Optimizing infra-red light collection for high-speed video-based eye tracking

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Background

Infra-Red (IR) video-based eye trackers provide a non-invasive, relatively inexpensive way to measure human eye movements. Although most standard commercially available IR video-based trackers sample eye-position at 60Hz, recent advances in technology now allow some to operate at 240Hz . This enables eye-movement measurement at a temporal resolution high enough to capture the full range of human eye movements. To achieve a high spatial resolution, high magnification of the image of the pupil is also required. Video-based eye trackers compute the horizontal and vertical positions of the pupil and corneal reflection by analyzing each video frame to determine their locations. The precision of these analyses is generally limited by the signal-to-noise ratio of the image of the eye. The short exposure time (4 ms) and high optical zoom greatly reduce the available light. This decreases the signal-to-noise ratio, and thus reduces the spatial precision of the eye-position measurement. Therefore, it is critical to optimize the IR light collection of these systems to maximize the camera response (image contrast). To increase the image contrast, one is forced to increase the IR illumination. However, IR light can heat and thereby dry the eye. If the IR illumination is too high, it can cause discomfort and potentially even injury. Thus, it is also essential to optimize the IR light collection to minimize the exposure to IR radiation. Both of these goals can be realized by making the judicious choices of optical components described in this report.

Configuration

To optimize the spatial precision of the eye tracker, the video camera's view of the eye must be approximately parallel to the line of sight, and the illumination of the eye should be uniform. Additionally, neither the camera nor the IR illuminator should block the stimulus display. To satisfy these constraints, we use the configuration shown in Fig. 1.

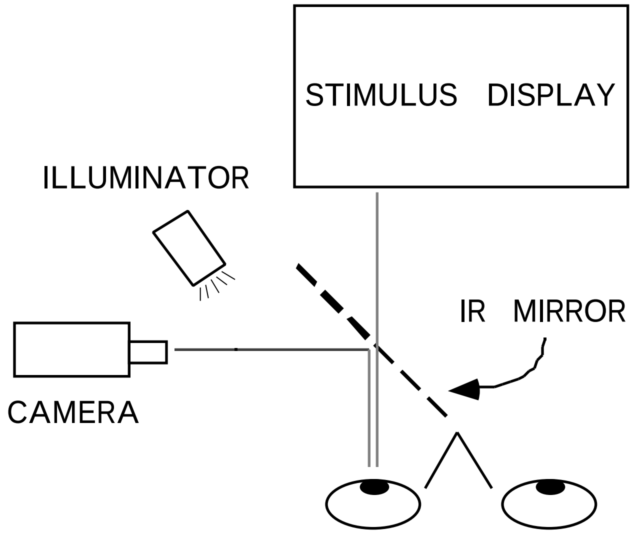

Fig. 1 Eye-tracker setup configuration. The distance between the source and the eye is ~14cm. The viewing distance between the observer and the display is ~57cm, and the optical distance between the camera and the eye is ~20 -25cm (dependent upon amount of zoom).

Minimizing IR exposure

The ISCAN IL-400 illuminator uses an ESX slide projector bulb, which emits light over a large range of frequencies (ultra-violet through infra-red). Its output passes through a band-pass IR filter (2” diameter round), which was chosen to pass light between approximately 700nm and 1100nm (see Fig. 2 for complete spectral data). To eliminate more of the visible light a high-pass filter was also used which blocks <~800 nm (see Fig. 3 for complete spectral data). Thus, the eye is illuminated with non-visible light yet its exposure to IR radiation is limited only to that which the camera is sensitive. Useless, but potentially harmful, far IR light is eliminated at the source. This allows us to increase the effective illumination using only the near IR light that will actually increase the signal-to-noise ratio.

