OPTICAL SYSTEM DESIGN FOR HUMAN EYE USING GENETIC ALGORITHM

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Abstract

In this paper, an accurate optical system for human eye is designed using new approach based on the genetic algorithm (GA). The eye is assumed consists of two optical elements: cornea and eyelens, the remaining contents are just a supplements for these optical elements. The optimal eye design is obtained by GA with some restrictions related to the determination of the generic structure of the eye. The resulted eye is then tested by comparing its optical functions; once with that of the perfect eye, and another with that in literatures. As a results, the genetic eye was identified the characteristics of the real-life eye, which ensure the efficiency of the evolutionary methods to achieve an intended optical design.

تصميم المنظومة البصرية للعين البشرية بأستخدام الخوارزمية الجينية

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الخلاصة

في هذا البحث، تم تصميم المنظومة البصرية للعين البشرية بأستخدام طريقة جديدة مبنية على الخوارزمية الجينية (GA). اُفترضت ان العين تتكون من عنصرين بصريين هما: القرنية والعدسة، اما بقية محتويات العين فهي ملحقات لهذين العنصرين فقط. وبذلك تم الحصول على تصميم العين الامثل بواسطة الخوارزمية الجينية بعد احتساب بعض المقيدات المتعلقة بتحديد التركيب العام للعين. تم اختبار العين الناتجة وذلك بمقارنة دوالها البصرية مرة مع العين المثالية، واخرى مع تصميم اخر مُعتبر منشور في الادبيات. بالنتيجة، كانت العين الجينية تطابق مواصفات العين الحقيقية–الحية، وهذا يؤكد كفاءة الطرق النشوئية في الحصول على التصميم البصري المراد.

1. Introduction

Optics is the oldest science in physics, recent it is used in variety of applications, such that unique features and capabilities are often required to optimize the system designed for a specific application. Optical system design (OSD) need first to analyze important features according to some applications include: imaging system, visual systems, telecommunications systems, UV or IR systems, and microlithography (optical stepper) systems [1]. Among all these applications, a human eye optical design is considered to be an essential part of visual systems; the human eye is a complex and optimal behavioral structure, which can not be industrialized. In this paper, we model, optimize, design and then test the human eye by new proposed approach based on evolutionary method.

The shape of the human eye is aspheric of about 22*mm* diameter with a light sensing organ called retina lies on the inside back surface. The main body of the eye has to be sphere so as to be able rotate in its socket. It is not a perfect sphere in that there is a protuberance on its front that has a reduced radius of curvature compared to the remainder of the eye. This protuberance is found because the liquid of the eye has an index of refraction close to that of water. A sphere of this index of refraction will not focus incoming plane waves onto its rear surface but to a point behind that surface [2]. Figure (1) shows a vertical cross section of the human eye configuration, the optical components of the eye are briefly explained in the following:

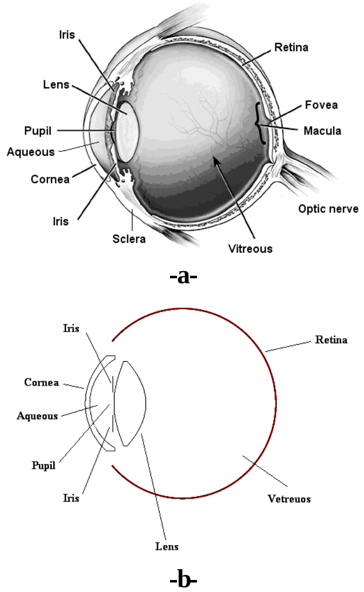


Figure 1: Human eye configuration.

Cornea

Cornea is more sharply curved, tough, and transparent membrane [3]. The cornea is first surface of the eye. It is an extension of the sclera, which is the tough, white outer shell of the eye. The transparency of the cornea is facilitated by the regular arrangement of the layers of collagen fibers that comprise most of the corneal thickness. Periodic closures of the eyelid maintain a thin tear film on the cornea's external surface, which ensures a smooth refracting surface. The changes in tear film give rise to scattering and small changes in optical aberrations. The cornea is about 0.5 to 0.6 *mm* thick at its center, it has a mean refractive index of about 1.376 and its first surface has a mean radius of curvature of about 6.5 to 7.7*mm* [4], [5].

