Using Evolutionary Algorithms For Designing 3D Novel Objects

Yavuz Selim DOĞAN[1], Fatih V. ÇELEBİ[2], Hilal KAYA[3]

[1]Turkish Military Academy, Ankara, Turkey
y.selimdogan@gmail.com
[2]Ankara Yıldırım Beyazıt University, Ankara, Turkey
fatihvcelebi@gmail.com
[3]Ankara Yıldırım Beyazıt University, Ankara, Turkey
hilalkaya@ybu.edu.tr

Abstract

Multicellular creatures start their life cycle by self-replication of the starting cell (the zygote) according to the instructions written in the DNA. The rules, written in the DNA, determine the final design of the organism. This process can be simulated in a digital environment, improved by evolutionary process and can be used to produce inventive designs.
The purpose of this study is to test the ability of computers to make novel designs by mimicking embryological development. A program, developed for this, produces cube-shaped symbolic cells. Shapes emerging from the combination of hundreds of cells are compared to target shapes. DNAs of shapes are evolved by genetic programming to increase the similarity to the target shape. In the tests made with 4 different target shapes, it has been observed that the implemented system can make voxel based designs with the success rate between 53% and 85%.

1. Introduction

In the nature, there are creatures that are specially designed to overcome difficult tasks such as flying, swimming, using energy efficiently, surviving in a desert etc. There is an extraordinary coding-decoding mechanism under these designs which come from a single cell. The same mechanism can be used for 2D or 3D designs made in a computer environment, if it is known which instructions are encoded in the genes for this mechanism to work like a clock.

While there are no advanced computers yet, great computer theorists like Alan Turing, John von Nueumann, Norbert Wiener suggest that biologic systems can be imitated computationally for artificial intelligence[1]. Biologically based systems used to generate design can be grouped into 2 main categories[2]:

- Gramatic methods
- Artificial embryogeny.

Gramatic methods are generally used to produce results similar to the plant morphology. Using an initial set of derivation rules, an initial string is derived and a longer output is obtained. Each character in this output is read one by one with the aid of a translator, and a 2D or 3D design is made. With the help of this method, NASA has developed a system that designs antennas relatively similar to trees. That system designs antenna shapes like in Fig.1 and these antennas are successfully used in some space vehicles[3].

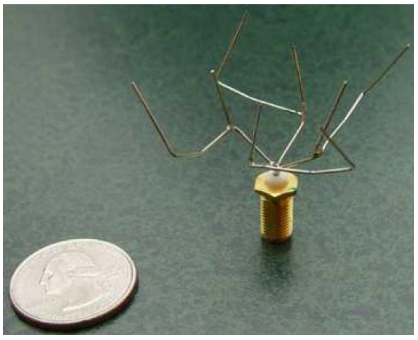

Fig. 1. An evolved prototype antenna of NASA[3]

This work focuses on a system which is known as "artificial embryogeny" or "artificial cell chemistry" which Alan Turing proposes as a concept[4]. In this method, the cells respond to a number of chemical, electrical, or physical signals that originate from the environment or are produced in their own cytoplasm. In fact, a cell does not make a choice in the reaction process. Instead, it acts as an automat that implements the rules encoded in its DNA. In DNA, a wide variety of instructions such as alteration, division, suicide, and how they are applied are coded in detail. Virtual cells produced in the computer environment can perform similar functions by reading their digital DNAs. With the actions of thousands of players, the design of the organism takes the final shape.

DNA must be encoded very sophisticated so that such a system can produce useful results. The slightest faulty code in DNA can make the final organism useless. At this point, evolutionary algorithms (EA) are involved in the work. EAs try to discover the genotype that will produce the closest shape to the desired result by generating thousands of different combinations of DNA with crossing over, mutation and elitism operators.

