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Pugnale, Alberto; Sassone, Mario

Published in:
Proceedings of International Symposium of the International Association for Shell and Spatial Structures (IASS) : Structural Architecture - towards the future looking to the past

Publication date:
2007

Document Version
Accepted author manuscript, peer reviewed version

MORPHOGENESIS AND STRUCTURAL OPTIMIZATION OF SHELL STRUCTURES WITH THE AID OF A GENETIC ALGORITHM

Alberto PUGNALE
PhD Student
Politecnico di Torino
Torino, ITALY

Mario SASSONE
Assistant Professor
Politecnico di Torino
Torino, ITALY

Summary

The paper presents a method to generate and structurally optimize the shape of free form shells by means of a genetic algorithm. The shape of the shell is described with the aid of a NURBS representation and the algorithm modifies and improves it on the basis of the structural behaviour. A FEM analysis is performed for each individual and at each generation of the evolutionary process, in order to evaluate the structural behaviour in terms of maximum vertical displacement under a distributed load condition. The method is applied to a recent example of free-form architecture and the results are discussed referring in particular to the role of the architect as 'decision maker' in the evolutionary process. From this point of view the necessity to fit different requirements (structural, functional, aesthetic) involving the work of many professionals, can then be interpreted as a problem of multiobjective optimization.

Keywords: genetic algorithms, computational morphogenesis, optimization, free form design.

1. Introduction

The genetic algorithms, and more generally the evolutionary computational techniques, can be applied with success to a wide range of structural and architectural problems. The structural optimization of complex structures, as membranes, shells [1], grid-shells [2], has been historically an important research field since the work of Gaudì and the experiences on physical models. The use of evolutionary algorithms in this kind of problems is relatively recent [3][4] and it goes in parallel with their use in other structural applications, specifically in topological optimization of trusses [5][6]. The recently developed technique of Evolutionary Structural Optimization (ESO) [7][8] seems to approach the design problem with particular attention to architectural and aesthetic aspects. In other disciplines the use of genetic algorithms is diffuse since thirty years, starting from the studies in biology, on the adaptation in natural and artificial systems, until the research on the genetic programming [9]. John Frazer is the pioneer that in '70s brought this kind of research inside the architectural design, thus evolved in the personalization of the software and in parameterization [10].

The evolutionary approach to architecture is a powerful strategy, able to handle complex problems, involving different requirements to be fit, from the structural and economic aspects to the constructional, functional and aesthetic ones. The traditional multidisciplinary approach, in which different professionals are involved in design each one solving just a specific problem is put in discussion by the recent developments of computational technology and many architects feel that their role in the design team is changing, as the interest for the Non-Standard Architecture and for the interactions between architecture, engineering, mathematics and computation seems to testify.

In this contest the application of a genetic algorithm to the morphogenesis of the structural and architectural shape of a free form concrete shell can help to better understand the role of the architect and of the engineer in the design process. There is an intrinsic difference between the form-finding strategies usually adopted in the design of tensile structures or in grid shells and a morphogenetic process of structural optimization. In the first case the solution is well defined, even if unknown. It can be represented by a minimal surface or it can correspond to an equilibrium configuration of a cable net under a specified load condition. Into a morphogenetic design process, the final, sub-optimal solution is not univocally determined by a mechanical (or physical) property, but is the one which better fit a set of design requirements.

2. Morphogenesis of shell structures

In this paper the morphogenetic optimization process is applied to the structural and architectural design of free form concrete thin shells. Many approaches have been adopted in the past in the design of concrete thin shells: Torroja, Isler, Candela, for instance, designed many thin shell structures starting from the physical models and from the well known analytical solutions of a very small set of shapes. The italian engineer Sergio Musmeci used concrete thin shells in bridge design, through a form finding process. Thanks to the development of structural analysis tools a wider set of possibility opened to architects and the design process is no longer strictly governed by the structural behaviour. The role of the architect in defining the shape of the shell is more important than in the past and he can actively interact with the morphogenetic process.

In order to perform the computational generation and optimization of a shell structure three tools are necessary. First, the shape of the structure has to be defined from the geometric point of view. Different descriptions are possible: if the shape is relatively regular it can be described with the aid of an explicit function of two parametric variables and it can be modified by changing the values of the constant parameters involved in the description. If the shape is complex the surface can be described as a NURBS surface, i.e. a rational polynomial continuous function, defined by a set of control points. Secondly the structure has to be analysed and the structural behaviour studied. The surface needs to be discretized into a structural mesh and a linear or non linear structural FEM analysis can be performed, in order to evaluate the displacements, the buckling load or the dynamic behaviour. Finally, the genetic algorithm GA is necessary in order to perform the evolutionary optimization of the shape.