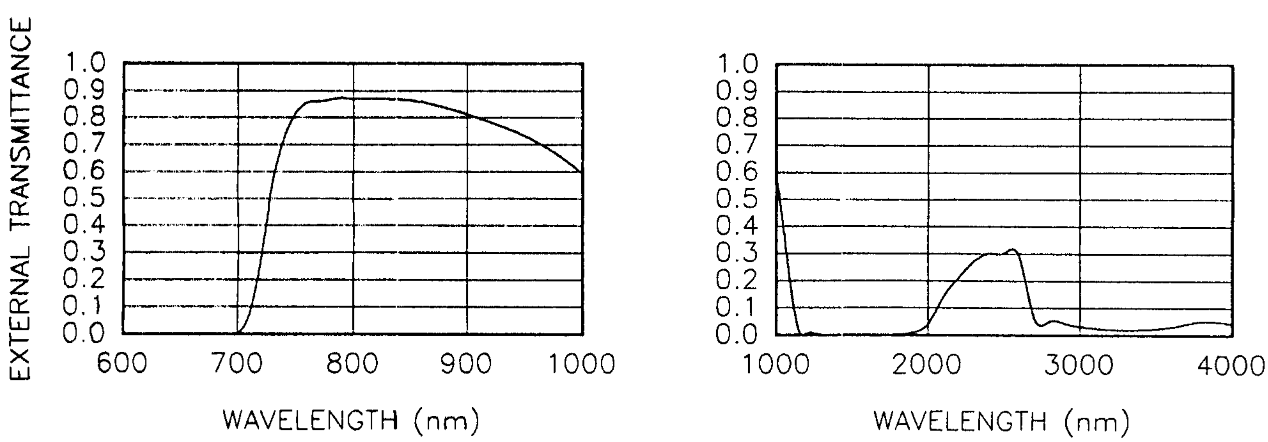

Fig.2. Schott Filter RG9 &Oriel 59509 Spectral Graph.

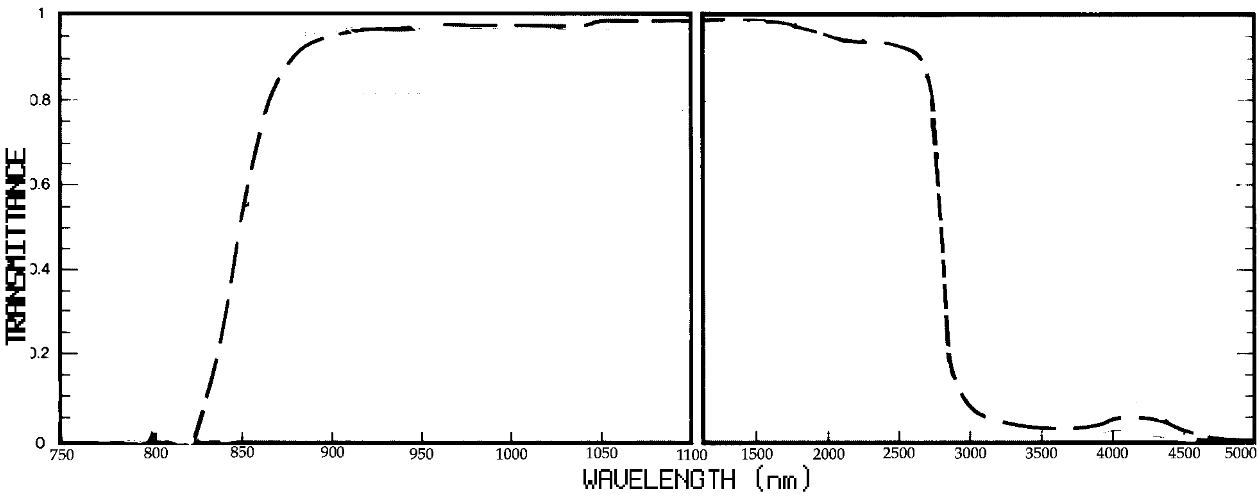

Fig.3. Schott RG850 & Oriel 59560 Spectral Graph.

