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Optical Requirements with Turbulence Correction for Long-range Biometrics

Junoh Choi, Grant H. Soehnel, Brett E. Bagwell, Kevin R. Dixon, David V. Wick
Sandia National Laboratories, PO Box 5800, MS 1188, Albuquerque, NM 87185-1188

ABSTRACT

Iris recognition utilizes distinct patterns found in the human iris to perform identification. Image acquisition is a critical first step towards successful operation of iris recognition systems. However, the quality of iris images required by standard iris recognition algorithms puts hard constraints on the imaging optical systems which have resulted in demonstrated systems to date requiring a relatively short subject stand-off distance. In this paper, we study long-range iris recognition at distances as large as 200 meters, and determine conditions the imaging system must satisfy for identification at longer stand-off distances.

Keywords: Biometrics, iris recognition, adaptive optics, atmospheric turbulence, horizontal path imaging

1. INTRODUCTION

Iris recognition has grown over the years to establish itself as a reliable biometric for identification. Identification using an image of the iris relies heavily on the quality of the image. Various methods have been proposed to screen iris images for image degradations such as defocus, motion blur, and occlusion.[1,2] On the hardware side of the iris recognition, attempts at capturing a pristine image of the iris have resulted in systems that require still subjects at a close standoff distance. These strict constraints on the subject have been relaxed in recent years by the introduction of systems with increased capture volume, longer standoff distance and/or shorter residence time that can capture an acceptable image of the iris[3,4,5]. The longest standoff distance specified among the current iris recognition systems is in the order of a few meters[5]. In this paper, we first review the first-order design process for an iris imaging system to identify fundamental factors that determine the image quality. We study iris recognition at greater distances, out to 200m, and define iris imaging system parameters required for reliable performance. We also study the effects of turbulence on iris recognition at large distances by simulating ground level horizontal path imaging at various distances. The results show that turbulence correction is required beyond the standoff distance of 42m using a lower iris image quality standard of 100 pixels across the iris and 27m following a more stringent requirement of 200 pixels across the iris.

2. IMAGING SYSTEM DESIGN

One of the factors that drive the design of an optical system is the requirement of the image quality. For iris recognition, the image quality requirement is given in terms of resolution by the ISO/IEC 19794-6:2005, which recommends a minimum of 100 pixels across an iris. Using a diameter of 10mm for an iris, the pixel size at the iris plane is 0.1mm to meet the standard for recognition. At the image plane, a 100 pixel image of the iris covers 740um for a typical CCD with a 7.4um pixel size. We proceed with the first order design of the imaging system using thin lens approximations. Throughout this study, the ISO/IEC standard of 100 pixels across the iris diameter is used for image quality and a wavelength of 850nm is used unless stated otherwise. The magnification of the system, ratio of the image size to the object size, is -0.074 with the negative sign representing an inverted image. By specifying an object distance, the standoff distance, we can now calculate the focal length of the optical system using thin lens equations[6]. Focal length is given by

$$f = \frac{m}{(1-m)} z \,, \tag{1}$$

where f is the effective focal length of the imaging system, m is the magnification of the system, and z is the object distance. As an example, an object distance of 200m requires the effective focal length of the iris imaging system to be approximately 13.8m. Focal length and the object distance define the system magnification and ensure that the system operates at a specified magnification to get at least 100 CCD pixels across the image of an iris. Having a 100 pixel iris image does not guarantee a successful identification however, as the image can be degraded by various factors including defocus, motion blur, low resolution, gaze angle, and occlusion. Of these factors that adversely affect the quality of the iris image, low resolution is the only factor that can be compensated for in the imaging system design stage while others are effects resulting from the image acquisition process.

Performance of an optical system is limited by two factors: aberration and diffraction. Aberrations can be well corrected, albeit at the cost of a more complex system, and considered a non-limiting factor in optical performance. Diffraction however, is a phenomenon that is inherent in all optical systems and cannot be corrected. Assuming the imaging system is well corrected for aberrations, the imaging performance is only limited by diffraction and the system is said to be diffraction-limited. The resolution of a system, which is related to the smallest spot size that the optical system can resolve, can be compared using the diffraction-limited spot size. Equation 2 shows relationship of the diffraction-limited spot size to the imaging system parameters.

$$\text{Diffraction-limited spot diameter} = 2.44\lambda \frac{f}{D}. \tag{2}$$

Equation 2 shows that the spot diameter is related to the wavelength λ, focal length f, and the aperture diameter D. The ratio of the focal length to the aperture diameter is known as the f-number (f/#) of the system. The focal length of the system is used in the equation because an infinite conjugate configuration is assumed. However, under the conditions of finite conjugate imaging, the focal length f is replaced by the object or image distance to calculate object or image space resolution. It is evident from Equation 2 that with a constant wavelength and aperture size, the diffraction limited spot size in the object plane increases as the object distance is increased. This implies that the imaging system's resolution capability is reduced. Therefore, to maintain the resolution limit of an optical system to specifications, it is imperative that the aperture size of the system is selected accordingly.