In the past studies, robots bodies, beams, realistic human organs etc. generating systems have been introduced by different varieties of voxel based systems or artificial embryogeny methods [5-7]. However, there is no comparative study of how successful these methods are. The reason of this lack, there is no objective way to measure how novel a design is. In order to be able to have an idea ofthe success of the embryogeny algorithm used in this study, 4 different shapes in different characteristics and complexity have been identified as targets. The goal is to measure the searching/exploring ability of the algorithm that is left as "blind" in the search space. This study is presented and explained in detail in a M.Sc thesis at Ankara Yıldırım Beyazıt University[8].

2. Biological Background

If we want to imitate real creature development in the digital world, we can not go beyond the knowledge of chemistry and biology. However, biology as a science advances with studies on countless living things ranging from humans to bacteria. In this study, a single biological development that belongs to particular species is not considered. Instead, embryological developmental stages common to many multicellular organisms have been investigated and these have been adapted to the digital environment by simplifying them.

In general, the development of the species in eggs or in the womb is examined in 2 steps:

- early embryological development
- later embryological development [9].

In the first stage, the egg combines its own genetic material with the material carried on a sperm and constructs the DNA of the newborn organism. It then splits up rapidly to form a mass of stem cells that come from tens of replicas.

In the later embryological stage, stem cells begin to differentiate to form different subsystems of the organism. Nervous system, muscle system, legs, arms etc. develop simultaneously to form the final organism.

DNA codes are read and applied continuously in all stages from the first fertilization until the death of the creature. DNA contains instructions for thousands of different jobs. The description of all the proteins to be synthesized is written in DNA. The description of the protein that is instantly needed is copied from the DNA with the aid of enzymes and written into the transient memory: RNA. RNA carries the code to the ribosome, and the ribosome produces the protein from amino acids according to this information.

2.1 Cellular Differentiation

Some regions of the DNA helix are locked and are not used. Locked genes can be activated (gene expression) or active genes can be locked (gene repression) according to the intracellular substance concentration in the cells coming from the outside[10]. In order for the stem cells to be able to change, each cell must know which task to undertake in the organism. For example, not all cells are altered to be the building blocks of the nervous system. The position information of the cell determines the destiny of the cell. Cells consider the types and concentrations of substances in the intensive fluid in order to understand the their location. The distribution of the "morphogen" labelled substances in the egg determines the morphology of the living thing[4]. DNA has "hox" genes that contain a morphogen-subsystem match[11]. In the mutant drosophila flies seen in Fig.2, the hox genes were altered. As a result, the leg structure is emerged at the location where the antenna should be formed. The morphogenic variety that the cell perceives from the outside triggers the transformation of the cell.

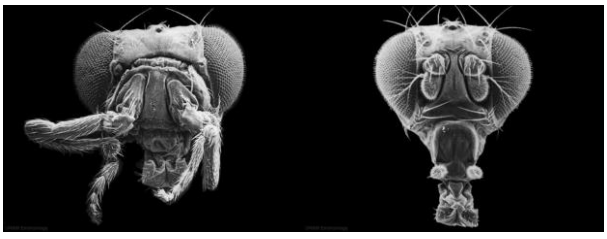

Fig. 2. Mutant and normal drosophila melanogasters[11]

2.2 Programmed Cell Death: Apoptosis

Programmed cell death - apoptosis - serves a certain purpose. For example, as seen in Fig. 3, the fingers are adjacent in the first weeks of the human embryo [12]. In the following weeks, the cells between the fingers die in a programmed manner, allowing the formation of gaps between the fingers.

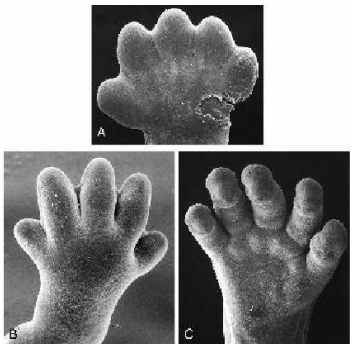

Fig. 3. Human hand at 28 days (A), 51 days (B), 56 days (C) [12]

These three mechanisms must be well understood in the computerised design: division, differentiation and apoptosis because millions of cells of the organism's structure constitute the final design by the help of these mechanisms.

