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A Review of Resolution Losses for AR/VR Foveated Imaging Applications

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***Abstract*—Foveated imaging is of great interest for Augmented and Virtual Reality applications. The resolution losses off-axis simulated in foveated imaging are modelled using cone density on the retina. This article reviews the other factors limiting the resolution off-axis in AR/VR, in particular the impact of the eye lens. Several off-axis resolution simulations are proposed and compared in order to provide some theoretical compression ratios for 4K and 8K display systems. A model taking into account both the cone density across the retina and the optical performance of the eye lens is proposed and evaluated. The variability and challenges of modelling the human eye resolution losses are also discussed, in particular in the case of age-dependence.**

***Index Terms*—Foveated Imaging, Optics, Augmented Reality, Virtual Reality, Displays**

I. Introduction

The role of the human eye in vision is at the core of some fields of Image Processing such as Image Quality Analysis or Colour Rendition. The role of the human eye in Image Processing has been explored explicitly for instance by [1]. Although dependent on the size of the pupil, the resolution of the human eye is high near the center of the field of view but drops sharply off-axis. This effect, known as foveation, can be used in order to adapt the image content to the visual capabilities of the eye.

Foveated Imaging has been researched mainly for image compression purposes [2], [3]. Together with an eye-gaze tracking apparatus, it is possible to selectively downsample and compress some areas of the image to adapt it to the visual perception. A novel interest in the technique has emerged because of possible applications in Augmented Reality (AR) and Virtual Reality (VR) [4], [5], where foveated imaging can be successfully used to reduce the amount of computations needed for the rendering of a high resolution image [6], [7] and thus provide an immersive gaming experience (high resolution and high frame rate) on low power devices.

This paper is organized as follow : section II provides some background on foveated imaging and its relation to the human eye. Section III provides a selection of human eye models for the wide-field and compares the theoretical off-axis performances for the human eye. Section IV shows the theoretical compression performance obtained with the different loss models (eye models, cone density and a hybrid model). Section V presents some of the challenges associated with the use of foveated imaging for AR and VR applications.

II. Resolution losses in foveated imaging

A. Overview of the human eye

The basic human eye anatomy is depicted in figure 1. The imaging elements of the human eye are the cornea, the pupil, the aqueous humor, the eye lens and the vitreous humor [8]. The image is formed on the curved surface of the retina, containing the photosensitive cones and rods which are used in photopic and scotopic vision respectively.

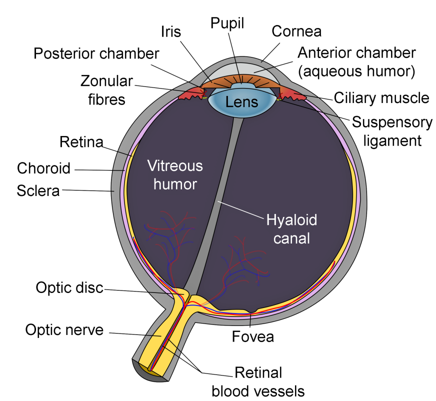

Fig. 1. Human Eye Anatomy.

In order to quantify the human eye resolution, the widely accepted 20/20 visual acuity criterion states that the peak resolution of an emmetropic eye is of typically 1 arcmin [8]. However, this criterion hides a wide diversity of optical performance among the population, specifically related to the age [9] and a lower resolution off-axis.

B. Optics and Retina Resolution Limitations

For AR/VR applications, the eye is placed in photopic vision conditions. For this reason, the foveal cone spacing of the retina has been used in order to estimate the resolution loss off-axis [10]. However, the resolution of the human eye is also affected by aberrations of the eye lens and diffraction. For a pupil diameter $d > 2$mm, the eye is no longer diffraction-limited. This pupil diameter corresponds to a light level lower than 4400cd/m^2 [11], which typically corresponds to indoor conditions. The contribution of the cone density to the foveation effect varies with the diameter of the pupil of the eye. A comparison between the ensquared energy (50%) as obtained from the optical design software ZEMAX and the average cone size as reported by [12], [13] is shown in figure 2 and will be used in section IV as a part of the resolution loss models.