Continuing with the example of an object distance of 200m where the object space pixels were calculated to be 0.1mm in size, the pixels should be positioned at the peak of each smallest resolvable spot on the iris. Diffraction limited spot diameter specifies the size of the smallest resolvable spot and the minimum separation between the spots is given by the Rayleigh criterion. The Rayleigh criterion is a widely accepted standard for minimum resolvable detail that states that two diffraction limited spots should be separated by at least 1.22λ(f/#), equal to the radius of a single spot, to correctly resolve the two spots[7]. Following the Rayleigh criterion, the pixel spacing, assumed here to be equal to the pixel size, corresponds to the minimum spot separation, which is the radius of a diffraction limited spot. Then the smallest spot resolvable on the iris plane is twice the pixel size (0.2mm), resulting in 50 diffraction limited spots across an iris that spans 100 pixels. Using Equation 2 to solve for the aperture diameter D, at a distance of 200m and a wavelength of 850nm, the diameter of the imaging system has to be approximately 2m. If the aperture size of the optical system is smaller than the required diameter calculated from Equation 2, an image of the iris can still have 100 CCD pixels across an iris but will be at a lower resolution. To illustrate this point, we obtained iris images that span approximately the same CCD pixels but at different resolution settings. Figure 1 shows images of the same iris obtained at different f/# settings to vary the resolution and intensity profiles along the line indicated in the iris images. The image on top is taken at f/11 and the bottom image is captured at f/2.8.

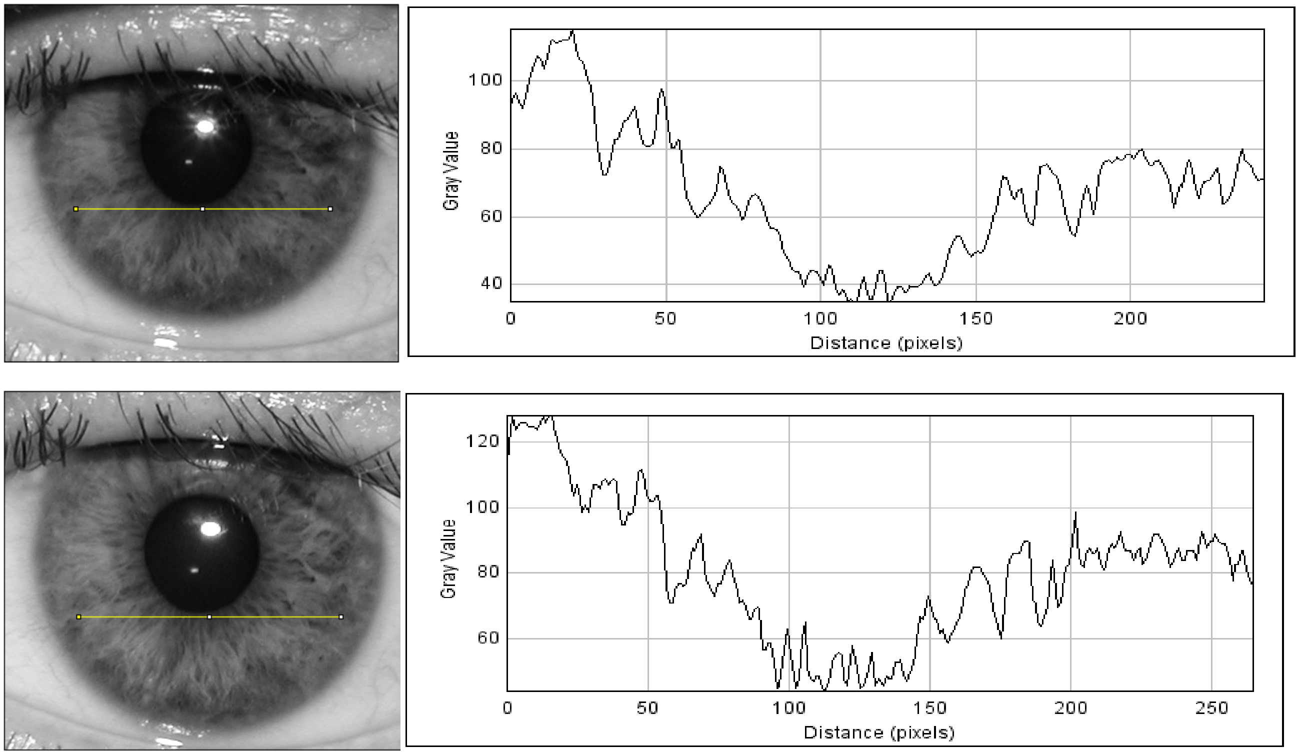

Figure 1: Comparison of iris images at different resolutions with intensity profiles along the yellow line.