Maximizing the camera response

To optimize the camera response, the power it receives in the region of the spectrum to which it is sensitive must be maximized but it is important that the power in the visible spectrum (which extends to ~800nm) be minimized so that the observer sees only the stimulus. Although the room is dimly lit, stray visible light from objects located in the camera's field of view could degrade the image of the eye. A COHU 6400 series monochrome CCD camera was chosen because its sensitivity extends well beyond the visible region into the near IR to about 1000nm. As reported in its specification sheet, its quantum efficiency is 30% at 800nm and falls to about 5% at 1000nm (see Fig. 4 for complete spectral data). To maximize the amount of IR light collected while minimizing the amount of visible light, we optimized three optical elements: the lens, the mirror, and the camera filter. A low f-stop (F1.2) lens (Computer TV Zoom lens M6Z 1212, Edmund Scientific #D53,153) was selected. Second, a large (4"x5") 45° incidence hot-mirror (see Fig. 5 for complete spectral data) was chosen that passes nearly all visible and reflects nearly all IR light (>95%). Before the reflected light enters the camera, it passes through a final IR filter, which passes IR yet blocks most visible light below 650 nm (see Fig. 6 for complete spectral data). This filter replaced a Hoya RM90 filter (blocks <~ 700 nm) which eliminated much more of the near IR to which the camera is sensitive and thus required a much higher illumination (see Fig. 7 for complete spectral data). While the new filter passes a small amount of visible light (> 650nm), this does not significantly degrade the image or interfere with the visual stimuli.

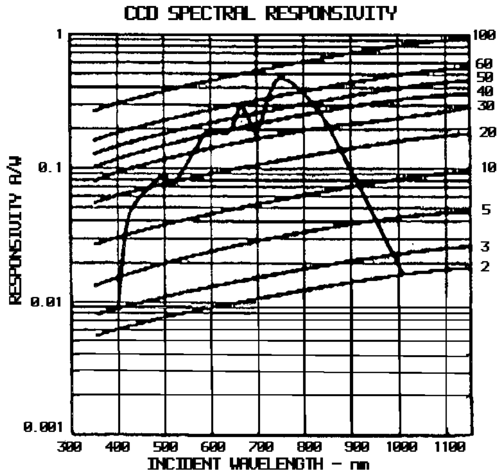

Fig.4. COHU Inc. Camera 6310 Spectral Graph.

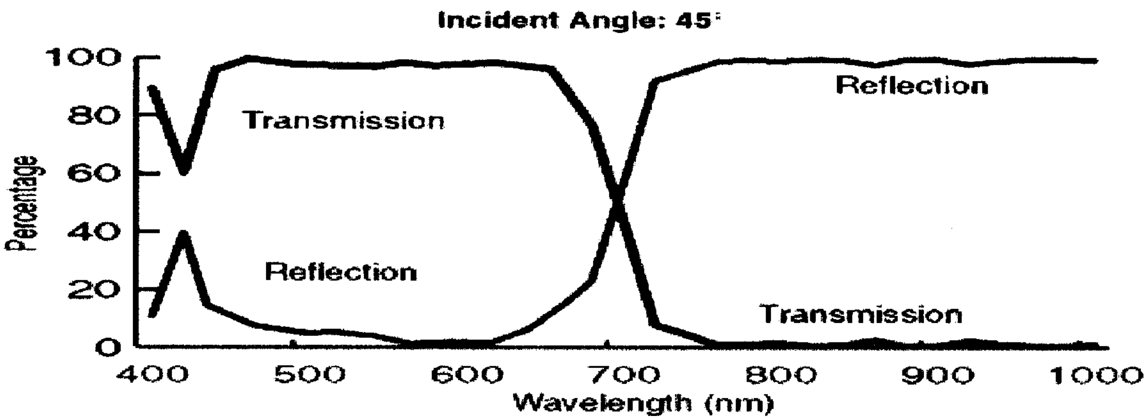

Fig.5. Hot Mirror Spectral Graph (Edmund Scientific part #D43,958)

