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Shape optimisation using evolutionary techniques in product design

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Abstract

Shape or surface optimisation in product design is a very essential and time-consuming process, especially at the conceptual design stage. In this paper, we introduce a research project aiming to develop an evolutionary design system capable of evolving product shape designs that are easy to manufacture and satisfy the given geometric constraints. One of the issues in applying evolutionary techniques to conceptual design is how to represent designs in a way in which genetic algorithms can be used to support the process of generating and optimising innovative and imaginative geometric components and parts. This paper examines two stages of using genetic algorithms in product shape design-the representation of shapes or phenotype and how to encode designs in a manner analogous to genes in nature, which can be manipulated by genetic algorithms. The early research result and directions for future work are also presented in this paper.

Keywords: Shape representation; Shape optimisation; Genetic algorithm; Phenotype; Genotype

1. Introduction

The competition in the current global markets is commanding rapid improvements in product performance and quality with the reductions in costs and development time-scales. This forces the product-oriented manufacturing enterprises to seek more advance technologies to gain profits by reducing the design development time. As a result, design automation is required to improve the functionality of the designs and reduce the development time and thus reduce the cost, especially when designing complex surfaces are required. Designing the shapes of products is the primary activity of the design process and the CAD/CAM systems used today for the designs provide limited facilities for automatic optimisation of surfaces. They supported an iterative surface optimisation, which is very time consuming and requires an enormous amount of skilled engineering labor.

On the other hand, evolutionary computation techniques have been successfully applied to engineering design optimisation, constraint satisfaction, symbolic equation solving and manufacturing process planning.

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These adaptive and generative techniques provide more creative and intelligent support to designers than other design support systems that have to rely on geometric representations and explicit deductive inference mechanisms. However, the application of evolutionary computation techniques, such as genetic algorithms (GAs) (Davis, 1991; Goldberg, 1989; Holland, 1975), in product design has been limited (Gen & Cheng, 1997; Hawkes & Abinett, 1984). The difficulty arises from the fact that product design requires a wide variety of knowledge and information at the early creative state of the design process that is difficult to formulate in a computer system (Karl, 1997; Medland, 1986; Roy, Furuhashi, & Chawdhry, 1999). One of the important issues in applying evolutionary techniques to conceptual design is how to represent 3D structures in a way in which genetic algorithms can be used to support the process of generating and optimising innovative and imaginative geometric components and parts (Frazer, 1995; Graham, 1995). So this paper examines two stages of using genetic algorithms in design-how to encode designs as chromosome and how to translate certain manufacturing constraints into the evaluation functions which can be manipulated by GAs.

In this paper, an improved simple GA is used to demonstrate the concept that surface optimisation can be effectively supported within an existing CAD system. Work in this paper focuses on the most difficult aspect of design representation, the geometry or shape of design, based on the ergonomic and aesthetic consideration, and factors such as materials and costs are not considered at this stage. Based on the discussion and analysis of the existing shape representation methods, how to choose optimal characteristic parameters for shape design and how to define the combination of the geometry or shapes from simple to complex are presented in this paper. The methods presented in this paper have been tested in the early case studies on the simple ruled and non-ruled surface optimisation problems. The analysis of the initial research results and the discussion of the future work are also presented in this paper.

2. Shape representation and optimisation

Existing solid modeling systems provide facilities for creating, modifying and inspecting models of 3D solid objects, but there are a large number of different possible methods for representing such models in a computer. However, representation schemes may be divided into six general classes (Rooney & Steadman, 1997): Pure primitive instancing; Generalised sweeps; Spatial occupancy enumeration; Cellular decomposition; Constructive solid geometry (CSG) and Boundary representation. Among them, constructive solid geometry and boundary representation are widely used methods. In CSG, a part is defined by applying Boolean operations on primitive solid whereas B-rep defines a solid by its bounding surface. Currently, there is no single geometric representation that could be best for every design task. Therefore, almost all CAD systems are hybrid systems to use multiple representations to provide efficient tools for difficult design tasks.