Although it may seem reasonable to reduce the aperture size to increase the depth of field and relax the defocus error constraint, required resolution will not be obtained. Therefore, aperture size is rather a strict constraint in the optical system design to achieve desired level of performance.

3. EFFECTS OF TURBULENCE

3.1 Effects on system design

Atmospheric turbulence has been extensively studied in the field of astronomy[8]. Since turbulence is most severe near the ground, it becomes significant over relatively short ground-level horizontal paths as compared to the longer vertical paths of astronomical imaging for space objects[9]. Turbulence results from random fluctuations in the temperature and pressure in the atmosphere. Fluid mechanics causes the air to consist of pockets of randomly varying temperature and pressure. This in turn causes the atmosphere to have a randomly varying index of refraction which distorts a wavefront propagating through the atmosphere and degrades the quality of the final image. In order to understand the effects of turbulence on iris recognition at large distances, we study the effects on ground-level horizontal path propagations ranging from distances of 10m to 200m.

The strength of the index of refraction fluctuations must first be defined and is characterized by the parameter C_n^2, referred to as the structure constant of the index of refraction fluctuations. Models have been developed to give typical C_n^2 values as it varies with altitude for various locations and time of day. For this study, C_n^2 assumes a constant value of $4.233 \cdot 10^{-15}$ which was obtained from the Hufnagel-Valley model at an altitude of 2m above ground[9]. Once the structure constant C_n^2 is characterized, we can calculate the Fried parameter r_0,which is a measure of the severity of propagation through turbulence[9]. The equation for calculating r_0 is given by

$$r_0 = 0.185 \left[\frac{4\pi^2}{k^2 \int_0^L C_n^2(z) dz} \right]^{3/5}, \quad (3)$$

where $k = 2\pi/\lambda$ is the wavenumber, z is the direction of propagation, and L is the length of the propagation path. r_0 has units of meters, and represents the largest aperture size where diffraction limited imaging is still possible. Therefore, assuming aberrations have been well corrected, an optical system with an aperture smaller than r_0 will perform at the diffraction limited level while a system with an aperture larger than r_0 will result in images that are affected by turbulence. Figure 2 shows a plot of r_0 as a function of propagation distance ranging from 10m to 200m. Also included in the plot is the aperture size, D, required for an imaging system that will resolve 50 diffraction limited pixels across the diameter of the iris in the same range of distances. As mentioned in the previous section, 50 diffraction limited pixels across the iris diameter satisfies the ISO/IEC standard for iris image quality at 100 pixels across the iris. Note that at an object distance of about 42m, the aperture size needed for diffraction limited performance becomes larger than r_0. This indicates that for object distances greater than 45m turbulence will distort the spot size on the iris beyond 0.2mm, lowering the system resolution limit below the image quality requirement for iris recognition. Using the standards and models we have stated, additional compensation is required for diffraction limited imaging of iris at distances greater than approximately 42m. For comparison, if the iris image quality of 200 pixels across the iris is used, the threshold distance shortens to about 27m. Figure 3 shows the Fried parameter plot, on a different scale, for the higher image quality of 200 pixels across an iris. Incorporation of adaptive optics in the imaging system that compensates for effects of turbulence is necessary for successful iris recognition at great distances.

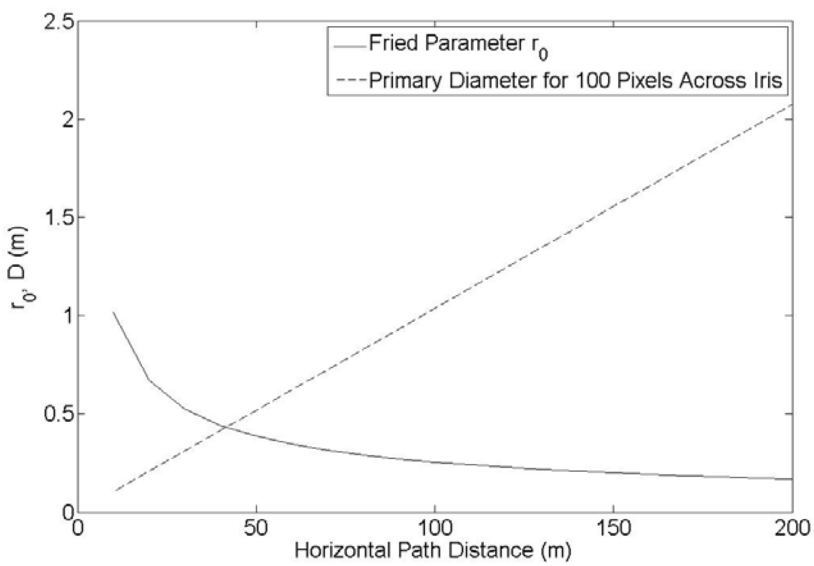

Figure 2: Plot of r_0 and the minimum aperture size needed to resolve 100 pixels across the 10mm diameter of the iris for horizontal object distances ranging from 10m to 200m. For 100 pixels across the iris, turbulence dominates at distances greater than approximately 42m.