Iris and Pupil

The light then passing through the Iris. The iris situated in the aqueous humor, is a diaphragm that gives the eye its characteristics color and controls the amount of the light that enters. The amount and location of pigment in the iris determine whether the eye looks blue, green, gray, or brown [6]. The entrance and exit pupils have a crucial role in image and vision quality. With high lightness levels the pupil size is small, thus stopping peripheral rays, which are typically more aberrated. For low lightness levels, the number of photons is also low and the signal-to-noise ratio decrease, then the pupil dilates to increase the number of photons [7], the determine that the pupil size that offered the best lateral resolution was typically between 3 and 4 *mm* in diameter [8].

Eye lens

The crystalline lens is a capsule containing a fibrous jelly hard at the center and progressively softer at the outer portions. The crystalline lens is held in place by ligaments which attach it to the ciliary muscle [3]. The most important optical constants of the lens of the normal human eye are the refractive index that is varies between 1.383 at the periphery and 1.420 in the center, the radius of curvature in unaccommodated state and at anterior pole is 7 to 8 *mm* either at posterior pole is about -5.5 to -6 *mm*, and the thickness is unaccommodated state about 2.5*mm* [9].

Retina

The retina is the inner layer of the eye. It contains the light receptors; rods and cones, thus it severs as the film of the eye. The retina also has many interneurons that process the signals arising in the rods and cones before passing them back to the brain [10].

Aqueous and Vitreous Humors

The iris and lens divide the eye into two main champers; the front chamber, which is filled with a watery liquid called the aqueous humor [10]. The aqueous has an average refractive index is 1.333. The second is rear chamber; also it is filled with a jellylike material called the vitreous humor. The vitreous humor, a transparent substance whose refractive index is 1.336; close to the sea water [6].

2. Problem Description

OSD to model the human eye is not easy operation due to many optical parameters should take in mind [11]. For a given data ranges for such parameters, it is difficult to find the optical eye design and determine its optical features. For example; for both cornea and eyelens, one must determine the following parameters: the two radii of curvature (R_1, R_2), index of refraction (n), diameter (D), Thickness (t), distance in between (d), in addition to the index of refraction of both the aqueous (n_a) and vitreous (n_v). To make optimal eye design, all the above mentioned parameters should be optimized to be in balance. Also, the performance of designed eye should seem to be proficiently.

In this paper, we suggest using the GA to optimize the optical parameters, and find the optimal design of eye. Thereby, we will divide the optical parameters into two groups; fixed and variable. Fixed parameters are determined before the optimization process; such parameters get singular values given in the studies of interest. Variable parameters get their values through a predefined acceptable range. The performance of the resulted optimal design is measured in terms of specific quality measurements that can evaluate the quality of the formed image and efficiency of the eye.

3. Related Work and Contribution

Few literatures are found in this field, no publishing refers to how optimize the optical system of the human eye. Elder literatures concerned with designing the eye, while the moderns are discussing the performance estimation based on some assumed designs. The important related works in the field of interest are mentioned in the following.

3.1 Related Work

Several schematic models for the human eye varies from very traditional models to modern ones are given in literatures. One of the most popular is that of Gullstrand which a simplification of Helmholtz's eye model [12]. The Swedish Ophthalmologist Allvar Gullstrand conducted important research in the field of physiology, and in 1911 received the Nobel prize for his work regarding the eye as an optical design. While Gullstrand’s simplified schematic eye treats the cornea as a single refracting surface, just as the previous model from Helmholtz-Laurence, in Gullstrand’s non-simplified model the cornea is considered to have two surfaces, which guarantees a perfect image formation at the retina. Although it simplifies the cornea, the vitreous and the aqueous humor, this model is especially suitable for the computation of intraocular lens (IOL) power, as it also contains the anterior and posterior surface of the crystalline lens [13]

