Mass-Customization in Design Using Evolutionary and Parametric Methods

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Abstract

This paper describes a project within the authors' ongoing research in the field of Generative Design. The work is based on the premise that computer-aided design (CAD) should evolve beyond its current limitation of one-way interaction, and become a dynamic, intelligent, multi-user environment that encourages creativity and actively supports the evolution of individual, mass-customized designs which exhibit common features.

The authors describe this idea by illustrating the implementation of a research project, which explores the notions of mass-customization in design by using evolutionary and parametric methods to generate families of simple objects, in our case a door handle. The project examines related approaches using both complex CAD/CAM packages (CADDS, CATIA) and a proprietary software tool for evolutionary design. The paper first gives a short historical and philosophical background to the work, then describes the technical and algorithmic requirements, and concludes with the implementations of the project.

1 Introduction

The idea of Mass-Customisation is not a new one. Shipbuilding is a good example of individual designs being borne out of common lore of common, effective design elements. This lore would manifest itself in 'ship classes', or families of related designs, in which the basic root scheme reflected the general function of the ship. Brigantine, Cruiser, Battleship, etc. each define a 'class' of discernible designs, but the fascination lies in the way how the different designs find different functional advantages, while remaining within their respective classes. In fact, each battleship design, even within a closely related class, was unique, reflecting the newest military knowledge or specific functional modifications. However, to integrate each of these unique features meant altering, or *customizing*, the root design. It is of particular interest, then, to observe the dissipation of acquired knowledge in time through the *evolution* of successive designs.

The idea of being able to manufacture a family of objects or products which have a common foundation in their design, structure and functionality, but are each unique in their individual manifestation, has long fascinated architects, designers and engineers. The basic understanding of a design family has always been tied to the notion that within a family variation is possible, indeed desirable and often necessary. This understanding is always inextricably linked to some form of implicit or explicit collection of 'rules' or 'guidelines' that decree the nature of the produced object. It is the flexibility of operation within the constraints, or 'parameters', of these rules that produces a 'family' of objects, and the voluntary or involuntary breaking of these boundaries which either broadens the range of a family or gives rise to a new one.

Elements of flexible manufacturing at both the design level and the assembly level have been increasingly evident in the last thirty years. These are driven by economic considerations. A good example is the aircraft industry. After the Second World War, manufacturers could no longer afford to offer a different aircraft for a different requirement. The speed at which markets developed meant that it was faster and cheaper to derive *variants* of an existing design, *modified* to fulfill new needs (e.g.: Boeing 367-80 ® Boeing 707 passenger jet, KC-135 tanker, E-3A AWACS sentry). This has become even more evident in the latest designs, in which not individual models, but whole *families* of aircraft are launched. These consist of an array of *related* models, which share parts, manufacturing, and flight-training *commonality* while containing enough 'room' for growth within the *root* design (e.g. Boeing 777 family) (Sabbagh 1996). This is also evident in the automotive industry, where individual users (customers) are able to specify a wide range of components. In the end, each *instantiation* of, for example, the Volkswagen Golf, is unique in its combination of chosen components, from basic inexpensive model to muscled sports car, while remaining a true Golf.

The emergence of new manufacturing methods, from CNC machining and CAM to flexible molding and robotic production lines, means that the rapid diffusion and development of Information Technology has much more to offer to the process of design and manufacturing than just computerized control of factories and assembly lines. The ability to combine an understanding of creative rule-based design systems with flexible methods of production will enable a new form of manufacturing which is freed from predefined geometric constraints and which efficiently translates rules which govern a design into tangible form. By varying these rules, we are able to achieve a broad family of interrelated, industrially manufactured, individually unique products.

In our research, we have concentrated on a simple design object – a door handle – through which to explore the ideas set out in this paper.

2 Mass-Customization Through Parametric Design

Basic Mass-Customization is achieved by modifying the definition parameters within a design framework. A basic design is established in its morphology, which does not change during the customization process. In this sense, there is no one 'root design', but rather many variations of it, each of which is instantiated by its individual, unique parametric values. In the case of our door handle, a basic design can consist of length, thickness, width and so on, as many as are required to define a handle. Obviously, the design can be more *fine grain* in its definition by employing a larger set of parameters. Once established, the parameter set that defines the design is not changed.