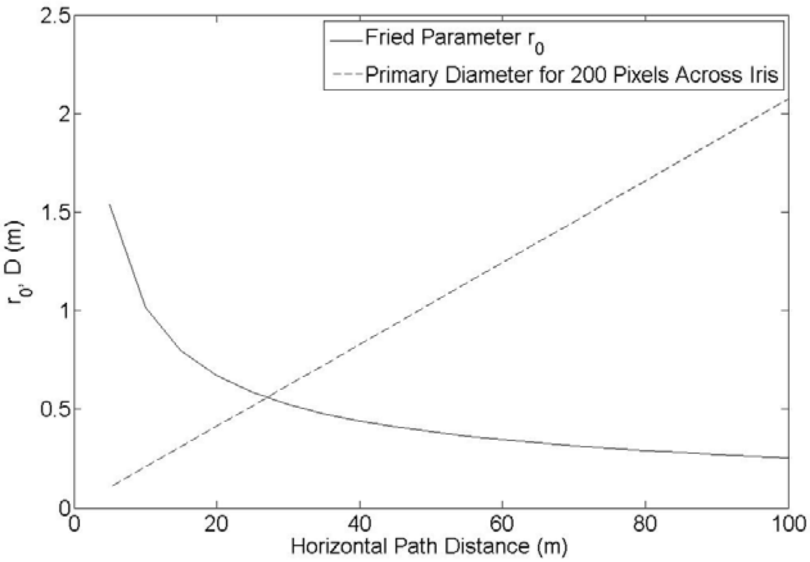

Figure 3: Plot of r_0 and the minimum aperture size needed to resolve 200 pixels across the 10mm diameter of the iris for horizontal object distances ranging from 5m to 100m. For 200 pixels across the iris, turbulence dominates at distances greater than approximately 27m.

Adaptive optics systems contain a wavefront sensor and a wavefront corrector. The wavefront sensor detects the wavefront deformed by turbulence and the wavefront corrector compensates for the detected effects of turbulence. For a closed loop adaptive optics correction system, r_0 also indicates the maximum size in the pupil that a subaperture of the wavefront sensor should occupy and also the maximum separation between actuators of the wavefront corrector. The minimum number of subapertures spanning the width of the aperture, or likewise the minimum number of actuators spanning the width of the aperture is given by D/r_0 with D being the aperture diameter. Figure 4 shows the minimum number of subapertures needed across the width of the aperture for horizontal paths ranging from 10m to 200m at 10m increments. Note that fractions are always rounded up to the nearest integer. This plot shows that at the maximum distance of 200m, 13 subapertures are needed across the width of the aperture.

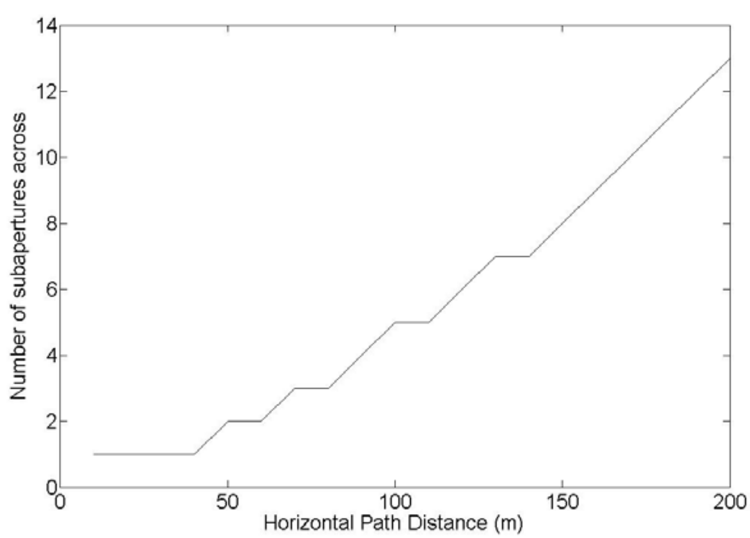

Figure 4: Plot of the minimum number of subapertures needed to span the width of the aperture and correct the turbulence corrupted wavefront for horizontal path distances from 10m to 200m at 10m increments.

3.2 Simulation of imaging through turbulence – on-axis

In order to study the effects of turbulence in more detail, simulations were run at object distances of 60m, 100m, 150m, and 200m. Simulation process involves averaging the point spread functions (PSF) generated from a large number of randomly generated wavefronts in the pupil representing distortions consistent with the statistics of the atmosphere. A diagram of the propagation model is shown in Figure 5. The propagation through turbulence is simulated by dividing the propagation path into sections. The wavefront distortion for each section is represented by a randomly generated phase screen. In this study five phase screens are used. Each phase screen represents the distortion due to turbulence in the 1/5 of the total propagation path preceding the screen such that the last screen lies in the pupil plane. To get an instantaneous realization of the wavefront in the pupil, a set of phase screens are generated, and the phase at each point in the pupil is calculated by tracing the ray from the object point to the point in the pupil and adding the phase at each of the five screens at the point of intersection with the tracing ray. The process outlined is capable of generating a wavefront in the pupil from the on-axis object point or any off axis object point.