Shape or surface optimisation is generally associated with structural optimisation where the objective is to minimise the mass with constraints imposed on stress, displacement, bucking and/or natural frequency. There are three distinct classes of shape optimisation problem (Richards & Sheppard, 1992): cross-sectional, geometrical and topological optimisation. Cross-sectional optimisation refers to the determination of specific geometric dimensions for a preselected design class such as the thickness of a shell or the diameter of a circular stress element. Geometric optimisation introduces additional design variables that allow for boundary movement. Due to its increased difficulty relative to cross-sectional optimisation, the geometrical changes are generally limited to a small region of the design such as around a fillet or hole. While geometric optimisation has been applied with some success, there is much work to be done in the area of geometric modeling, analysis and nonlinear programming methods before this class of shape optimisation can become an integral part of the design process. This research is more relative to geometric optimisation. Topological optimisation involves topological as well as geometrical cross-sectional modifications.

The application of evolutionary techniques in shape or surface optimisation is not new. The surface optimisation in car body and aircraft design have been well developed using evolutionary techniques. Earlier research is reported by Kaufmann (Kaufmann & Klass, 1988) with regards to car body design. They used an algorithm to define reflection lines on spline and family of planes on the surface to represent surface irregularities. Watabe (Watabe & Okino, 1993) have introduced a methodology to generate a suitable shape automatically using GA and by the application of Free-Form Deformation (FFD) technique, and the research aimed at generating optimal smooth surface from digitised point data using evolutionary algorithms.

Examples of using genetic algorithms as a part of complex design process to rebuild or optimise an airfoil shape are proposed by Periaux (Winter & Periaux, 1996).

3. Application development

The proposed project in this paper aims to investigate how genetic algorithms can be successfully applied in product design and to develop an evolutionary design system capable of evolving solid object designs which are easy to manufacture and can satisfy all the given constraints. When applying a genetic algorithm to any applications, four main elements must be considered (Bentley, 1999): Firstly, the phenotype must be specified, in other words the allowable solutions to the problem must be defined by the specification and enumeration of a search space. Secondly, the genotype or coding of the allowable solutions must be defined, which can be called representation. Thirdly, the type of genetic algorithms most suitable for the problem must be determined, in this part three operators: selection, crossover and mutation are considered. Fourthly, the fitness function must be created, in order to allow the evaluation of potential solutions of the problem for the GA. A simple flowchart of shape optimisation using genetic algorithm in our system is shown in Fig. 1. At the first step, the coding of a design for genetic algorithm must be carefully specified to allow effective and efficient genetic search to take place. The problem of how to encoded a design as a chromosome or string of genes or coded parameters is the problem of phenotype to genotype mapping (Bentley, 1996). However before any such mapping can be specified, an appropriate phenotype representation and genotype representation must be determined. The phenotype representation is how that phenotype is described, such as Bezier surface patches. The genotype is the total genetic coding of the phenotype and is directly manipulated by genetic algorithms. At the same time, the fitness function or objective function must be creative. Also selecting genetic algorithm parameters like mutation rate and population size is very different due to the many possible variations in the algorithm.

3.1. Boundary representation

Shape representation is an essential step for shape recognition and coding during the computer aided design process. During the product design process under the existing CAD system, like Mechanical desktop, AutoCAD, Microstation and Autodesk Inventor, sketch shape are chosen to represent the product profile and then extrusion, revolve or sweep is used to form the primitive solid. A shell solid model based on the extrusion from its sketch shape under Mechanical Desktop is shown in Fig. 2. A sketch shape of a remote controller is chosen as an example at this stage, which is very typical in design and manufacture since the shape consists of these basic elements with sub features such as channel slot, key holes, etc. The experiments which is being developed at present stage uses genetic algorithms to evolve and optimise the 2D and 3D shape of a remote controller