Emsley (1953) schematic eye was introduced. It is the simplest eye model since it contains just a single refractive surface. Due to its simplicity, it is widely used in undergraduate courses in optometry, ophthalmology and vision science [13]. Lotmar (1971) was modified the Gullstrands data to include dispersion data for the lens, cornea, and aqueous to be similar to water. Also, the anterior cornea surface was modified to be aspheric. Blaker (1983) presented more convenient model based on Lotmar model [13]. Greivenkamp and colleagues (1995) proposed an eye model containing four refracting non-spherical surfaces that considered retinal contrast sensitivity and refraction-limited properties. Liou and Brennan (1997) have proposed an interesting model, which is the closest to anatomical, biometric and optical data as compared to the physiological eye [13]. Pablo Artal et al (2006) show that the compensation is larger in the less optically centered eyes that mostly correspond to hyperopic eyes. This suggest a type of mechanism in eye's design that is the most likely responsible for this compensation [14]. Michael D.Tocci (2007) created a model of a human eye in ZEMAX using the Liou and Brennan (1997) eye model.

This is a fairly up-to-data and comprehensive model of the eye, the following studies are only done to investigate or improve the performance of previous designs [15]. Carvalho et al (2008) implemented a computer simulation of Hartmann-Shack (HS) patterns for real corneas. Placido images were captured for 10 eyes on a standard corneal topographer [16]. Sakamoto et al (2008) developed a method for estimated patient-specific ocular parameters, including surface curvatures, conic constants, tilts, decent rations, thicknesses, refractive indices, and index gradients [17]. Donnelly W. (2008) developed a commercially available eye modeling system, the advanced human eye model (AHEM). To mainstream optical software engines, ZEMAX and ASAP were used to construct a similar software eye model and compared with each others [8]. Navarro R. (2009) analyzed and compared eye models experimental findings to assess properties and eventually unveil optical design principles involved in the structure and function of the optical system of the eye [9]. Einghammer J. et al (2009) constructed a model from an eye's geometry, including axial length and topographic measurements of the anterior corneal surface [18].

3.2 Our Contribution

In this paper, the problem of optical system design for human eye is tackled by a proposed technique based on genetic algorithm. Genetic algorithm can be viewed as an evolutionary method of finite-state automata, when both transitions between states and generation are govern by an objective function. The basic theory of GA was developed in 1920's, but only in the last decade it has been extensively applied in a large number of problems. In fact, few studies about optical system design based on evolutionary methods are found due to its complex treatment. We address this challenge of GA based eye design to be a novel experiment in the field of interest.

4. Theoretical Framework

When a system of rays originally at single object point is constructed, so that the rays are uniformly distributed over the entrance pupil, the plot of their consequent intersections with the image plane is called *spot diagram*. The size of spot diagram shows to extent of the energy distribution and the shape is due to the type of aberration. When the spot diagram has been reduced to a size comparable to that of the central fringes in a diffraction pattern, ray theory causes to be as useful as wave theory [19]. The spot size (Z) of a single lens under diffraction limited condition is given by

$$Z = 2.44\lambda(f/no) \quad \text{………………(1)}$$

$$f/no = \frac{f}{D_o} \quad \text{………………(2)}$$

Where f is the focal length and D_o is the diameter of the aperture. The focal length f of a thick lens is reckoned with respect to the principle plans as:

$$\frac{1}{f} = \frac{1}{R_1} - \frac{1}{R_2} + \frac{(n_1 - 1)t}{n_1 R_1 R_2} \quad \text{……………(3)}$$

Where R_1 and R_2 are radii of curvatures, t thickness of lens, and n_1 refractive index. In general, the performance of the lens system in a specific circumstance should be determined by the ray tracing. The effect on the spot size caused by spherical aberration is strongly depending on *f/no* (and by the way on f; since *f/no=f/D*). the spot caused by diffraction increases linearly with f, thus for some lens types, spot size at first decreases and then increases with f, meaning that there is some optimum performance point where both aberration and diffraction combined to be as minimum as possible. In OSD consideration, f is called effective focal length (*EFL*), given as

$$\frac{1}{EFL} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2} \quad \text{……………(4)}$$