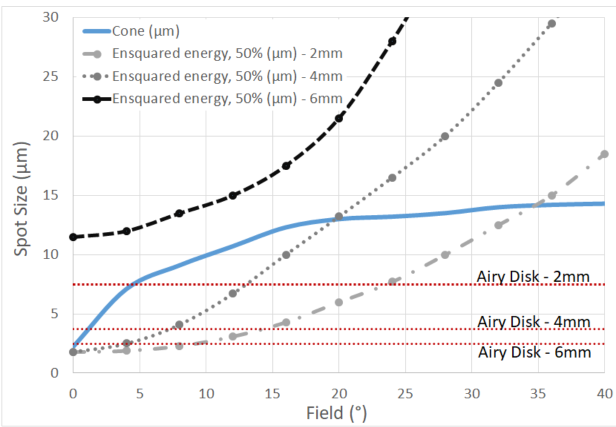

Fig. 2. Comparison of the equivalent cone spacing (μm) and the optical spot size from Navarro eye model (in μm, such that 50% of the energy is ensquared) for a pupil size of 2mm, 4mm, 6mm respectively. The diffraction limit is also plotted for the pupil size of 2mm, 4mm and 6mm.

The spot size analysis shows that the pupil diameter has a great impact on the behaviour of the optical system. In a typical VR case, with a pupil diameter of 4mm, the cone spacing is limiting between $0\,\text{deg}$ and $20\,\text{deg}$ and the optics is limiting between $20\,\text{deg}$ and $40\,\text{deg}$. In dim light (around 10cd/m^2), the cone spacing is no longer the limiting factor of the system. For some outdoor AR applications, the optics is never limiting.

The Modulation Transfer Function (MTF) can be estimated for both the retinal sampling (cf. Figure 3) and the lens system (cf. Figure 4). These functions can be cascaded with the neural sampling MTF [14] in order to obtain the visual system MTF.

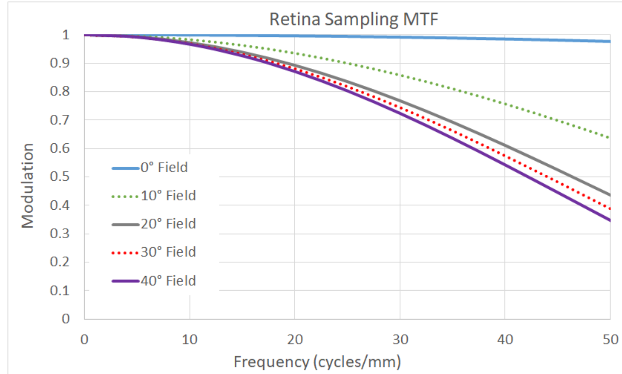

Fig. 3. Modulation Transfer Function estimated for the retina based on cone density observations.

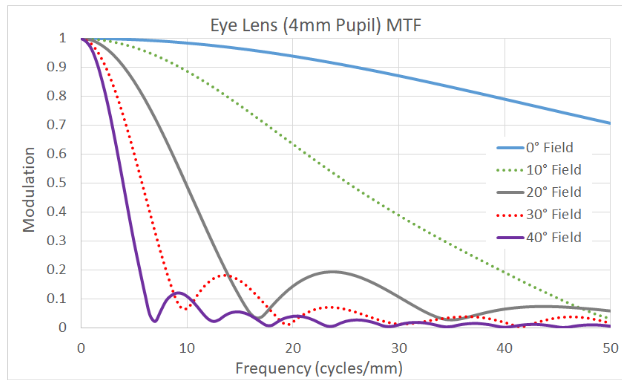

Fig. 4. Modulation Transfer Function simulated for the eye lens based on Navarro model with a 4mm pupil.