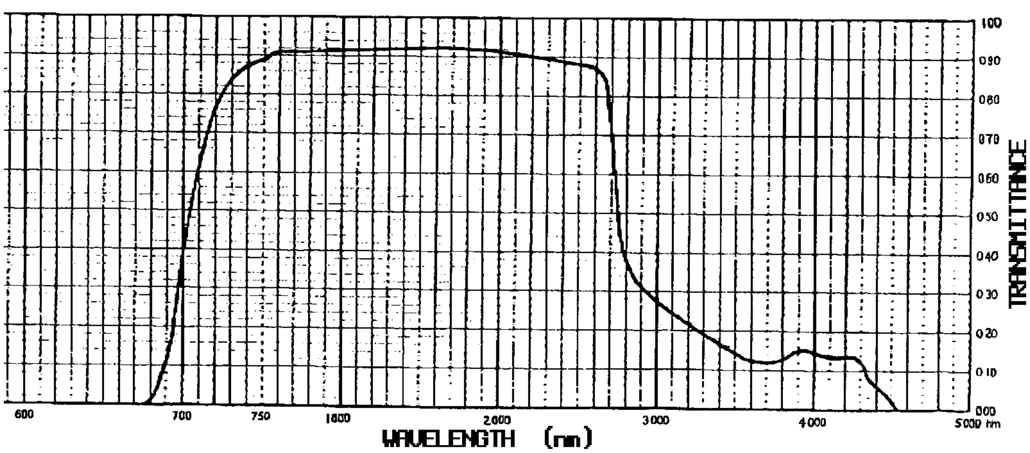

Fig. 6. Schott RG 695, Oriel 51340, Hoya RM70, B+W 092, or Wratten 89b Spectral Graph.

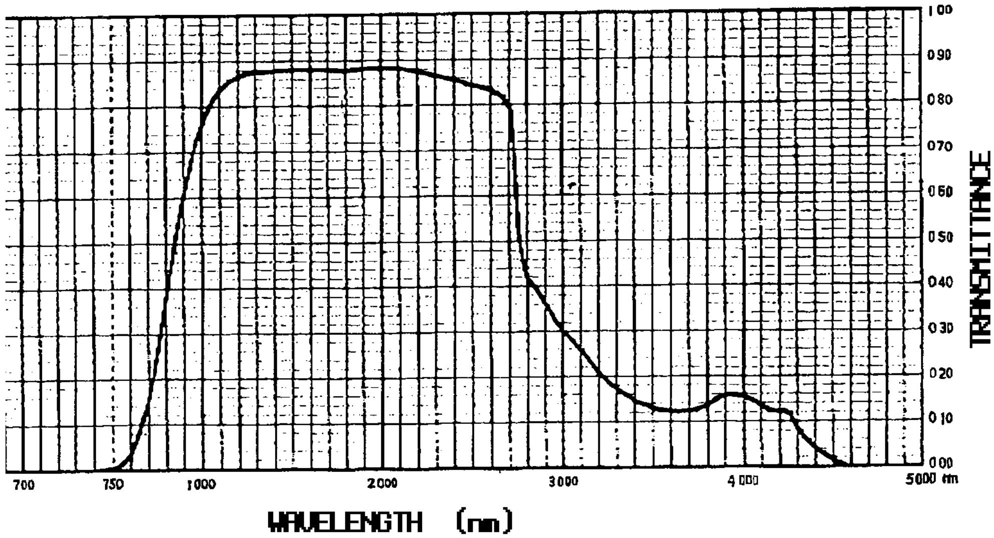

Fig. 7. Hoya RM90, B&W 094, or Wratten 87a Filter Spectral Graph

Measuring IR Exposure

To ensure that the IR exposure is at a safe level, it is necessary to measure all the IR radiation incident on the eye. This requires that the sensor's responsivity covers the full range of incident IR light. While the slide projector bulb emits a broad spectrum of both visible and IR light, the two illuminator filters block most light above ~1100nm (see Figs. 2 and 3). We used an ORIEL model #70261 detector, which is sensitive to IR radiation beyond 2000 nm, and measured a total corneal exposure of ~1 mW/cm^2. A safety limit of 10mW/cm^2 for total corneal IR exposure has been established by OSHA. Although there are also safety limits for retinal exposure to small or point sources, because our IR light source was diffuse, these limits are not an issue.

Conclusion

By carefully choosing the illuminator filters, camera filter, and hot mirror, a high-contrast IR image of the eye can be obtained, while the overall exposure to IR radiation can be limited to a safe low level. The set up described above produces an IR image of the eye that can serve as a low noise input to a IR video based eye tracker. Even at sampling rates as high as 240Hz, total corneal IR exposure can remain ~10 times lower than the OSHA safety limit (~5X lower than the exposure using the standard optical elements provided for 60Hz sampling). The 240Hz images generated allow for an eye-position precision as low as 0.05° (using the ISCAN RK726 PCI Tracker).

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