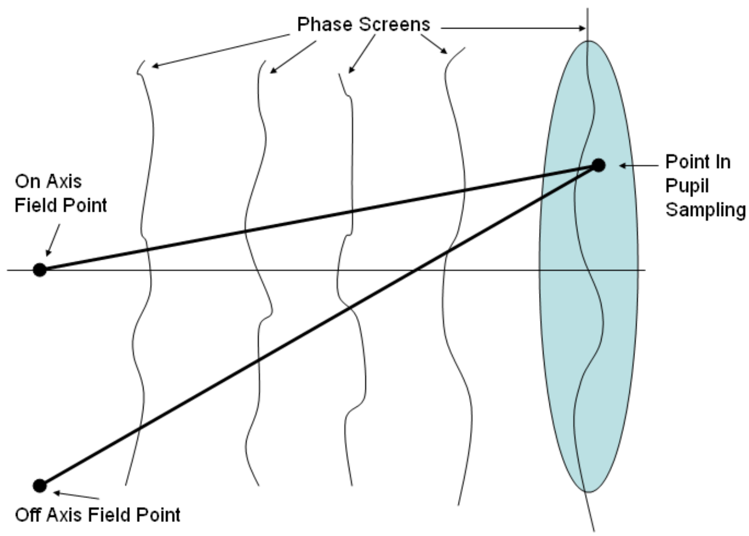

Figure 5: Diagram of turbulence simulation model

Once a randomly generated wavefront in the pupil is formed, the PSF from that wavefront can be computed. This represents an instantaneous PSF but because the wavefront distortions due to turbulence changes on the order of several milliseconds[9], the average of many instantaneous PSFs is calculated. The long-term or time-averaged PSF is computed in this study by averaging 6000 instantaneous PSF simulations as described above for object distances of 60m, 100m, 150m, and 200m. At each distance the aperture size is modified to match the diffraction limited spot diameter of 0.2mm on the object to meet the iris recognition criteria. The radially averaged long-term PSFs from these simulations are shown in Figure 6. PSFs have been normalized for easier comparison of the widths which dictate the spot size and consequently the resolution. There is only one diffraction limited cross-section because the aperture size was adjusted to produce the same diffraction limited spot diameter of 0.2mm (0.1mm radius) for every object distance. The increased width of the PSF at large distances implies that the system resolution has been lowered by the factor of the increase and that the quality of the iris images will be degraded, affecting the recognition process. The comparison of PSF simulations show that even when the imaging system is designed for diffraction limited performance at large distances, turbulence will be the limiting factor for final image quality.

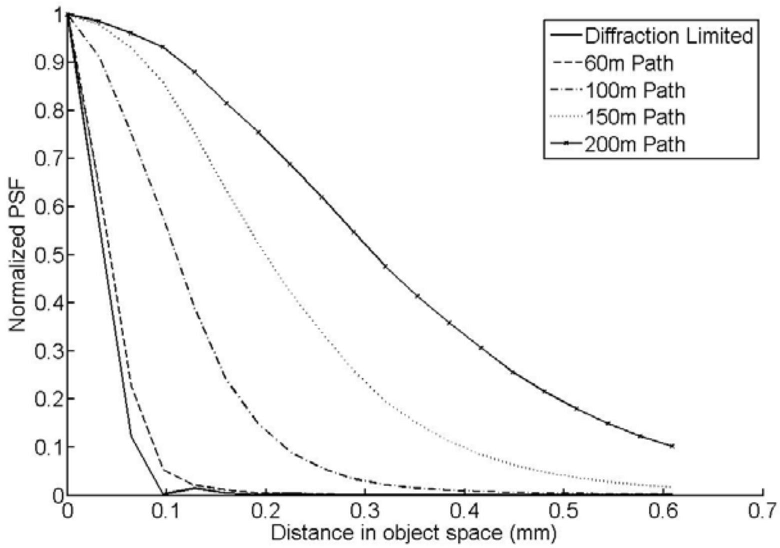

Figure 6: Turbulence corrupted long-term PSFs for object distances of 60m, 100m, 150m, and 200m and aperture sizes scaled to produce a diffraction limited spot diameter of 0.2mm on the object

The same aberrated wavefronts generated in the simulations above are used with a deformable mirror model to perform a correction for the turbulence. The deformable mirror is assumed to have 13 actuators spanning the width of the aperture to match it to the model shown in Figure 4. When placed in a circular pupil, a total of 136 actuators are modeled. The PSF cross sections for the corrected wavefronts are shown in Figure 7. As evident from the plots, wavefront correction can produce a near diffraction limited PSF at every object distance, showing that accommodation for turbulence effects is crucial for long-range iris recognition.

