS***Settings.exe, as opposed to ***EG***Settings.exe, and the settings file for the disability software is CurrentConfig.***ecs***, as opposed to CurrentSettings.***eg***.

6.1 Saving and Restoring Parameter Values

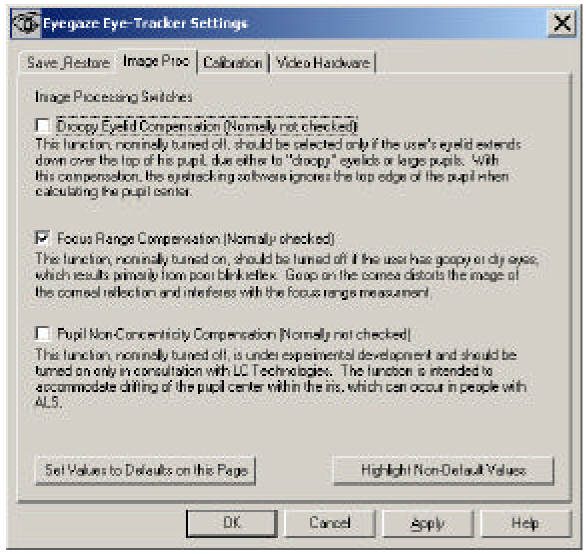
Old sets of parameter values may be saved for later recall. When you click on the "Save Restore" tab, the EGSettings program gives you the options of backing up the existing settings and/or reverting to previously saved settings. When you back up the existing settings, the program nominally names the saved file: "ECS Settings_On_*month_day_year*.eg", where *month*, *day*, and *year* are the present date, so it is easy to recall when you saved the file. You may, however, edit the file name as you wish.



When you retrieve old settings, the program lists all the file names of all the prior settings you have saved and allows you to select the one you wish to retrieve.

6.2 Setting Image Processing Characteristics

The Image-Processing parameters control how the eyetracking software analyzes the camera's images of the eye. To edit the Image Processing parameters, click on the "Image Proc" tab.

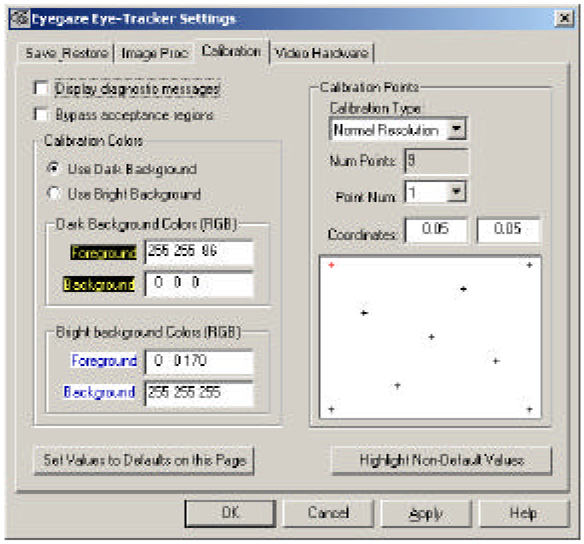


The following table provides detailed explanations of the image processing parameters:

Droopy Eyelid Compensation	On or Off	Droopy Eyelid Compensation should be selected only if the user's eyelid extends down over the top of his pupil. With this compensation, the eyetracking software ignores the top edge of the pupil when locating the pupil center. (Normal condition is OFF, i.e. *no* check in box.)
Focus Range Compensation	On or Off	Focus Range Compensation, nominally turned on, corrects gazepoint measurements as the user moves his head forward and backward. This function should be turned off, however, if the user has goopy or dry eyes, which results primarily from poor blink reflex. Goop on the cornea distorts the image of the corneal reflection and interferes with the focus range measurement. (Normal condition is ON, i.e. check in box.) (see Section 1.9)
Pupil Non-Concentricity Compensation	On or Off	Pupil Non-Concentricity Compensation is intended to accommodate drifting of the pupil center within the iris and reduce post-calibration drift. If non-concentricity compensation is activated, the calibration "cycles" through the calibration dots twice, once with a dark screen background and once with a bright screen background. (Also see Section 6.3.3, "Calibration Screen Settings.) This function, nominally turned off, is under experimental development and should be turned on only in consultation with LC Technologies. (Normal condition is OFF, i.e. *no* check in box.)

6.3 Setting Calibration Parameters

The "Calibration" page of the EGSettings program allows you to control the operation of the Eyegaze calibration procedure.



6.3.1 Displaying Diagnostic Messages

For cases where a user is having difficulty getting through the calibration procedure, the calibration program has an option to display the reason that it is not accepting the present calibration point. To activate these diagnostic messages, check the "Display Diagnostic Messages" box. With the diagnostic messages activated, one or more of the following messages appear when the calibration procedure does not accept a point within a few seconds:

Inconsistent tracking	the eyetracker is occasionally missing, i.e. not finding, the eye during the calibration-point acceptance period
Gaze not still	the measured gaze is not sufficiently still, i.e. fixated, to accept the calibration point
Gaze not on point	the user's gaze is not sufficiently close to the calibration point
Gaze hasn't moved	the user's gaze has not moved from the prior calibration point
Out of focus	the eye is not in sufficient focus for calibration

Note: The calibration procedure requires the eye to be in better focus than is required during normal eyetracking operation.