2.1 Parametric Design Systems

The employment of a powerful CAD/CAM software package can provide a strong foundation to the project. In our research we have been employing CADDS, an extremely sophisticated parametric solid modeler, and more recently CATIA, which has its origin in the aviation industry where Dassault Systèmes originally developed it for the design of jet fighters. Both systems have crossed over from engineering to within the areas of industrial design and architecture. CADDS has been successfully used on various design projects (Burry 1996; Goulthorpe and Burry 2000) while CATIA has famously proven its mettle on Frank Gehry's Guggenheim Museum in Bilbao.

2.2 Parametric Mass-Customisation using CADDS

Like many powerful CAD packages, CADDS can interact with external databases and generate geometry from numeric data. In this case, a definition of a door handle was built up within CADDS, and driven by parameters (variables) in Microsoft's Excel spreadsheet software. The Excel document contains the data necessary to describe curvature, size, etc. of a set of complex 3D surface geometries, which are connected to form a single solid volume of the handle. The data is transferred to CADDS which generates the solid.

The solid's structure is defined in CADDS in terms of the curves which describe it and how these are interconnected. Parametric control, however, also implies value constraints of minima and maxima within which a particular parameter must lie in order to define a *valid* shape – in our case, 'valid' means a viable door handle which has correct proportions in terms of leverage of the handle to the spindle, etc. Thus, a user can 'design' his or her door handle by manipulating the individual parameters within Excel to produce various *topologically identical* yet *morphologically diverse* objects. The handle was then manufactured using Rapid Prototyping machines such as Actua.

In short, both the morphological structure of the design and the definition-space of all permissible parametric values within the design describe a "design family"; the role of the designer undergoes a paradigm shift from *master craftsman* of an individual design to *master programmer* of a design system.

3 Mass-Customisation Through Evolutionary Design

Evolutionary Design describes methods that use rule-based evolutionary algorithms to generate a common family of individual designs. These can be optimized according to particular criteria, or can form a wide variety of hierarchically related design solutions, while supporting our design intuition. Detailed explanation of this innovative form of design computing is beyond the scope of this paper and can be found elsewhere (Frazer 1995).

In the case of our door handle project, we were keen to transcend the limitations of a purely parametric system such as the one described above, and broaden our solution range within the design's scope.

3.1 Encoding Methods

In order to operate on the design numerically through evolutionary tools, our door-handle must be able to be 'digitized' as a three-dimensional object. There are different understandings of how a design should be encoded in terms of the description of its form and geometry. This can be described as **Step 1** in the overall process. Methods include:

(1) Parameters are assigned to definition curves that define spline-surface, which make up the handle object;
(2) The handle object is treated as a topological surface, which is defined by a cloud of surface points.

Method (1) can be explored through the CADDS or CATIA systems, while method (2) makes use of a proprietary software tool developed by the author.

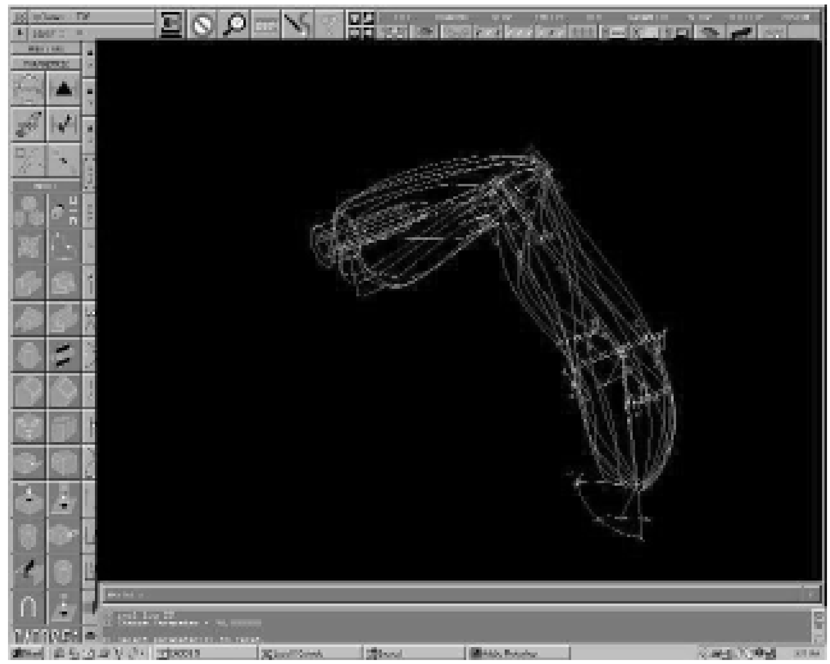


Figure 1. CADDS Modeling System.