Where f_1 and f_2 are the focal length of the first and second optical elements, and d is the distance between them. Practically, some modification should be imposed on equation (1) to compute spot size formed by the eye. The modification includes adding the spherical aberration terms. Hence, the spot size of the spot formed by the eye can be calculated from the following equations [20, 21].

$$Z_T = 2.44\lambda(f/no) + \frac{Af}{(f/no)^3} \quad \text{……..(5)}$$

Where A is a constant given by the following expression:

$$A = \frac{n+2}{n(n+1)^2}R^2 - \frac{4(n+1)}{n(n-1)}R + \frac{3\mathrm{n}+2}{\mathrm{n}} + \frac{n^2}{(n-1)^2} \quad \text{……….(6)}$$

and

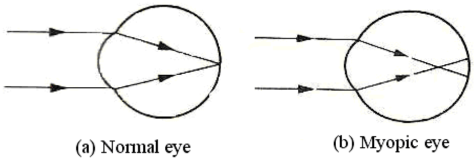
$$R = \frac{R_2 + R_1}{R_2 - R_1} \quad \text{…………………..(7)}$$

In the present research, both the spot size and EFL are used as objective functions to forward drive the optimization process into correct path. Their values of emmetropic eye were input to the optimization engine as priory information, and the deflections were estimated each time to improve the successive solutions.

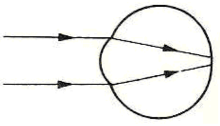
4.1 Focusing in Eye

The focusing in the human eye is dynamic; where the eyelens is capable to reduce or enlarge its radii of curvature when look at near or distant object. This mechanism of the eyelens makes exact focusing whether the viewed object is close or distant. As a result, the focus on the retina of the rays coming from close object is same as that of distant object; this is due to the radius of curvature of the eyelens determined for distant object imaging is become greater than that of close object.

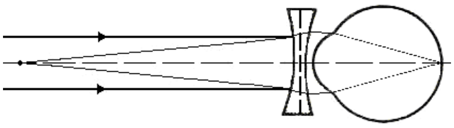
In special cases, defocusing in the eye is occurring due to incorrect relation between the various parts of the eye considered as an optical system. A normal eye forms on the retina an image of an object at infinity when the eye is relaxed, such eye is called *emmetropic*. If the far point is not at infinity, the eye is *ametropic*. The two simplest forms of ametropia are *myopic* and *hyperopic* shown in Fig (2-b,c) [3]. In myopic eye, the eyeball is too long in compression with the radius of curvature of the cornea, and rays from an object at infinity are focused in front of the retina. In the hyperopic the eyeball is too short, and the image of an infinity distant object would be formed behind the retina. It should be mentioned that the defocusing occur in the eye due to defects "only" affect the eye such a myopia or hyperopia. Such defocusing is not aberration because there is one focus formed on the optical axis, which can be corrected by just adding a proper lens in front of eye as shown in Figure (2-d, e).