3. Implementation

Similar to the real world, digital creatures must also have an observable phenotype and its genotype. In the virtual egg, a certain number of cubic cells come together to originate the phenotype. In order to be able to see the embryos produced by the program, the eggs that are generated at each stage are printed on the screen with the Unity3D game engine[13]. The system is programmed with C# programming language and 3 classes are created for the cell, the egg and the DNA units. The program initially produces a certain number of eggs. At the beginning, each egg contains 1 cell (zygote) and 1 DNA. All cells that are reproduced from a zygote have the same DNA.

DNA keeps precondition-action pairs. At every iteration, the state of the cell is checked. In response to this state, the reaction that the cell should give is searched on the DNA. Actions corresponding to each precondition are randomly determined in the first generation. In subsequent generations, as a consequence of the mechanism of evolution, cells are reprogrammed to select more accurate actions. At the end of each iteration, the embryos formed in the egg are scored according to their resemblance of the target shape. A summary of all steps is shown in Fig.4.

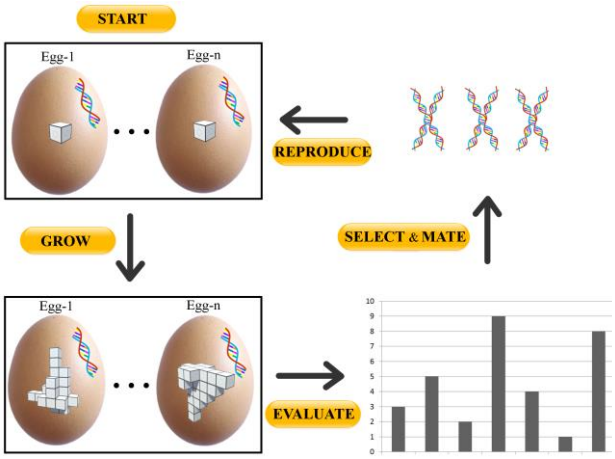

Fig. 4. Illustrations of the egg, embryo, cell and the DNA

DNA dictates to the cell one of 8 different actions according to the state of the cell:

- make copies in 6 different directions
- commit suicide
- do nothing and keep the current situation

Internal and external factors determine the state of the cell. Internal factors are protein/enzyme concentrations in the cytoplasm. External factors are the signals transmitted by neighbouring cells and cell location data. According to the cell type, electrical signals or chemical substances between cells can be transmitted in thousands of different combinations. In this work, it is assumed that only one of 10 different signal types can be sent to reduce the computational complexity. While a cell is deciding, it consults with each of its 6 neighbours one by one. Internal signal and 6 different signals coming from 6 neighbours constitute the "precondition" of the cell. As a result, the cell can copy itself to one of the 6 directions, die, or retain its last state without doing anything.

The position information required for cell differentiation is provided by the "regions". The region information used in place of morphogen density divides the egg to 27 (3x3x3) different sections. The region where the cell is located may cause it to choose a different action.

It is impossible to implement an infinite number of cells in a computer environment. To reduce the computational complexity, the environment resolution should be kept low. In this study, the environment resolution is determined as 27^3 so each egg can have 19683 cells maximum.

4. Evolution

All EAs are based on the gradual development of randomly generated genotypes [14]. The evolutionary process begins with a group of individuals: the initial population. A new generation is created by the mating of individuals in this population. The purpose of pairing and crossing-over is to obtain an even more successful individual than its parents with beneficial features.

In each generation, the individuals at the pool are graded according to their closeness to the solution of the problem. Hereditary material of prospective individuals providing a more successful solution should be more dominant in the next generation. Thus, as the generation changes, the total quality of the population will continuously increase. In order to do this, parent choice is made with natural selection strategy: an individual's likelihood of being a parent is directly proportional to its fitness.