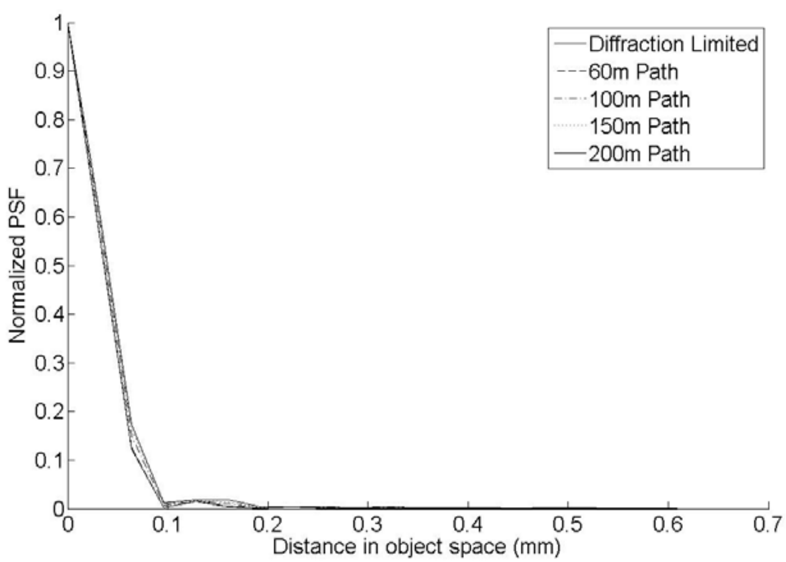

Figure 7: Long-term PSFs for object distances of 60m, 100m, 150m, and 200m and aperture sizes scaled to produce a diffraction limited spot diameter of 0.2mm on the object. Turbulence distortion was simulated and corrected with a 130 actuator deformable mirror.

To see how the varying spot sizes relate to the image quality for iris recognition, we calculate the optical resolution in number of pixels across the diameter of an iris for three different cases. In all three cases the Rayleigh criterion is used to calculate the number of pixels across an iris and the inherent optical aberrations from the system are assumed to be negligible, providing a diffraction limited imaging. The first simulation ignores the effects of turbulence; the second case calculates the resolution when the imaging system is limited by the effects of turbulence. Lastly, the third calculation is done using a model that corrects the effects of turbulence. The results are plotted and shown in Figure 8. It is evident from the plots that the atmospheric turbulence has a dominating effect on object space resolution at stand-off distances greater than 42m.

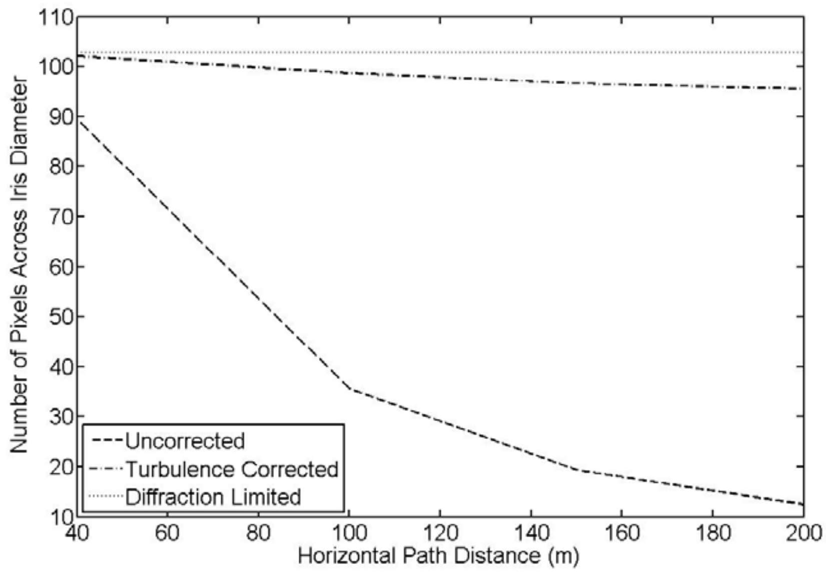

Figure 8: Resolution obtained at the iris(object) in number of pixels across diameter for object distances of 60m, 100m, 150m, and 200m for diffraction-limited, turbulence-limited, and turbulence-corrected cases.