III. Human Eye Models

A. Criterions for the choice of an optical model

Eye models have been researched as early as the XIXth century. Following the first widely-accepted model from Gullstrand [15], a wide range of models have been proposed having different levels of complexity in optical design (spherical surfaces, aspheric elements [16], [17] or even GRIN lenses [18]–[21]). [22]–[25] have reviewed and compared the results of different eye models.

All eye models are not usable for foveated imaging purposes as most of them replicate the eye behaviour near the optical axis with little concern for the wide-field. Since only the central part of the field of view is cone-density-limited, the eye-model is required to predict the resolution loss off-axis. In the case of AR/VR, both accomodation of the eye and light intensity can have an influence on the performance off-axis as detailed in section V. In VR, the lighting conditions are fixed, while AR brings a wide range of light levels and requires a pupil size dependent model [26]–[28].

B. A selection of wide-field Eye Models

In order to estimate the off-axis resolution loss, the following eye models have been selected and compared :

- Revised Gullstrand Model [15], [29], known as Gullstrand-Le Grand model
- Navarro eye model [30]
- Arizona eye model [8]
- Dainty-Goncharov eye model [31] using GRIN lenses

All of these models are wide-field and assume emmetropia. The Navarro eye model as well as the Arizona eye model can be tuned depending on the level of accommodation of the user eye. The Dainty-Goncharov model contains some parameters for adaptation to the age of the user eye (cf. section V-B1).

C. *Off-axis resolution for several models*

The eye models have been simulated using ZEMAX software for a 20 year old eye, with a pupil diameter of 4mm corresponding approximately to the average size of the pupil for an eye exposed to a 200cd/m^2 light source, typically found in computer screens. The field of view observed is $40\,\deg$ from the optical axis for both X and Y axis. The results obtained are presented in figure 5.

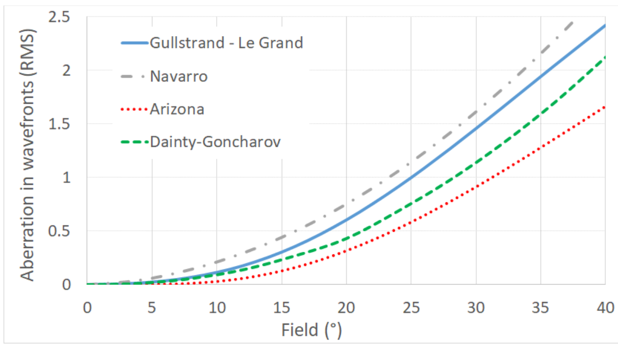

Fig. 5. Comparison of the eye models : Gullstrand-Le Grand, Kooijman, Navarro, Arizona, Dainty-Goncharov.

These different models predict a similar behaviour off-axis, with a visible drop in visual acuity beyond $15\,\deg$ off-axis. By design, the simulation corresponds to optical aberration data measured on a population with similar age and pupil dimensions [32].

IV. Compression Ratio for Foveated Imaging

A. *Use cases*

In this section, rectangular display systems are considered. The compression rate achieved using foveal imaging is related to the gaze orientation : the worst compression rate is obtained when the user is looking at the center of the display ("Center Gaze"), and the best compression rate is achieved when the user is looking at a corner of the display ("Corner Gaze").

B. *Results*

The information from the selected eye models is used in order to simulate the theoretical optimal compression of the image assuming a square $40\,\deg \times 40\,\deg$ field with a total 4K equivalent resolution (2880 × 2880px, cf. Table I) and 8K equivalent resolution (5760 × 5760px, cf. Table II), all observed with a typical screen light intensity (4mm pupil size). The "Hybrid" model is designed using the combination of the cone density and the optical aberrations, for a pupil size of 4mm and 6mm respectively.