3.2 Design Criteria

Door handle manufacturers such as FSB have assimilated the tactile qualities of 'grip' and 'feel' have been assimilated into a '*lore*' of door-handle design. Concentration on the tactile rather than visual aspect challenged us to transcend our architect's intuition and engage the design in a more critical way. In order to evaluate these qualities within an evolutionary mechanism, the participation of a body of users is necessary to determine in which design they are emerging in a desirable way.

3.3 Generation Parameters

A generative design tool uses a Genetic Algorithm to extract information which makes up a successful design by breeding families of related forms and testing them against a selective environment. In our project, the parameters driving the generative process are described as follows:

- Establish evaluation criteria: Grip
- Establish scoring (value) system: Feel
- Determine data type: Handle Geometry
- Encode data: Geometric Description

3.4 Generative Cycle

The cyclical process of encoding, generating and evaluating outputted forms through a generative system is described below. The steps are:

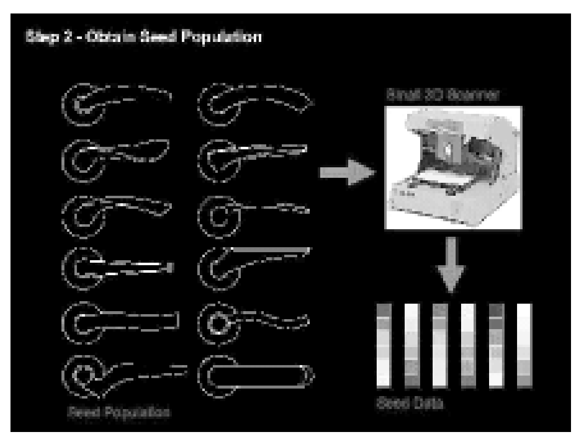


Figure 2. Scanning a seed population.

Step 2 – Obtain Seed Population: The root of any generative process requires a seed – an initial set of data which is then modified. Given FSB's acquired knowledge of door-handle design and fabrication, a selection of their best-known pieces in production was used as a starting population. The designs are codified by using a 3D scanning system (3D digitizer) or by configuring existing CAD data obtained from FSB.

Step 3 – GA Sequence: The core step of the generative process. The GA generates a new population of form data by generating a child population using breeding, crossing over and mutation of the initial data (Figure 3).

Step 4 – Evaluate Population: The generated data is translated into tangible form through the use of CNC/CM or rapid prototyping machinery. The manufactured door-handles are tested in a real environment – in this case, a collection of ‘demo’ users consisting of students, colleagues and outsiders. Each of these users is required to give a verdict on various tactile and possibly visual aspects of each handle, on a scale of 1 – 10. These values are compounded to a ‘score value’. These values are used as *fitness* value for the GA in the next generation. A repetition of this sequence soon generates a collection of door handles, which reflects the user group’s preferences within the design (Figure 4).

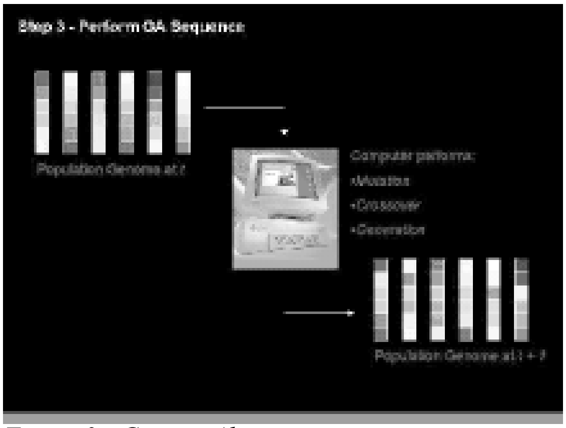


Figure 3. Genetic Algorithm generative sequence.

3.5 Evolutionary Parametric Design Using CATIA

CATIA is a modeling and construction tool that combines a suite of “workbenches” for lines and surfaces to create complex solid models. Like many solid modelers, CATIA employs a tree-based nested representation for the models being created, in which the design is broken down into subtree components, and each leaf describes a design component, such as an individual shape, and outline ‘sketch’, a Boolean operation, and so on. In this sense, CATIA enforces a clear, hierarchical *grammar* of the design, in which certain components may only be placed in certain sequence of the design-tree, in order to produce a coherent, logical design. Figure 5 shows a screenshot of CATIA V.5; the tree-structure is visible on the left of the image.