3.3 Simulation of imaging through turbulence – off-axis

The results shown in Figure 7 are produced by generating and correcting the on-axis wavefront. However, the on-axis wavefront correction will not sufficiently compensate for wavefront aberrations from off-axis field points because off-axis object points traverse slightly different paths through the turbulence on their way to the pupil. This is evident by different points at which the off-axis object ray pierces the phase screens compared to the on-axis object ray shown in Figure 5. The result is that the on-axis turbulence correction is only valid for relatively small field angles. That angle is estimated by the isoplanatic angle which is the field angle at which the wavefront correction performance falls below a threshold. One approximation for this angle θ_0 is given by [9]

$$\theta_0 = 58.1 \cdot 10^{-3} \lambda^{6/5} \left[\int_0^L C_n^2(z) z^{5/3} dz \right]^{-3/5} . \tag{4}$$

Equation 4 is used to calculate the diameter of an area in object space that the isoplanatic angle subtends. The calculated area is called the isoplanatic patch and represents an area in the object plane within which a turbulence correction only for the center point of the area is valid over the whole area. A plot of the isoplanatic patch diameter as a function of object distances from 10m to 200m is shown in Figure 9. The radius of this isoplanatic patch at 200m is approximately 0.095m off-axis on the object. For a turbulence correction centered between a subject's eyes, a 95mm radius is just large enough to obtain a good image over both eyes.

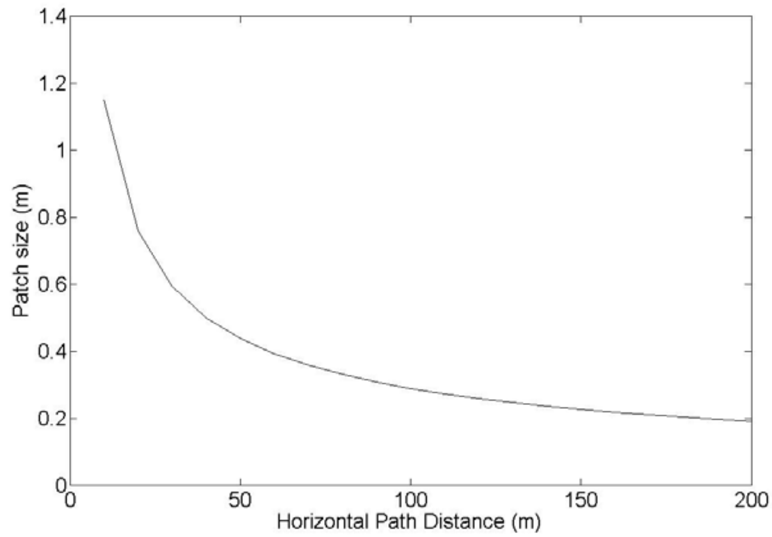

Figure 9: Isoplanatic patch size for object distances from 10m to 200m. This is the diameter on the object over which a turbulence correction is valid.

To further study the effects of turbulence corrections on off-axis field points, off-axis PSFs are generated for the longest object distance of 200m. This is done by simultaneously generating a turbulence corrupted wavefront at the aperture of the system for the on-axis field point, as well as off-axis field points located 0.1m, 0.2m, 0.38m, and 0.76m from the on-axis field point. The on-axis wavefront correction is then applied to the off-axis wavefront aberrations. Figure 10 shows these off-axis PSFs. Note that 0.1m is slightly beyond the radius subtended by the isoplanatic angle, and the on-axis and 0.1m off-axis PSFs are both nearly diffraction limited. Beyond the 0.1m off-axis point there is a significant widening of the PSF, though even at 0.76m it is still well within the completely uncorrected on-axis PSF.

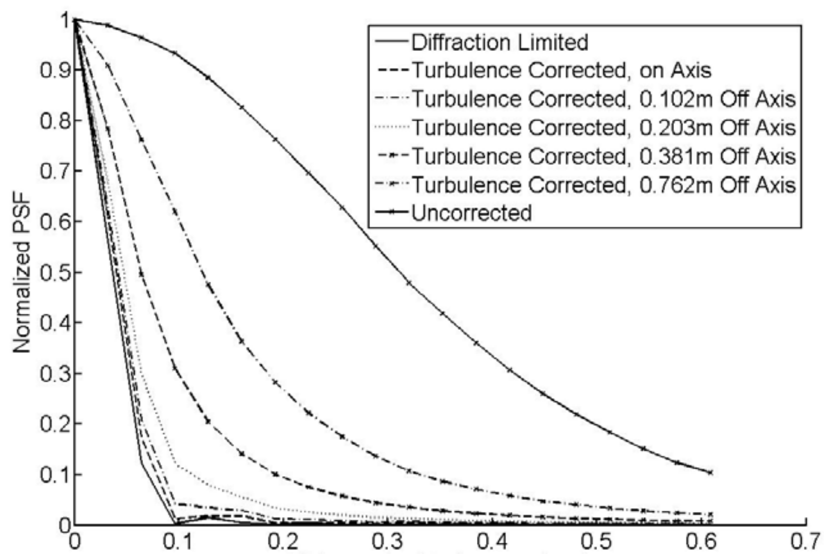

Figure 10: Off-axis PSFs generated by applying an on-axis correction for a turbulence corrupted wavefront from an off-axis location in the object plane at a distance of 200m.