Unsurprisingly, these results show that very high resolution systems benefit the most from foveated image compression. In particular, more than half of the computation power could be saved in the case of an 8K display system. Modelling resolution loss off-axis only using the eye lens aberrations is

TABLE I
4K Display Compression using Foveated Imaging

Loss Model	"Center Gaze"	"Corner Gaze"
Gullstrand-Le Grand	14%	31%
Navarro	17%	35%
Arizona	5%	16%
Dainty-Goncharov	8%	23%
Cone density only	70%	75%
Hybrid - 4mm	74%	84%
Hybrid - 6mm	84%	89%

TABLE II
8K Display Compression using Foveated Imaging

Loss Model	"Center Gaze"	"Corner Gaze"
Gullstrand-Le Grand	52%	64%
Navarro	55%	67%
Arizona	44%	56%
Dainty-Goncharov	48%	60%
Cone density only	84%	87%
Hybrid - 4mm	86%	92%
Hybrid - 6mm	92%	95%

inaccurate because of the near-axis performance. Combining optics and retinal information offers a greater compression on the outside regions of the image and thus slightly increases the compression achieved. As expected, the impact of off-axis optical aberrations is greater for reduced illumination conditions (6mm eye pupil). In fact, for this 6mm eye pupil size, the cone density is not limiting as shown in Figure 2. Including the optical aberrations of the human eye also models the peak resolution variation with the light intensity, contrary to the cone density model.

V. Limits and Challenges of Foveated Imaging in AR and VR

A. *Influence of environment and device*

1) Ambient Light: In the case of Augmented Reality, the ambient lighting is directly related to the amount of optical aberrations because of the size of the pupil. In low light conditions, the compression ratio can be increased.

2) Latency and saccadic omission: Any display has some latency, which makes eye gaze prediction even more critical. One can increase the resolution of the image off-axis in order to enable a more confortable user experience even in the case of eye gaze-tracking errors or saccadic omissions [4].

B. *Influence of the user*

1) Age: The age of the user has a great influence on the validity of the model of the human eye, since the eye lens parameters vary over time as described by [31].

2) Accomodation: Accommodation of the eye changes notably its performance on and off-axis. The role of accommodation is taken into consideration by several models (Navarro, Arizona). In principle AR/VR, the accommodation should remain constant as the object is theoretically projected at infinity.

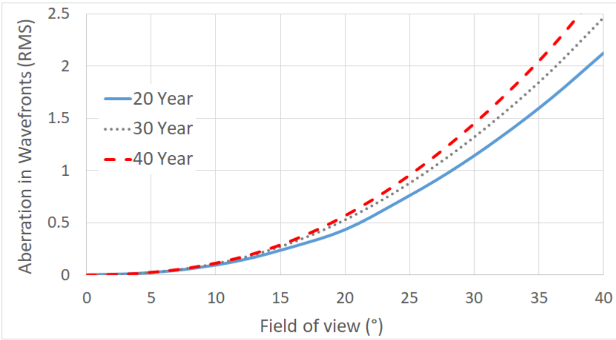

Fig. 6. Evolution of the resolution loss for different ages (respectively 20, 30, 40 years) as predicted by the Dainty-Goncharov eye model, based on the study of 1097 eyes from patients aged 18 to 68 years.

3) Non-emmetropic eye: This article has used several eye models assuming emmetropia. Since all users are not emmetropes, the eye correction (glasses or contact lenses) should be taken into consideration in the loss of resolution map. [33] proposes a model for eyes suffering from myopia.

VI. Conclusions

Several eye models have been presented and reviewed in the light of AR/VR applications. The compression ratios computed in the case of 4K and 8K displays indicate a strong interest for real-time AR/VR applications to use foveated imaging in the rendering process. This paper demonstrates the need to take into consideration the optical losses in addition to the cone density in order to simulate better the actual perception of the human eye indoors and obtain a higher compression. However, the environment and user eye properties create some variability among the panel of users. In this regard, the use of a general model such as the Arizona model or the Dainty-Goncharov model can enable a more personalized experience through the adaptation of the display to the accommodation or age of the user respectively.

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