Genotypes can consist of bits, numbers, characters, or simple if-then-else rules depending on the nature of the problem. As the meaning of the genes changes, the crossover and mutation mechanisms underlying the evolutionary process change. In this study, genomes come from precondition-action scores. According to this system, scores are given for 8 different actions by looking at the preconditions of the cell. The result of consultation with neighbouring cells, the action with the highest total score is applied in the next iteration. During the crossover, the action scores of the DNAs of the parents are transferred partly to the child's DNA.

All the genes in the initial population constitute the gene pool. The gene pool does not change with mating alone. In order to add new features/genes to the gene pool, gene valuesthat do not normally exist at the beginning should be added to the system. For this, mutation operator is applied by randomly changing some valueson DNA after each mating. In the mechanism of mutation implemented in this study, the scores given to the actions are changed by random selection.

As a result of all these steps, new children are produced from successful parents. Among children, there may be poorer individuals than parents. Elitism has been achieved using the steady-state genetic algorithm so that overall quality never drops. According to this algorithm, the old and the new generation of people are merged and sorted according to their quality. Individuals below a certain quality level are deleted from the pool. Evolution continues with the remaining individuals.

Heuristic algorithms do not guarantee the best solution; instead, they continuously search on the solution space until they are stopped somehow. When the algorithm stopped, the individual providing the best solution among all the competitors is used. In this study, the evolutionary development process is run for 12 hours and the designs are generated using the best DNA of the last generation.

5. Experiments And Results

It can not be precisely measured novelty of the designs made by computers or people. The success of a program that makes original designs is a relative concept. In this study, designs are compared with target shapes to be able to evaluate with a numerical values. Outputs are tested using 4 different target shapes. It is preferred that the target shapes have different characteristics as much as possible. The cells in the embryo produced by the program and the target cells are compared one by one. Match percentage is used to calculate fitness value.

In each test, eggs with different numbers of cells are used. Cell amount greatly affects the performance of the system. For this reason, instead of generating a certain number of embryos for each test, embryos are used after 12 hours running of the program. Program is run on a computer with Intel core i7-3770 processor (3.4 GHz, 4 cores) and 16 GB memory. For future works, the program can be adapted to run with parallel computing.

5.1 Test-1: Sphere

In this test, a hollow sphere consisting of 494 cells is set as the target. The target shape shown in Fig.5 consists of 2 balloons with a radius of 6 and 7.

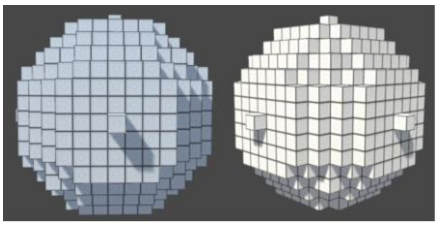

Fig. 5. Target-1: Hollow sphere

Since the program is initiated by a cell placed in the egg centre, the inner cells must commit suicide during the later embryological development stage. The initial shapes produced with random DNAs are shown in Fig. 6.

Fig. 6. Initial embryos with random DNAs

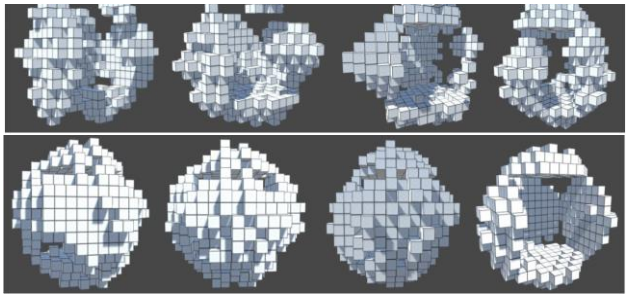

Fig. 7. Embryos from the 20th and the last generations

As it can be seen in the first row of Fig. 7, when the 20th generation is reached, the evolutionary mechanism has discovered carving the centre of the embryo. The best embryos of the 6000th generation reached after 12 hours are shown in the second row of Fig.7. In the last iteration, 59% of the cells are located in the correct position.

5.2 Test-2: Umbrella

In this test, an umbrella-shaped target consisting of 316 cells is identified. The target shape is shown in Fig.8 and sample embryos from the 20th and 7000th generations are shown in Fig.9. The most successful embryo has a 53% overlap rate.