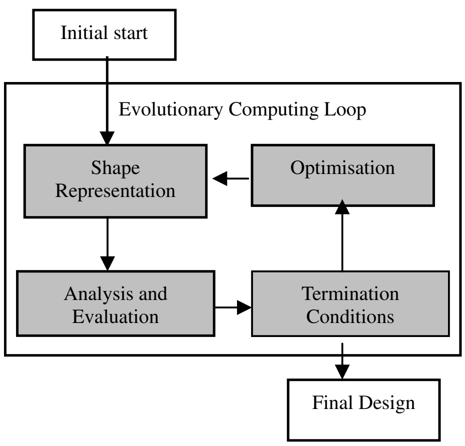

Fig. 1. A simple flowchart of shape optimisation using Genetic Algorithm.

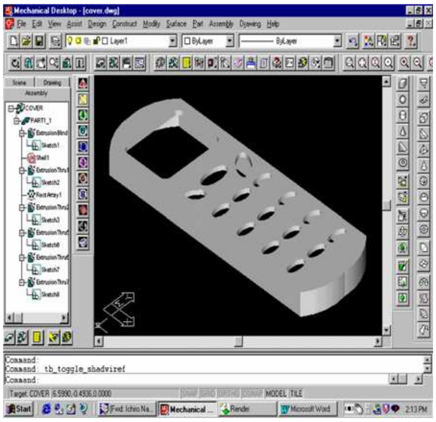

Fig. 2. A shell solid model in Mechanical Desktop.

and after these case studies more other basic shapes will be developed as the basis for evolving new complex structures. To simplify the problem, the boundary representation of the controller is treated as the sketch shape, the optimal shape depends on the boundary representation and the design variables selected to represent it. Both rectangle and B-spline are chosen as the boundary representation methods at the early stage. Case studies on both have been developed in this section. The initial results of studies based on this improved simple Genetic Algorithm are illustrated next.

For overall proportion the outline is considered as bounded as a rectangle, four parameters are used to its representation. There are two methods: using the centre point coordinates and length, width of the rectangle; or using point coordinates of the two points on the diagonal. So in this study, length, width and centre point coordinates of a rectangle are chosen as the characteristic parameters, or genes of the chromosome and suitable ratio of the length and width is defined as the evaluation condition during the evolutionary process. When two or three rectangles are considered, more variables are involved. In order to avoid the overlapping of rectangles and simplify the shape constraints in this case, we suppose the included two rectangles are adjacent without intersection and the third one is bounded to contain the other two.

Based on successful experiment on rectangle, further research of more shapes can be done through the change of the type and length of the chromosome. As to representation of a curved shape, the first and most natural one that is generally considered is a point by point representation. It is quite interesting since in engineering most of airfoils shapes are given in the form of table functions or fixed points (Watabe & Okino, 1993). Thus, the optimisation problem parameters could be those very points that define the shape. But many drawbacks have been found of this approach. In most existing CAD system, Bezier splines represented by the control points on it become the favored choice for the curved shape representation. B-splines are widely used for geometric modeling because of their local control and continuity properties. In B-spline approximation, it is

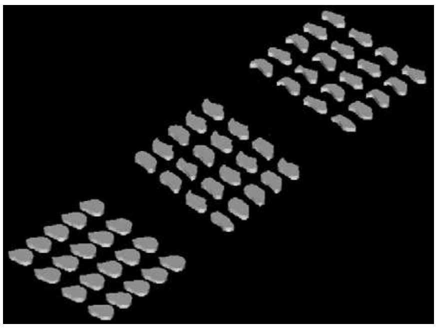

Fig. 3. Various results generated through changing the variable bounds in the shape representation.

