EYE EVOLUTION SIMULATION WITH A GENETIC ALGORITHM BASED ON THE HYPOTHESIS OF NILSSON AND PELGER

R. Salas Machado, A. Castellanos, R. Lahoz-Beltra

Abstract: *The present work addresses for the first time the simulation of the evolution of an elemental eye by means of a simple genetic algorithm. The problem of the gradual evolution of a structure as complex as the eye was raised by Darwin, being still at the beginning of the 21st century a source of controversy between creationists and evolutionists. Taking as a starting point the paper of Nilsson and Pelger and their hypothesis that the evolution of the eye can be studied if we limit ourselves to its optical geometry, we show how eye evolution could take place gradually applying the principle of natural selection. Our model is limited to studying how an array of photosensitive epithelial cells is bent gradually to achieve a camera obscura.*

Keywords: *Eye evolution, intelligent design theory, genetic algorithms, Nilsson and Pelger.*

ACM Classification Keywords: *I.6 Simulation and Modeling*

Introduction

Currently there are scientific problems that go beyond an area of knowledge, being studied in different disciplines. For example, in biology the study of the evolution of certain organs or appendages in living beings raises serious problems in finding a satisfactory explanation about the stages through which they passed during their evolution. In our opinion many of the ideas and methods used in this work will also be useful in industrial design problems. Coming back again to the field of biology, at present two examples illustrating these difficulties are the evolution of the eye and the evolution of what is known as the bacterial flagellar motor. As it is known the eye is the organ of the visual system whose purpose is the vision. A first primitive version of the present eye goes back to the Cambrian explosion, 600 million years ago [Breitmeyer, 2010]. From this explosion of life, took place the evolution of an ancestral proto-eye originating the eye that today have very different animals such as mollusks, vertebrates, cephalopods, annelids, crustaceans and some cnidarian (i.e. cubozoa). In evolutionary biology the accepted explanation is that all modern eyes come from the same eye, species sharing some common facts: (i) the 'basic organ' would be a layer of photoreceptor cells attached to an optic nerve; (ii) eye development depends of a common gene shared by different species, called PAX6 gene, and (iii) all the improvements that a modern eye presents would have emerged evolutionarily in just a few million years.

Interestingly, when Darwin introduced his theory of evolution by natural selection, he recognized [Darwin, 1859] some difficulties in explaining satisfactorily the evolution of the eye:

"Reason tells me, that if numerous gradations from a simple and imperfect eye to one complex and perfect can be shown to exist, each grade being useful to its possessor, as is certainly the case; if further, the eye ever varies and the variations be inherited, as is likewise certainly the case and if such variations should be useful to any animal under changing conditions of life, then the difficulty of believing that a perfect and complex eye could be formed by natural selection, though insuperable by our imagination, should not be considered as subversive of the theory."

But where does the problem arise from Darwinian theory with a simple explanation of the evolution of the eye? The problem of Darwinism comes up in the idea of the gradual development of complex structures [Conway-Morris, 1998], e.g. the eye. In 1996 Michael J. Behe writes the book *Darwin's Black Box: The Biochemical Challenge to Evolution*: A book that introduces a new version of creationism based on what is known as 'intelligent design theory'. According to this hypothesis certain features of living systems are explained by the action of intelligent agents resulting in complex and specified information. The book introduces a criticism to the mechanism of gradual changes when such mechanism is applied to the evolution of complex organs. The theory of intelligent design is based on two principles. On the one hand, the principle called (i) *irreducible complexity* states that certain organs cannot evolve by small and successive changes of a precursor ancient organ. On the other hand, another principle known as (ii) *complex specified information* states that anything with a less than 1 in 10^{150} probability of occurring is a consequence of the intervention of intelligent agents [Dembsky et al., 2007]. In summary, the *problem of design* arises in those living systems composed of several interacting components that contribute to the basic function. In such systems if any one of the components is removed then the system stops working correctly. That is, the system seems to be designed for the purpose of performing a certain task or specific function, such as engineers when designing a device or machine.