The simulated off-axis PSFs are used to compare resolution at the object plane under three different settings. Following the analysis done for the on-axis simulations, a diffraction limited, a turbulence limited, and a turbulence corrected cases are studied and compared. Figure 11 shows the resolution in number of pixels across an iris as a function of displacement of the iris from the turbulence corrected point. The turbulence corrected resolution plot in Figure 11 shows a fast fall-off beyond 0.1m, signifying the importance of having an iris within the isoplanatic patch to produce an image for successful iris recognition.

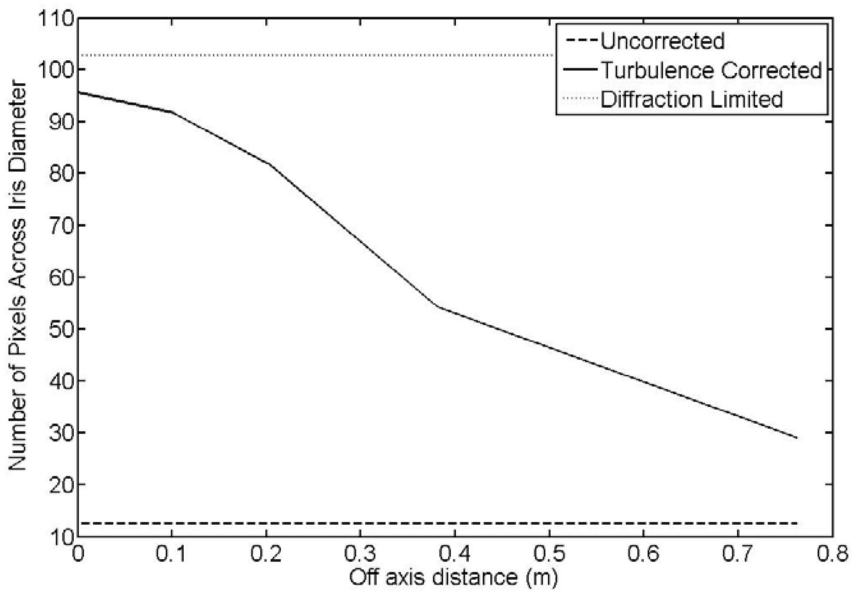

Figure 11: Resolution of iris imaging system at an object distance of 200m as a function of distance from turbulence corrected on-axis point.

4. CONCLUSIONS

Iris recognition takes advantage of the uniqueness of the human iris to perform a reliable identification. However, iris recognition requires a sharp image of the iris that meets the image quality condition specified in the standards. Obtaining an acceptable iris image to successfully perform recognition at large distances is a challenge as more factors are introduced to the image acquisition process. We have shown that turbulence correction is necessary to perform iris recognition for standoff distances greater than about 42m. This is based on an ISO/IEC resolution requirement of 100 pixels, the assumed turbulence strength, and the imaging wavelength of 850nm. If the resolution requirement is 200 pixels, then turbulence correction becomes necessary beyond about 27m. We also simulated PSFs for various distances and off-axis points with and without turbulence correction to show that without turbulence correction, the image quality rapidly falls below the standard that the imaging system was designed to meet, and consequently adversely affects long-range iris recognition.

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REFERENCES

[1] Daugman, J., "How Iris Recognition Works", IEEE Trans. on Circuits and Systems for Video Technology, vol. 14, no.1 pp. 21-30, (2004)

[2] Wei, Z., Tan, T., Sun, Z., and Cui, J., "Robust and Fast Assessment of Iris Image Quality", [Advances in Biometrics], Springer Berlin / Heidelberg, (2005)

[3] Matey, J.R., Naroditsky, O., Hanna, K., Kolczynski, R., LoIacono, D.J., Mangru, S., Tinker, M., Zappia, T.M., and Zhao, W.Y., "Iris on the Move: Acquisition of Images for Iris Recognition in Less Constrained Environments", Proc. of the IEEE, Vol. 94, No.11, (2006)

[4] Yoon, S., Jung, H.G., Suhr, J.K., and Kim, J., "Non-intrusive Iris Image Capturing System Using Light Stripe Projection and Pan-Tilt-Zoom Camera", CVPR '07, Page(s):1-7,17-22 June 2007

[5] Bashir, F., Usher, D., Casaverde, P., Friedman, M., "Video Surveillance for Biometrics: Long-Range Multi-biometric System", AVSS '08, Page(s):175 – 182, 1-3 Sept. 2008

[6] Greivenkamp, J., [Field Guide to Geometrical Optics], SPIE Press, Bellingham, Washington, (2004)

[7] Born, M., and Wolf, E., [Principles of Optics], Cambridge University Press, (1999)

[8] Devaney, N., "Review of astronomical adaptive optics systems and plans", Proc. of SPIE Vol. 6584, 658407, (2007)

[9] Roggemann, M.C., and Welsh, B.M., [Imaging Through Turbulence], CRC Press, Boca Raton, FL, (1996)