6.3.2 Bypassing Acceptance Regions

The "Bypass acceptance region" box should be checked only if the Eyegaze camera is moved to a position other than its normal location below the screen and centered horizontally.

Nominally, the calibration procedure requires the user to look at the displayed calibration dot before it accepts the calibration point and progresses to the next point. It verifies that the user is looking at the dot by checking that the glint-pupil vector is within a reasonable "acceptance region." The glint-pupil acceptance region is a function of the calibration-dot location with respect to the camera position. If the camera is moved from its nominal position, the acceptance regions no longer correspond to the calibration dot locations, and the calibration procedure does not accept calibration points. Checking the "Bypass

Acceptance Region" box allows the calibration program to accept calibration points without verifying that the user is looking at the dot.

6.3.3 Calibration Screen Colors

For best eyetracking accuracy, the calibration screen color should be set to match the brightness of the screens used during eyetracking data collection. This minimizes the amount of pupil dilation or constriction that occurs between calibration time and test time, and thus reduces post-calibration drift.

Two calibration color palettes are available to be set: one for a dark screen background and one for a bright screen background. Each palette contains a background color for the whole screen, and a foreground color for displaying the calibration dots and text. The colors are specified in red, green and blue (RGB), with the value of each color ranging between 0 and 255. The selected colors are shown in the "Foreground" and "Background" labels to the left of the color input fields.

If a normal "single-pass" calibration is used (i.e. if the "Pupil Non-Concentricity Compensation" option has *not* been set on the Image Processing page, Section 6.2) you tell the calibration program which color set you want by clicking the appropriate "Dark" or "Bright" radio button. On the other hand, if the "Pupil Non-Concentricity Compensation" option *is* set, the calibration program goes through the dot sequence twice, and both color sets are used.

6.3.4 Calibration Types

To best suit the user, the calibration procedure may be controlled to perform one of three Calibration Types:

Normal – 9 calibration points, small dots
Simple – 5 calibration points, larger dots, easier for the eye to track
High Resolution – 13 calibration points, small dots

The normal 9-point calibration is optimum for most users and applications.

The simple 5-point calibration is easier for a user to get through, and it may be preferable for some people with limited eye control. On the other hand, the 5-point calibration typically results in poorer eyetracking accuracy than would be obtained if the user were able to get through the normal 9-point calibration.

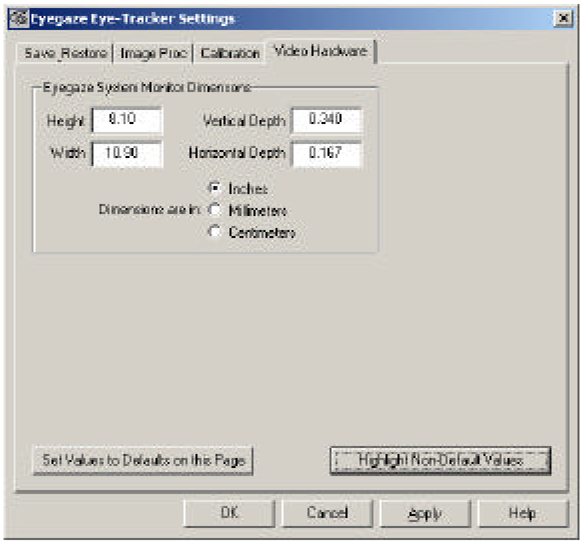
The high-resolution 13-point calibration may provide slightly more accurate eyetracking for some people than the normal 9-point calibration.

6.3.5 Changing Calibration Dot Locations

If it is desired to move the locations of the calibration points on the screen, the EGSettings program allows you to modify the dot coordinates. To move a calibration point, first select the desired "Point Num." The program highlights the location of the selected point in red. Then edit the x and y coordinates as desired. Coordinate values are expressed in terms of full screen width and height. The values may not be less than 0.00 or greater than 1.00. When you finish editing a coordinate value, the program moves the calibration point on the display, so you can see where it will be on the real calibration screen.

6.4 Setting Video Hardware Parameters

The "Video Hardware" page of the EGSettings program allows you to specify monitor and frame-grabber parameters.



6.4.1 Eyegaze Edge Monitor Dimensions

If eyetracking is being performed on the Eyegaze Edge's own monitor (single computer configuration), and it is desired to measure gaze coordinates in physical dimensions, i.e. in inches or centimeters, as well as in pixel coordinates, the Eyegaze software must know the physical dimensions of the screen. Set the physical dimensions in the "Monitor Dimensions" boxes. (The Vertical and Horizontal Depth parameters, which are expressions of screen curvature, are not presently used.)