Each of the three computational tools has is own internal representation of the solution: a matrix of control points for the NURBS; a discrete finite element mesh, with constraints and loads in the FEM solver; a genetic binary code in the evolutionary algorithm. Hence an important part of the of the procedure is devoted to translate the information from one representation to the other.

2.1 The geometric representation of solution

A free-form surface can be represented as a two dimensional NURBS with a suitable degree of approximation [11]. The surface is completely defined by a net of control points, by a vector of weights and by the polynomial functions degree in the parametrical directions. One of the most important features of NURBS is the local control: with respect to the Bezier curves, the presence of a weight associated to each control point allows to locally modify the surface by changing the control point coordinate, without modify the rest of the surface. This property is important when the position of some points is fixed, as in the case of constrained points, or when one or more edges of the surface is defined. The positions the free control points are then assumed as design variables in the morphogenetic optimization.

2.2 The coding

The evolutionary algorithm works on a coded representation of the surface. The coordinate z of the NURBS control points are stored into a two dimensional matrix. If this matrix is coded in a one-dimension binary chromosome, containing all the genetic information about the individual, the classical crossover operation can introduce a kind of asymmetry in the process, related with the way the matrix is reshaped into a vector. If the vector is obtained reordering the matrix by rows and columns, for instance, the single or multiple crossover cuts will divide the matrix in submatrices in a specific direction. This problem can be solved by reshaping the matrix in other ways, as taking the elements randomly, in order to avoid any asymmetry, but the best approach is to adopt a two dimensional binary representation of the chromosome and defining a suitable two dimensional crossover operator [12].

2.3 The domain

The choice of an appropriate domain for the design variables is a fundamental task. The whole design process is strongly influenced by the definition of the range of variability of each variable. When a very small range is adopted, the final solution is relatively close to the starting ones, and the algorithm improves the mechanical behaviour without altering significantly the global shape. In this case the initial shape, from which the initial population is randomly generated, can be drawn by the architect on the basis of the aesthetic and architectural requirements. The process of optimization modifies this first tentative solution in order to improve its structural performance.

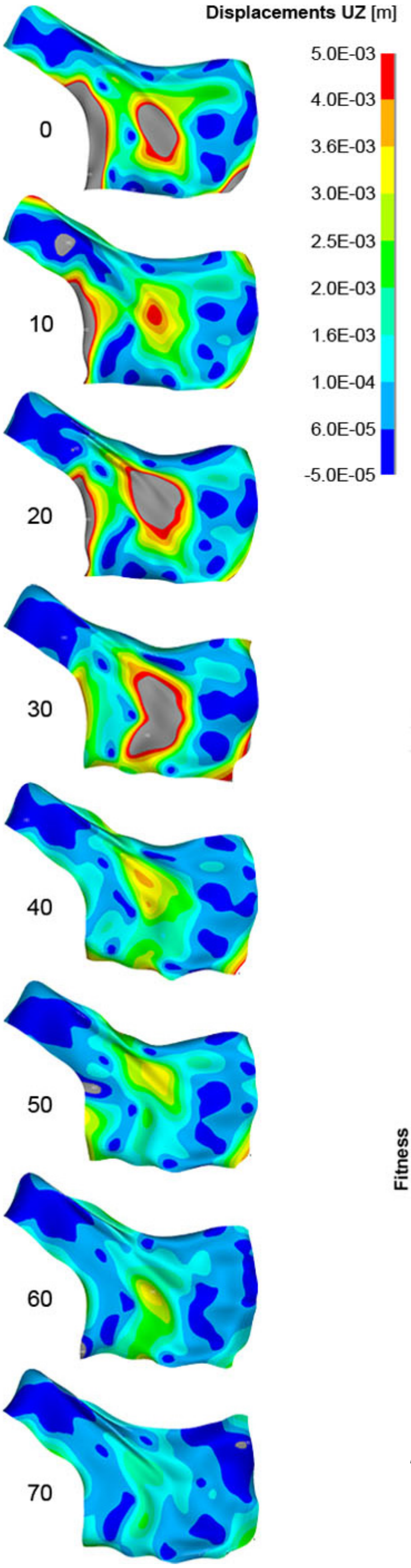
If a wider range is assumed for the design variables, the evolution of shapes acts as a true morphogenetic process. The initial population is composed of random generated individuals and the evolution selects the one (or the ones) with the best fitness value. Unsuitable or incorrect shapes are frequently generated, depending on the definition of the fitness function: if only the structural behaviour is taken in account, for instance, the result can be not interesting from the aesthetic point of view or economically unsustainable. Nevertheless the morphogenesis always produces solutions with high fitness values, due to the robustness of the genetic algorithm, and the architect obtains an interesting set of new structural shapes, capable to fit the structural requirements. The designer controls and rules the morphogenetic process acting on the constrains, on the domain and on the fitness function, so that the evolutionary shape generation can be regarded as a true, even if not conventional, design process.