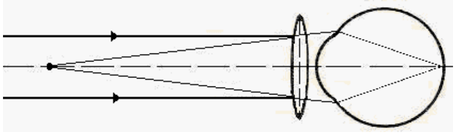
(a) Normal eye (b) Myopic eye



c- Hyperopic eye



d- Myopic eye correction



e- Hyperopic eye correction

Figure 2:Defects of eye and their corrections

4.2 Genetic Algorithm (GA)

Genetic algorithm is an efficient search algorithm that simulates the adaptive evaluation process of natural system. It has been successfully applied to many complex problems such as time scheduling optimization and traveling salesman problems [22]. Each individual in the GA population represents a possible solution to the problem. Finding individuals, which are the best suggestions to our problem and combining these individuals into new individuals, is an important stage of the evolutionary process. Using this method repeatedly, the population hopefully evolves good solutions. Specifically, the elements of GA are: selection (according to some measures of fitness), crossover (a method of reproduction, "mating", the individuals in the current generation into new individuals in the next generation), and mutation (changing a random selected genes). The following algorithm shows the basic steps of the GA [23].

```
Initialization: Generate random population of N chromosomes
Do While the stop condition is not satisfied
    Evaluate: the fitness g(x) for each chromosome x in the population
    Do While the new population not completed
        Selection: Select two parent chromosomes from a population according to their fitness
        Crossover: with a crossover probability, crossover the two parents to form a new offspring (children)
        Mutation: with a mutation probability, mutate new offspring
        Accepting: place new offspring in new population
    End while
    Replace: Use new generated population for father runs
End while
End.
```

5. GA approach to eye design

We use GA to find out (design) optical system of human eye, with determining its optical features for each element. In our approach, the eye is assumed to be consisted of just two optical elements; cornea and eyelens. The remaining are: pupil which is just stop ling between them, aqueous and vitreous are medias in which the ray translated, and retina is a screen that presents the image. The indices of refraction are taking same values in different human eye; such that they are assumed to be fixed at their values, while the other parameters are taken as variable through their range of its variety. Table (1) presents the fixed and variable components for each element in the eye; according to our approach.

The process of applying the GA on the proposed eye needs first to govern the path of the algorithm to be in the correct direction. This requires assuming two important processes: first, setting the minimum and maximum limits for the variable parameters, and suppose a proper fitness functions to measure competence of the resulted eye design.

Later, each optical design is assumed to be an individual chromosome consists of a set of genes representing the optical parameters; R_1, R_2, D, d, t, n_o, n_1, and n_2. The collection of P_s-individuals is the population size of each generation. In the first generation, the genes of each individual are chosen randomly from the range of varying each parameter (between the minimum and maximum values). The second generation is given birth by crossover the best individual chromosomes found in the first generation (best individual is chosen according to assumed fitness function). Thus, the second generation is better than the first one, also the third generation is better than the second, and so on even achieving the optimal chromosome at last generation. The last generation consists of P_s individual chromosomes (eye design). The way of applying the GA approach till achieving the optimum design is illustrated in the following:

able 1: shows the fixed (f) and variable (v) parameters.

Optical element	Optical features							
	R_1	R_2	t	D	d	n_o	n_1	n_2
Cornea	v	v	v	v	v	f	f	f
Eyelens	v	v	v	v	v	f	f	f

5.1 Gene Restrictions

In order to make the cornea is always positive (minscus) with actual size, it must be putting some restrictions for the random generation routine. Not the cornea only, but all the optical elements in the eye should be restricted. Therefore, it was very necessary to determine the minimum and maximum limits for each gene to be a predefined information input to the random generation routine. Thereby, genes in the first generation will be chosen randomly from their range between the minimum to maximum limits. Gene values are taken with single numerous precision. The following table shows the predefined information as suggested restriction parameters.

Table 2: Information table: suggested restriction parameters.

Optical element	Gene	Min limit	Max limit
Cornea (aspheric)	R_1	6.5	7.7
	R_2	6.5	7
	t	0.5	0.6
	D	8.13	8.23
	d	3.2	3.6
	n_o	1	1
	n_1	1.376	1.376
	n_2	1.333	1.333
Eyelens	R_1	7	8
	R_2	-5.5	-6
	t	2.482	2.517
	D	6.92	7.112
	d	0.625	0.645
	n_o	1.333	1.333
	n_1	1.38	1.42
	n_2	1.336	1.336

5.2 GA Implementation

The variety of the refractive index of the eyelens should be fitted by a behavioral descriptor model. Since there are just two value are available from literatures (1.402 at the center of the eyelens, and 1.38 at its dim), this necessitate the fitting to be linear as follows.

$$n_{lens} = -0.011428 r_p - 1.42 \ldots\ldots\ldots\ldots\ldots(7)$$

Equation (7) describe the positional dependency of the refractive index (n_{lens}) of the eyelens as a function of the ray position (r_p) from the optical axis.