Now, what does a biological problem, such as the evolution of the eye, have to do with natural computing? Genetic algorithms as well as other evolutionary algorithms are methods of optimization inspired by Darwin's natural selection mechanism. As such an optimization method, a GA uses an objective measure that guides the search for an optimal value, whether it is a maximum or a minimum. The problem arises when GAs are applied to the simulation of biological evolution: GAs use an evaluation function, objective function or fitness function that measures the goodness of a design. It is precisely at this point of reasoning that lies the main problem that we try to solve in this paper: to what extent does the fitness function contains information about the solution we are looking for? How much information does the fitness function contains about the optimum design? [Salas Machado et al., 2016].

In this work adopting a functional definition of design and using a simple genetic algorithm [Lahoz-

Beltra, 2016], we simulate the evolution of an elementary eye. This elementary eye is just a camera obscura (Figure 1), thus a closed box in one of whose ends there is small hole to the outside. When from the outside the light from a scene enters the hole and is received by the layer of photosensitive cells, then the image is reproduced (inverted and reversed). In the model we assume that we have a layer of photoreceptor cells. By means of natural selection, the layer of cells is progressively curved until a camera obscura is obtained. The model defines what a design is based on [Ralph-Wand 2009] definition: a design is the (i) specification of an object, (ii) manifested by an agent, (iii) intended to accomplish goals, in a (iv) particular environment. In our case (i) it is an eye, (ii) an algorithm, (iii) vision and (iv) a multicellular organism, specifically an animal. Next, we define the model used in the simulation experiments.

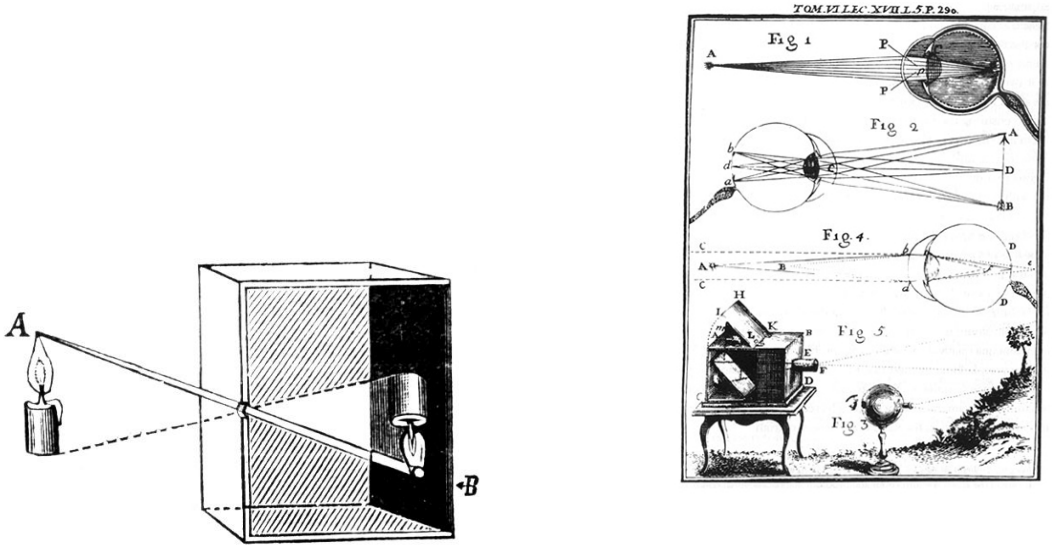

Figure 1. (Left) Camera obscura. (Right) Comparison of eye and camera obscura, early eighteenth century

Model of the evolution of an elementary eye

The model basically generate an array of 3x3 for each elementary eye. In this matrix the elements represent cells such that a value of 1 simulates the presence of epithelium and 0 its absence, i.e. vitreous body filling the cavity. All eyes begin evolution in a primitive state (t=0) in which the eye is a matrix of cells without any vision composed by a layer of cells or epithelium:

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In the model we have assumed the existence of an 'eye population', all eyes being in the initial state shown above. The optimal eye, that is to say that eye with some degree of vision, would be similar to a camera obscura, being represented by the matrix that is shown next:

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101

The model is based on the following assumptions:

(a) We consider only a layer of epithelial cells sensitive to light, without considering the problem of the evolution of photoreceptor cells [Nilsson and Pelger, 1994].