Fig. 8. Target-2: Umbrella

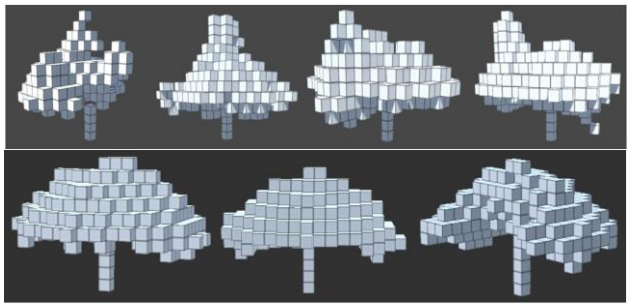

Fig. 9. Embryos from the 20th and the last generations

5.3 Test-3: 2D Star

In this test, a 2-dimensional star-shaped form of 179 cells is used. The goal is to see the ability of the algorithm to completely eliminate one of the dimensions. Fig.10 demonstrates the target shape and embryos from the 20th (first row) and last generations (second row) are seen on Fig.11. The success rate is 85% at the last generation.

Fig. 10. Target-3: Two dimensional star

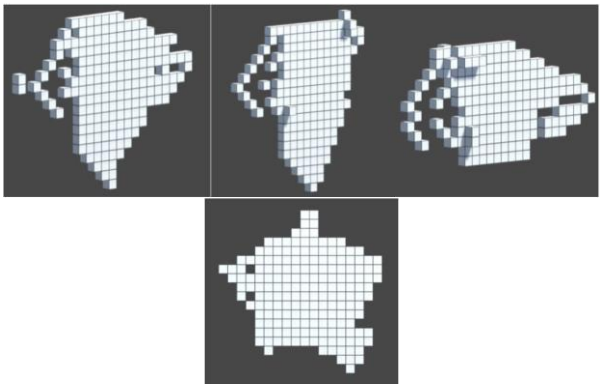

Fig. 11. Embryos from the 20th and the last generations

5.4 Test-4: 3D Star

In this experiment, a bulging star with 763 cells is used. The evolution is very slow because the number of cells is relatively large. Approximately 1000 iterations are completed in 12 hours. The target shape, and embryos from the 20th and last generations are seen on Fig.12 and Fig.13. The success rate is 84%.

Fig. 12. Target-4: Three dimensional star

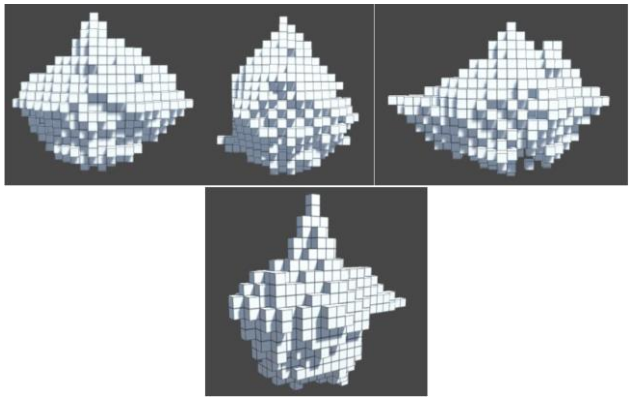

Fig. 13. Embryos from the 20th and the last generations

5.5 Results

The results of 4 tests are shown in Table 1. The evolution process for the first 400 generations is shown in Fig.14. As each cell makes its own decision in the egg, generating an embryo takes more time in proportion to the number of cells. It seems that the first 200 iterations are enough for almost final results.