3. Applications and Results

The design method described above has been applied to a real case study. In 2004 the construction of the new Kahamigahara crematorium in Gifu, Japan, has been completed (Figure 1). The Toyo Ito architectural concept has been constructively and structurally developed in collaboration with Mutsuro Sasaki. In this building a large reinforced concrete roof covers the inner blocks, supported by a set of pillars. As it can be seen in Figure 1 and in Figure 2, top left, the shape of the shell is free-form in plan and in the front view as well as the randomly positioned columns at the ground level. The design of the shell structure has required the shape to be optimized from the structural point of view by means of a sensitivity analysis, in order to obtain the most structurally efficient configuration, accordingly with the concept of the architect. The shape has been optimized from the structural point of view by means of a sensitivity analysis, in which is the function to be minimized. After the sensitivity coefficient of each structural node have been determined, the optimal configuration has been calculated iteratively by minimising the total strain energy [13].

Due to its characteristics this structure is a very good case study for the application of the genetic algorithm based process of optimization and morphogenesis. In fact, if the optimization process adopted in the concrete roof design is mainly a refinement procedure, in which the shape proposed by the architect is slightly modified in order to reach the best mechanical behaviour, a true morphogenetic optimisation process can be regarded as a way to generate a set of sub-optimal solutions, on which the architect can operate selectively. The optimal final solution will then be the result of the interaction between the generative tool and the architect and the engineer work. In this contest the evolutionary algorithms seem to be the most robust and versatile tools of analysis, capable to explore a wide range of possibilities, limiting the convergence to local minimum solutions, but always allowing the whole process to be controlled and guided by the architect decisions.