(b) We evolve an elementary eye, without going into physiological or zoological considerations.

(c) Unlike the work [Nilsson and Pelger, 1994] we do not estimate the number of generations required but instead we do simulation experiments.

A main feature of our model is that is based on the hypothesis of Nilsson and Pelger [Nilsson and Pelger, 1994] which we could summarize in the following sentence "the problem of the evolution of the eye is solvable if the evolution is limited to its optical geometry".

In other words, a complex structure or its design could evolve through the mechanics of natural selection when the structure is transformed into another equivalent that is the sum of simple quantitative characteristics. For example, the Dawkins model of biomorphs illustrates a complex structure that is the result of the sum of simple quantitative features [Guil López et al., 2016].

Using a simple genetic algorithm [Lahoz-Beltra, 2016] the evolution of the 'eye population' towards the optimal eye is simulated by evaluating each 'eye design' by means of a parameter V_{max} related to vision and which is termed as maximum detectable spatial frequency. This frequency is a measure related with the resolution of the perceived image in the eye. From a computational point of view, e.g. in a photograph, the resolution of an image is defined as the total number of pixels it contains. For instance, assuming that human eye is like a video stream, [Clark, 2016] has been estimated for the human eye an image resolution of 576 megapixels. In Nilsson and Pelger's model [Nilsson and Pelger, 1994] the resolution of the image captured by an eye is evaluated based on the theory of [Snyder, 1979] and [Warrant and McIntyre, 1993]. According to this theory in an eye the frequency V_{max} is calculated by the following expression:

$$V_{max} = (0.375 . \frac{P}{A}) \ln \left[\left(0.746 A^2 \sqrt{I} \right) \right]^{\frac{1}{2}} \quad (1)$$

where A represents the aperture (diameter) of the eye and P is the nodal distance or pit depth. In the model we assume that the intensity of the light I is kept constant during a simulation experiment, being equal to 1.

In our model *A* value is given by the number of 0s in the last row of the matrix that conforms it. In the model, and in order to ensure a minimum aperture, a penalty P_A parameter is declared and used in case the middle position in the last row is set to 1. Therefore, the final equation we used to ensure a minimal aperture is:

$$A = (m_w - ep + P_A)\frac{es}{m_w} \tag{2}$$

where m_w, *ep*, *es* are the arrays maximum width, is the epithelium in the last row and the size in mm of each part of the epithelium in the last row, respectively. P_A was set to 10 in the simulation experiments. Thus, in the spatial frequency the bigger the aperture the worst the resolution of the image. Also, by adding the penalty P_A parameter to aperture measurement we avoid obtaining an aperture equal to 0 avoiding in expression (1) a zero division. The size of the eye (*es*) is assumed equal to 10 mm.

Following, *P* value was obtained by measuring the epithelium thickness in the middle column of the array. The rest of the columns are inspected in the same way and in case we found a gap in the epithelium shape we use a gap penalty parameter *G* to count them. Therefore, the final equation we used is:

$$P = es - (mce_{end} - mce_{begin})\frac{es}{m_d} \tag{3}$$

In the above expression (3) and for each one of the columns in the eye matrix, we track the starting mce_{begin} and ending mce_{end} points of the epithelium, being m_d the arrays maximum depth.

In order to illustrate the most peculiar steps of our algorithm, suppose the following example:

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111

First, we analyze each individual column of the matrix storing the mce_{begin} and mce_{end} values. In this case we found a gap in the second column, therefore the gap penalty *G* is increased by 1. Afterwards, we measure the epithelium in the last row in order to calculate the aperture. In this case, the aperture is 0 since m_w - *A* = 0, but considering the penalty due to the epithelium placed in the minimal aperture position we have an aperture of $10\frac{es}{m_w}$. With all these information, we are ready to calculate the fitness for a single eye for a later comparison.