Table 1. Results of 4 tests

	Cell Amount	Reached Generation in 12 Hours	Success Rate at 20th Generation	Success Rate at 100th Generation	Success Rate at Last Generation
2D Star	179	15.000	72%	78%	85%
Umbrella	316	7.000	34%	49%	53%
Sphere	494	6.000	48%	57%	59%
3D Star	763	1.000	73%	81%	84%

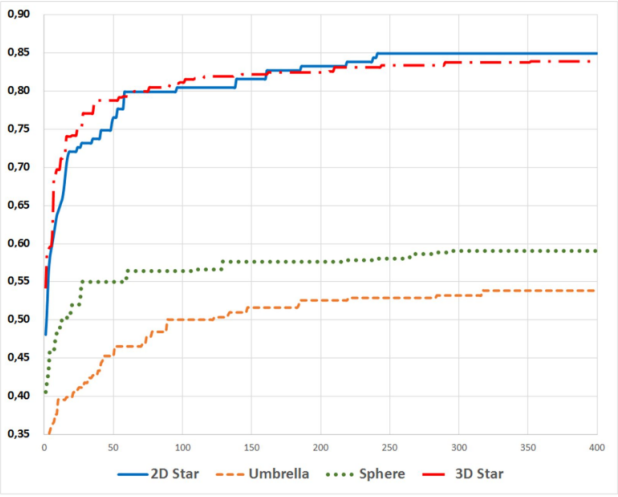

Fig. 14. Development processes of 4 test shapes

6. Conclusions

In a space with nxnxn resolution, 2^n different designs can be produced with 1 unit voxels. Finding the most appropriate one for a given problem is a Np-complete problem and approximate results can be obtained by using heuristic algorithms.

In this study, a kind of artificial embryogeny system is established to produce shapes consisting of a certain number of voxels. The system reads the instructions encoded on a fixed-length DNA and generates the design accordingly. The gradual evolution of the DNA brings the resulting design closer to the desired result. The system has been tested for its ability to explore various 3D designs.

The system has been run for 4 different scenarios and it has been observed that it can produce similar results to different characteristic designs. The designed mechanism can be adapted to real life problems by adjusting the fitness function. Even if the designs to be produced are not suitable for direct use, the results can be used for just inspiration.

7. References

[1] Mitchell, M., "An Introduction to Genetic Algorithms", MIT Press, 1998.

[2] Dellaert, F., "Toward A Biologically Defensible Model Of Development" 1995.

[3] Hornby, G. S., Globus, A., Linden, D. S., and Lohn, J. D., "Automated antenna design with evolutionary algorithms", *AIAA Space.*, 2006, pp.19–21.

[4] Turing, A. M., "The chemical basis of morphogenesis", *Philosophical Transactions of the Royal Society of London*, vol.237, no.641, pp.37–72, 1952.

[5] Cheney, N., MacCurdy, R., Clune, J., and Lipson, H., "Unshackling evolution: evolving soft robots with multiple materials and a powerful generative encoding", *Proceedings of the 15th annual conference on Genetic and evolutionary computation, ACM*, 2013, 167–174.

[6] Baron, P., Fisher, R., Tuson, A., Mill, F., and Sherlock, A., "A voxel-based representation for evolutionary shape optimization", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, vol.*13,* no.*3*, pp.145-156, June 1999.

[7] Fontana, A., and Wróbel, B., "Evolution and development of complex computational systems using the paradigm of metabolic computing in Epigenetic Tracking", 130, 27–34, 2013.

[8] Doğan, Y. S., "Using Evolutionary Algorithms For Designing Novel 3D Objects", M.S. thesis, Comp.Eng.Dept., Ankara Yıldırım Beyazıt Univ., Ankara., Turkey, 2017.

[9] Gilbert, S. F., "Developmental Biology", *Sinauer Associates,* 2000.

[10] Mannervik, M. "Transcriptional Coregulators in Development". *Science,* vol.284, no.5414, pp.606–609, April 1999.

[11] Turner, F. R., and Mahowald, A. P., "Scanning electron microscopy of Drosophila melanogaster embryogenesis", 68(1), pp.96–109, 1979.

[12] Sadler, T. W., "Langman, Jan. Medical embryology", Lippincott Williams & Wilkins, 2012.

[13] Available: https://unity3d.com

[14] Sivanandam, S.N., Deepa, S. N., "Introduction to Genetic Algorithms", Springer Science&Business Media, 2007.