Fig. 1. Kahamigahara crematorium, Gifu, Japan



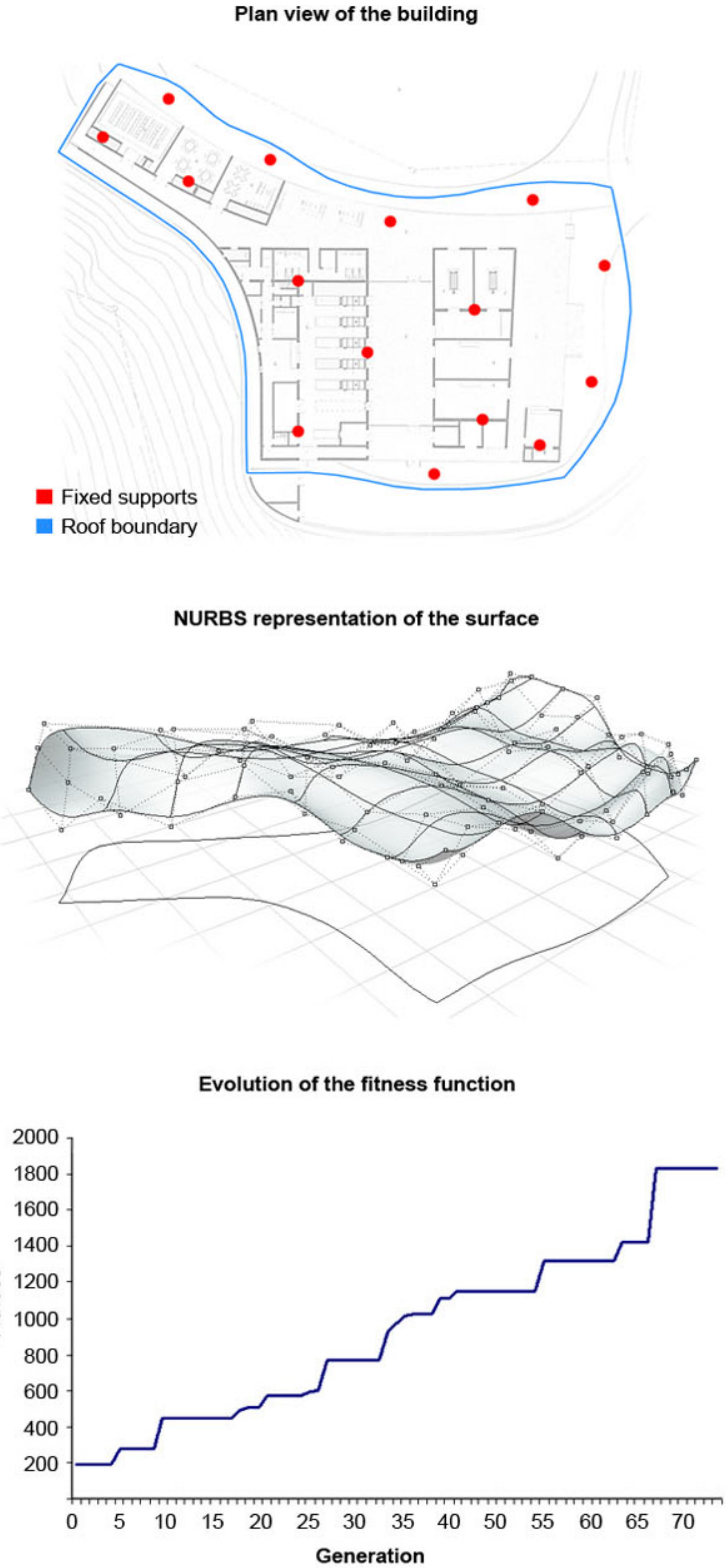


Figure 2. *left:* *maps of vertical displacements every 10 generations;*
right: *plan view of the building;*
optimal roof surface;
evolution of the fitness function

Starting from the characteristics of this project, the plan view of the building, the position and the height of pillars, as well as the plan projection of the roof boundary, are assumed in this paper as the fixed input data for the generation of the sub-optimal shapes. The thickness of the concrete shell is assumed of 15 cm and the dead load due to self weight is the only load condition applied during the FEM analyses. The shape of the shell is described by means of a 3th degree NURBS surface with a net of 10 x 10 control points. The vertical positions of control points are assumed as the design variables in the morphogenesis. A subset of control points are fixed during the morphogenetic process, because they represent the column-slab joints. Because the control points do not lie on the NURBS surface, fixing the control points does not guarantee the surface to pass through the constraint points when it is deformed. Two methods can be applied to solve this problem: first the surface can be defined by means of a net of interpolating points, instead of control points, so that the surface can be constrained to pass through a set of fixed points; secondly the constrains can be handled introducing a penalty in the fitness function [12] and then reducing the surviving probability of solutions that do not fit the constraints. The goal of the optimization process is to obtain a stiff structure, minimizing the maximum vertical displacement of the structure. An analogous result can be obtained calculating the fitness function from some other integral parameter of the structure, as the total strain energy. The maximum displacement is a good indicator of the global stiffness of the structure as well as the presence of local lack of stability.

The use of a local mechanical parameter allows to understand what are the parts of the structure where the algorithm is working, i.e. the parts in which the structural behaviour needs to be improved. In Figure 3, left, the vertical displacements are mapped on the roof surface at different stages of the evolutionary process. The maps show that at the first stages of the evolution both the edge and the centre of the structure have large displacements and that the algorithm reduces them alternatively. It is well known that free edges are the weakest parts of curves shells [1] and the algorithm spends a large part of the evolution in stiffening them.

The procedure can be improved using the Schema Theory [15], that is used to find, inside the genetic code of the best individuals of a population, common parts that support their fitness value. In order to improve the global performance of the shape, without lose these best parts in the reproduction and mutation phases, a genetic operation called "encapsulation" can be adopted, In this way, a shape with a low displacement value on the centre and a worst behavior on the free edges can evolve preserving the parts of its genetic code that geometrically describe its centre.

The structural morphogenesis can then be interpreted as a multi-objective optimization, in which the fitness is assigned on the basis of a multicriterion decision process [14]. Because different architectural requirements, as the structural behaviour, the cost, the aesthetics and functionality, are very often in conflict with each other, the fitness of individuals needs to be calculated considering different objectives. Furthermore, these competing measures of performance are frequently non-commensurable so that they can not be combined in just one fitness function. The final configuration will be an acceptable solution rather than an optimal solution, but all the objectives included in the fitness will be partially reached. The designer acts as the Decision Maker (DM) in the Evolutionary Algorithm (EA) based on the morphogenetic optimization process.