Table 1
Structural attributes representation of design cases

Structural attribute	Case1	Case2	Case3	Case4	Case5	Case6	Case7
Shell volume (L × W × H) cm	15.5 × 5 × 2	16 × 4.5 × 1.5	14 × 5.5 × 1.5	15.5 × 3.5 × 1.5	12 × 5.5 × 1.5	13 × 5 × 1.5	12 × 4.5 × 1.5
Shell shape	L/w > 3 & C	L/W ∼ 4 & R.	L/W ∼ 3 & R.	L/W > 4 & R.	L/W ∼ 2 & R.	L/W ∼ 3 & C.	L/W ∼ 3 & C
Wall thickness	0.25	0.25	0.25	0.35	0.2	0.25	0.25
Keys no.	34	18	28	23	25	18	15
Key-shape types	3	1	1	1	3	4	4
Keys spacing	1.5	0.8	0.8	2	1	1.5	1
Keys distribute	Even	E. & Up	E. & Middle	E.& U.	Uneven & Righted	Uneven	E. & Down
Display	/	/	/	/	/	/	Yes

important to have an appropriate number of control points. Generally, the smooth and fair curves are preferred to product surface especially in manufacture. So in this case, curved line becomes the sole elements in this shape representation, and then the problem of optimisation of the surfaces can be simplified as the optimisation of curves. Curvature of the curve can be treated as the evaluation condition in GA. Curvature is not the only constraints but the only chosen item here. The change of the variable bounds will change the results dramatically. The testing results can be seen in Fig. 3.

3.2. Case-based evolutionary design system

In studies illustrated above, only one part of the product is considered at the time. While an assembled product consists of various components, and a component is further comprised of different features, such as tabs, holes, ribs, etc. For a design task, the designer just inputs some descriptions of the new design through the system interface. Then the system can find and choose some partially matching or relevant case designs from the data library, which will be treated as the initial (seed) population for the genetic algorithm. Each design is described using the same formalism: attribute value pairs that describe the product features. The attribute values that are used to represent a case together can be transformed as the genotype of design. Structure attributes are physical features of a design. In order to facilitate more flexible and efficient data retrieval, the attributes used to describe the case items have been categorised into four classes: context, function, behavior and structure.

Take the controller design as an example, after the designer input his/her abstract design requirements, seven existing controller designs are supposed to be selected. The Table 1 lists out all the structural attributes representation of seven proposed cases. Then during the evolving process, both natural selection using constrains defined by designer as evaluation function of GA and artificial selection decided by the designer are available, and the designers will decided when is the end of this evolutionary process. The genetic algorithm operates on individual product genotypes by randomly mating and mutating them, detecting any changes in the corresponding phenotypes, determining if any of the resulting phenotypes is good enough to represent a solution to the problem being solved, and repeating the process if not. Each phenotype is a potential solution to the design problem being solved. New potential solutions to the problem are generated through the transformations of known phenotypes. This work is still on going, case or phenotype representation and genotype representation and the manufacturing constraint evaluation transformation are still the research focus.

4. Conclusions and future work

The paper is about the early stage work of the research project – the application of evolutionary computation techniques in design for manufacturability. This research is concerned with the development of a generic computer framework in which genetic algorithms are used to support the process of automatically generating the geometric forms of products using primitive shells that are easy to manufacture (Sun, Frazer, & Tang, 1999). The surface optimisation within a CAD/CAM system is founded to be very convenient for the designers. From the above studies, an improved surface and optimisations are useful for industrial applications. In this paper, the representation methods are representative but very simplistic since the structure of data and the shape feature represented correspond directly and only simple genetic algorithms are used. In the further study, shapes are represented by a process that consist of sets of manufacturing instructions and the manufacturability of shape will be used as evaluation. Furthermore, more comprehensive evaluation of entire surface needs to be developed and the integration with AI techniques (Frazer, Tang, & Sun, 1999), which will help in generating the required surface shape, will also be considered. A graphic interface that can enable users/designers to update the optimisation parameters is under developing.

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