Later, it is very important in this stage to choose a proper optical fitness function. The correct choice will lead to fast correct results. In the present work, two optical fitness functions are chosen: The first is the EFL, which measure the performance efficiency for the optical system (for an emmtropic eye; EFL_e=16.63mm). The second fitness function is the spot size (Z), which describe the image quality consisting by each individual design (for emmtropic eye; Z_e=5μm). Therefore, the use of these two fitness function will govern the path of improving the eye design in terms of performance and imaging. In the following, a detailed explanations about the steps of implementing the GA for the human eye are given:

1. Determine; the population size (P_s), number of generations (Gn), and probability of mutation (P_m).
2. For each gene specify; minimum (Min_G) and maximum (Max_G) limits of the gene.
3. Input the spot size (Z_e) and the effective focal length (EFL_e) of the emmetropic eye.
4. Initialization: generate (P_s) random individual chromosomes (eye design).

5. For each individual; compute the spot size (Z) and effective focal length (EFL), and then compute the two fitness function; $F_1=|Z_e-Z|$, and $F_2=|EFL_e-EFL|$.
6. Check all individuals to find the best one (minimized F_1 and F_2).
7. Select two individuals randomly, and chose the best (the best individual have F_1 and F_2 less than that of the others) for the next step "mating".
8. Crossover any two randomly chosen individuals. The crossover process is just swapping half the genes (randomly chosen) between chosen individuals for mating.
9. Randomly get P between (0-1) to be the probability of mutate current generation. If $P<P_m$ then do mutation else no mutation to do. The mutation is changing only one gene in same individual to take a random value from the range of its variety.
10. If the optimal chromosome is achieved then stop, else back to step 5.

6. Implementation results

The proposed GA approach was implemented by visual basic 6.0. The address of the software is to find out the optimal design of the human eye that can describe the performance and imaging of real-life eye. Through out the implementation of GA, the number of individual chromosome (eye design) is taken to be 100 at each generation. The number of generations was 80. The implemented software continue giving birth generations unless finding the optimal design (F_1=0, and F_2=0). The first randomly generation includes 100 individual chromosomes, each optical parameters is assumed to be one gene in the chromosome. If the gene is fixed, it takes a specific value from the predefined information table, whereas when the gene is variable it takes unspecific value in the range of its variety. Because the randomcity, eye designs in the first generations were far away from the optimal design. The results improved consequentially even achieving the last generation. Table (3) shows the numerical optical features of the optimal design shown in Figure (3) that resulted by the proposed GA approach.

Table 3: shows the optical features of the optimal design resulted from GA approach.

Optical element	Optical features							
	R_1	R_2	t	D	d	n_o	n_1	n_2
Cornea	6.75	6.51345	0.56	8.2	3.4	1	1.376	1.333
Eyelens	7.9251	-5.9649	2.5	7	0.635	1.333	1.42	1.336

Eyelens

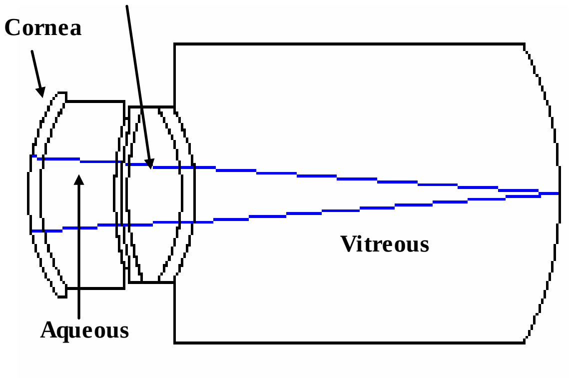


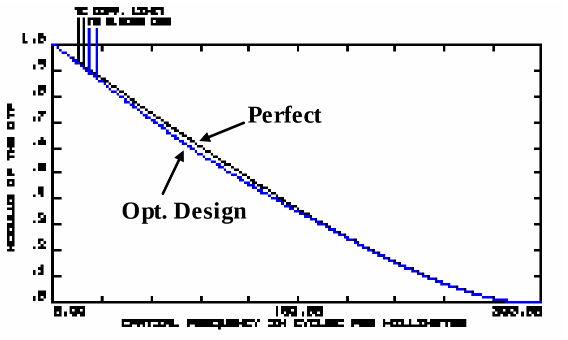
Figure 3: The resulted optimal eye design achieved by GA approach.