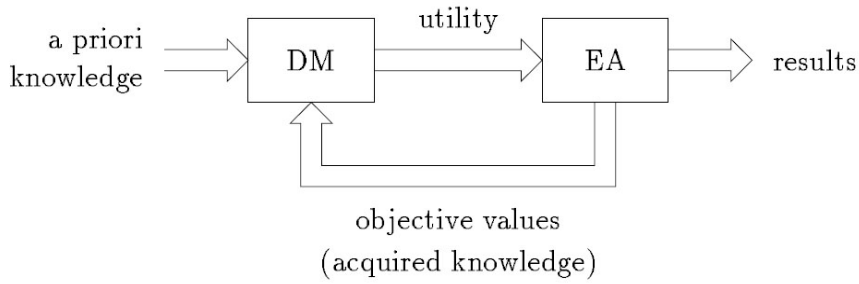


Fig. 4. A general multiobjective evolutionary optimizer (from Fonseca and Fleming 1995).

4. Conclusions

A method for shape generation (morphogenesis) and structural optimization of a reinforced concrete roof shell, based on the application of a genetic algorithm, is presented in the paper. The use of a NURBS representation of the roof allows to modify the shape by changing the position of control points or interpolating points, so that the coordinates of this points can be assumed as design variables. The structural optimization, based on reducing the maximum vertical displacement of the structure under the self weight, improves the structural behaviour of about ten times in 75 generations, modifying selectively the parts of the structure showing the worse behaviour.

In the frame of multiobjective optimization the application of this technique can be extended to the solution of more complex problems, involving structural behaviour, cost, aesthetics and functionality. The architect can keep the full control on the evolution of the project, focusing on the objectives and on the constraints of design.

5. References

[1] BLEZINGER, K., WÜCHNER, R., DAOUD, F. and CAMPRUBÍ, N., "Computational methods for form finding and optimization of shells and membranes", *Computer Methods in Applied Mechanics and Engineering*, Vol.194, 2005, pp. 3438–3452.

[2] SASSONE, M., "Geometry and Structure Generation in Grid Shell Design", *International Workshop on Computational Morphogenesis*, October 10-12, 2006, Nagoya, Japan.

[3] BANICHUK, N.V., SERRA, M. and SINITSYN A. "Shape, optimization of quasi-brittle axisymmetric shells by genetic algorithm", *Computers and Structures*, Vol.84, 2006, pp. 1925–1933.

[4] BAVEREL, O., NOOSHIN, H., KUROIWA, Y. and PARKE, G.A.R., "Nexorades" *International Journal of Space Structures*, Vol.15, 2000, pp.155-159.

[5] TOGAN, V. and DALOGLU A., "Optimization of 3d trusses with adaptive approach in genetic algorithms", *Engineering Structures*, Vol.28, 2006, pp. 1019–1027.

[6] IUSPA, L., SCARAMUZZINO, F. and PETRENGA, P., "Optimal design of an aircraft engine mount via bit-masking oriented genetic algorithms", *Advances in Engineering Software* Vol.34, 2003, pp. 707–720.

[7] CUI, C., OHMORI, H. and SASAKI, M., "Computational Morphogenesis of 3D Structures by Extended ESO Method", *Journal of the International Association for Shell and Spatial Structures*, Vol.44, 2003, pp. 51-61.

[8] YANG, X.Y., XIE, Y.M. and STEVEN, G.P., "Evolutionary methods for topology optimisation of continuous structures with design dependent loads", *Computers and Structures* Vol.83, 2005, pp. 956–963.

[9] KOZA, J. R., *Genetic Programming: On the programming of computers by means of natural selection*, The MIT Press, Cambridge, 1992.

[10] FRAZER, J., *An Evolutionary Architecture*, Architectural Publications Association, London, 1995.

[11] PIEGL, L. and TILLER, W., *The NURBS book: 2nd edition*, Springer, Berlin, 1997.

[12] RENNER, G. and EKÁRT, A. "Genetic Algorithms in Computer Aided Design", *Computer Aided Design*, Vol.35, 2003, pp.709-726

[13] SASAKI, M., *Flux Structure*, TOTO, Tokyo, 2005.

[14] FONSECA, C. M. and FLEMING, P. J. "Multiobjective Optimization and Multiple Constraint Handling with Evolutionary Algorithms-Part I: A Unified Formulation", *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans,*1998.

[15] HOLLAND, J. H., *Adaptation in Natural and Artificial Systems*, The MIT Press, Cambridge, 1992 (1975).