APPENDIX I: EYEGAZE EDGE CONTROL KEYS

The Escape and Function keys perform specific Eyegaze control functions while certain Eyegaze programs are running.

Eyegaze Control Keys:

ESC Terminate Program

Pressing the Escape key sets an external variable named "ig_escape_pressed" to TRUE (1). Testing this variable after a call to control_eyegaze() provides the application a method to terminate on request from the subject. It is the responsibility of the application to test this variable; the eyegaze software takes no action.

Calibration Control Keys:

The calibration program CALIBRAT.EXE uses the control_ eyegaze() function and responds to the following keys:

F1 Recalibrate

Pressing the F1 key sets a flag called "ig_cal_requested". An application program may check the calibration_requested flag and initiate the calibration process if desired.

F2 Skip Calibration Point

If it is difficult for the subject to look at the camera to start the calibration procedure, the Camera calibration point may be bypassed manually by pressing F2. Similarly, any on-screen calibration point may be bypassed by pressing F2.

F3 Accept Calibration

If the subject did not get a sufficiently accurate calibration to be accepted automatically, the calibration may be accepted manually by pressing F3 during the calibration point retakes or while the screen displays its message to restart the calibration. The Eyegaze Edge then accepts a less-than-perfect calibration and returns.

F4 Retrieve Calibration

The F4 key can be pressed at the beginning of a calibration procedure to recall a calibration that was previously saved to disk in CalibrationSaved.DAT. The F4 retrieve-calibration key, in combination with the F5 key to save calibrations, eliminates the need for a subject to recalibrate the system if another person has used the system in the mean time.

F5 Save Current Calibration for later Retrieval (Disability Programs Only)

Pressing F5 saves the current eyegaze calibration data for later recall by copying CALIBRATION.DAT into CalibrationSaved.DAT. CalibrationSaved.DAT can be recalled by entering the calibration procedure and pressing the F4 key.

Gaze Duration Control Keys [for use with ikeys()]:

F6 & F7 Decrease/Increase the Gaze Duration (Disability Programs Only)

Each manual press of the F6 key decreases the length of the Gaze Duration by one tenth of a second (for IKEYS applic ations programs that use eye-operated keys). The F7 key increases the Gaze Duration. When pressing either F6 or F7, the adjusted value of the Gaze Duration is briefly displayed in the upper right corner of the computer monitor.

Gazepoint Display Control Keys:

The locator dot is a small red cursor that appears at the subject's gazepoint on the computer monitor when running an IKEYS application. The following manual buttons control the behavior of the locator dot.

F9 Toggle the Locator Dot on the Computer Monitor (Disability Programs Only)

Pressing the F9 function key switches the display of the red Locator Dot on the monitor between three different modes:

in-key	the dot is displayed only when the subject is looking within a key
never-on	the dot is never displayed
always-on	the dot is always displayed

(The dot turns green when the Eyegaze Edge is tracking but the subject is looking off screen.)

F12 Toggle the Eye Image Display on the Computer Monitor (Disability Programs, Trace Program, GazeDemo Program)

Pressing F12 toggles the Eye Image Display between three states:

Off - no eye image display
Full camera image only
Expanded eye image and full camera image

See Section 2.4, "Eye Image Displays and Tracking Indicators".

BIBLIOGRAPHY

Bishop, P.O. (1981) Binocular vision. In Moses, R.A. (Ed.). Adler's Physiology of the Eye, Clinical Application. St. Louis: The C.V. Mosby Company.

Cleveland, D. (1989). Method and apparatus for locating image features. U.S. Patent 5,231,674.

Cleveland, D. (1990). Focus control system. U.S. Patent 4,974,010.

Cleveland, D. & Cleveland, N.R. (1992). Eyegaze eyetracking system. In Proceedings of 11th Monte Carlo International Forum on New Images.

Cleveland, D. et al. (1993). Eye tracking method and apparatus. U.S. Patent 5,231,674.

Hutchinson, T.E. (1989). Eye movement detector. U.S. Patent 4,836,670.

LaMarre, D.A. (1977). Development of criteria and test methods for eye and face protective devices. (Report from Contract 210-75-0058) U.S. Department of Health Education and Welfare, National Institute for Occupational Safety and Health.

Mason, K.A. (1969). Control apparatus sensitive to eye movement. U.S. Patent 3,462,604.

Merchant, J. & Morrisette R. (1973). A remote oculometer permitting head movement, (Report No. AMRL-TR-73-69). Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio.

Young, L., & Sheena, D. (1975). Survey of eye movement recording methods. In Behavior Research Methods and Instrumentation, 7(5), pp. 397-429.

LC TECHNOLOGIES EYEGAZE ANALYSIS SYSTEM
SECTION 2: USER'S MANUAL
TABLE OF CONTENTS

LIST OF FIGURES

US Patents: 6,598,971; 5,231,674; 4,974,010; 4,836,670