7. Evaluation

Ultimately, the effectiveness of the proposed approach is deformined by comparing different chosen optical performance measures between the resulted optimum eye design and its perfect state. We evaluate the resulted optimal design by testing its performance and imaging with help of Zemax software. Zemax is a valued software according to OSD researchers:

7.1 Performance Test

It can be use the *MTF* to test the performance of any optical system. *MTF* describe the amount of aberration and associated defocusing in the optical system. Figure 4 shows the *MTF* for the optimal design in comparison with the perfect case. It can be noticed that the *MTF* of the optimal design is very close to the perfect, also it identifying the *MTF* of that estimated in [11]. We thought that the *MTF* of the optimal design do not achieve the perfect for two reasons: First, because the fitting function of the refractive index of the eyelens, which was linear fitting, such function is infrequently found in nature. Second, because the residual spherical aberration, which do not affecting the quality of the vision since it is less than the spacing between any two vision sensors in the retina. Such least amount of aberration appears in the *MTF* with no effect on the vision quality. The image contrast of the optimal eye design regarded as high, thus it can be assumed the performance of genetic eye is perfect as that found in the real-life eye.



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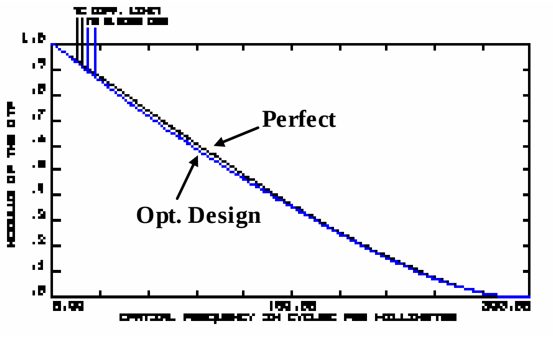


-b-

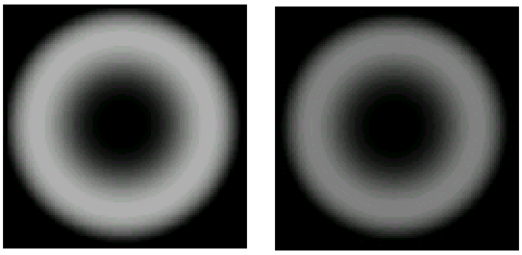
Figure 4

a- *MTF* of the optimal eye design comparing with the perfect case

b- *MTF* of the optimal eye design comparing with that achieved in [11]

7.2 Imaging Test

The test of the optimal design imaging depends on the size and diagram of the constituted spot by all rays in the retina. Least spot size means less rays separation and sharper imaging, which lead to higher resolution. Actually, the spot size of the optimal design invented by applying GA approach was $Z_{optimal}=5\mu m$, while $EFL_{optimal}=17mm$. These results ensure our interpretation related to the two reasons mentioned in the last section. In fact, the spot size is good since it optimized to be reached the target value, whereas the *EFL* was departing from the intended by a very small value, but it retained acceptable value due to it originally vary with the size of the eye (the size of eye is 23*mm* for emmtropic eye). Figure (5) demonstrates the spot diagram of the optimal design, which is same as the perfect case (diffraction only without aberration). Moreover, the comparison between the resulted spot diagram with that pictured in [11] shows no difference in between; both are same.



-a- -b-

Figure 5: a- Spot diagram of the optimal eye design.

b- Spot diagram of the eye design achieved in [11].

8. Conclusions and Future Work

Some noticed points can be conducted from the present work: The evolutionary methods are suitable for purpose of designing the optical systems, especially the complex ones, such human eye. The chose of the EFL and the spot size was appropriate in describing the performance and vision of the eye. As future work, one can improve the present work by taking in accounts the ammetropic eye as well as its correction.

9. References

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