Finally, the fitness value *f* was calculated as follows:

$$f = \alpha V_{\max} - \beta G \tag{4}$$

setting in (4) the values $\alpha = 100$ and $\beta = 10$.

The evolution of this ancestral eye is governed by some elementary rules of biological inspiration. In relation to the mutation operator, only the empty cells (0) are allowed to be occupied by epithelium (1) if they are surrounded by other cells with epithelium (1). This rule simulates a growth in the epithelium. Also, a cell occupied with epithelium (1) is not allowed to change to a 0 state, since this would simulate the rupture of the epithelium previously formed.

Simulation results

The main conclusion of this work is the possibility to successfully evolve an ancestral eye gradually by Darwinian natural selection when the goal is to obtain an organ equivalent to a camera obscura (Figure 2).

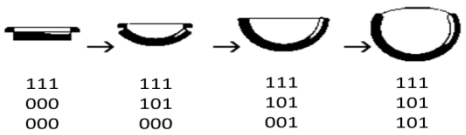

Figure 2. Elementary eye evolution.

Moreover, a simple genetic algorithm is sufficient to emulate the evolution of an elementary eye. Figure 3 shows the characteristic performance graph obtained in four experimental conditions. As the rate of mutation is reduced the average fitness of the population becomes more stable which means that the variation between the generations is lesser. However, we observed in the simulation experiments that a higher rate of mutation it is possible to reach the maximum fitness faster, i.e. better vision faster. For instance, in the 200 generation the overall fitness is already almost the maximum fitness for the higher mutation rate. In the other side, with a lower mutation rate the population seems to increase the fitness through generational steps: 1st region (0-100 generations), 2nd region (100-320 generations), 3rd region (320–450 generations), 4th region (450–500 generations). Once a region has been reached this average fitness behavior reflects a lesser variation between generations. In general, we appreciate that a lower crossover softens the performance graph what means that the propagation of individuals with smaller fitness, i.e. worse vision, is reduced.

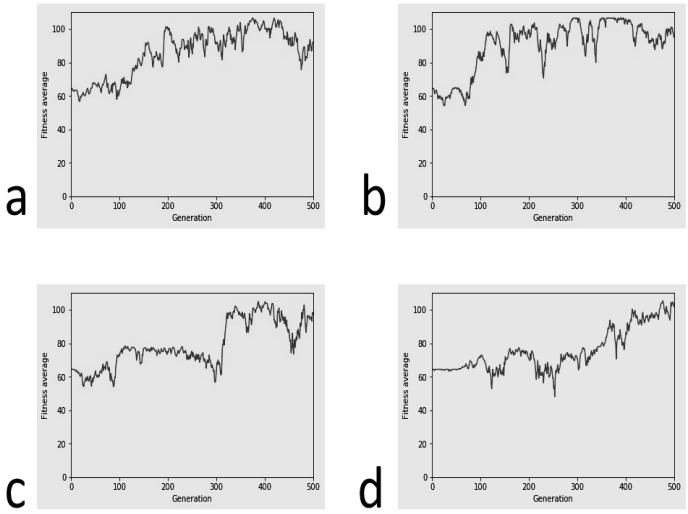

Figure 2. Simulation experiments with a population composed of 100 elementary eyes that evolved over 500 generations. (a) Crossover rate=0.65, eye mutation rate=0.1 and cell mutation rate =0.05. (b) Crossover rate=0.65, eye mutation rate=0.07 and cell mutation rate=0.05. (c) Crossover rate =0.65, eye mutation rate=0.07 and cell mutation rate=0.03. (d) Crossover rate=0.40, eye mutation rate=0.07 and cell mutation rate=0.03.

Conclusion

A model of eye evolution is proposed adopting as a starting point the Nilsson and Pelger hypothesis establishing that the evolution of the eye can be studied if we limit ourselves to its optical geometry. We show how eye evolution could take place gradually applying the principle of natural selection. Our model is limited to studying how an array of photosensitive epithelial cells is bent gradually to achieve a camera obscura.

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