Thus, CATIA defines designs by two criteria:

(1) The design-tree grammar which establishes the morphology of the design;
(2) The actual parametric definition data within the design-tree elements.

For parametric control, we establish a basic design within CATIA with a set of user-definable parameters. Through the Knowledge workbenches, we are able to program a set of parametric constraints that govern the range values of the parameters. These values may be explicit dimensions, but can also be implicit functions such as ratios, volume, or, through the integration of analytical tools within CATIA, structural performance values of a design instance, based on the application of a certain material.

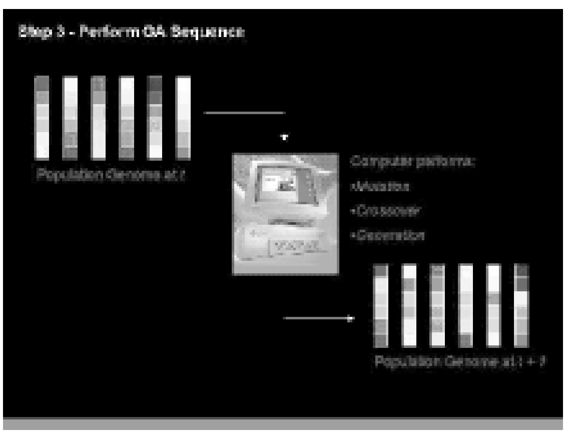


Figure 4. Evaluation of population.

The parametric design capabilities of CATIA described above are strongly complemented by a set of analytical tools, which include options for controlling parametric designs through rules and checking, plus the ability to elaborate design solutions by using rule-based control capabilities. The latter form a workbench known as Knowledge AI / Generative Design, which can be controlled through Visual Basic scripts (and in future, C++ plug-ins), and data processing by means of external databases or spreadsheets such as Excel in similar ways to CADDS. In particular, these features made CATIA a more versatile platform on which to develop the project further.

As described above, the system’s objective is to generate a family of related door handles, which can be evolved into increasingly ‘tacitly desirable’ designs based on the population

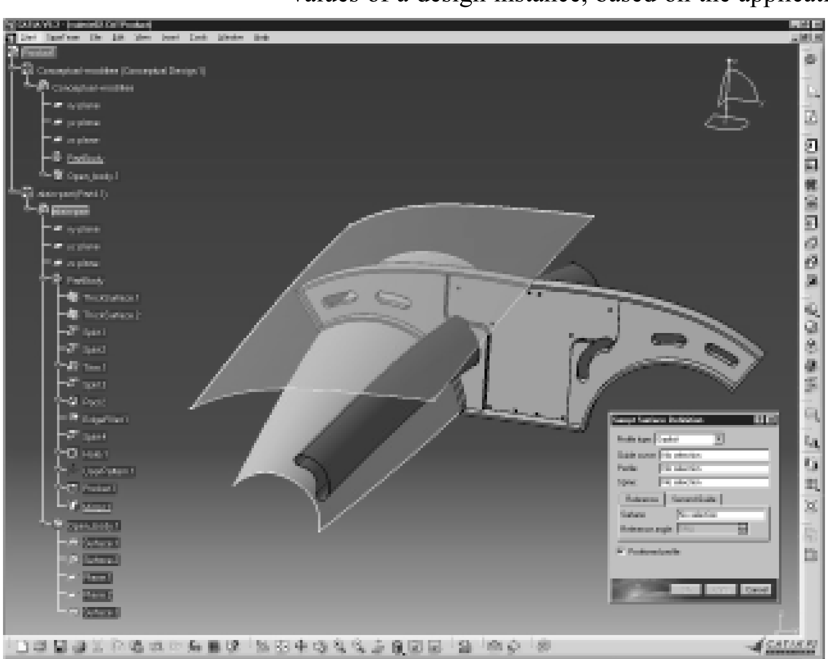


Figure 5. CATIA Modeling System.

of test-users' feedback. Given CATIA's *grammar* tree-structure approach, this can be driven in two ways ('grammar' here does not refer to the work of George Stiny et al., although an association or application thereof would be of interest):

(1) Using a basic root-design framework, evolve parameter sets which define the door handles;
(2) Evolve new versions of the design-tree itself, to produce new *grammar* configurations for defining the designs.

The latter, in particular, poses a great challenge as the logic behind the modeling system's description of designs must be catered for. In a sense, only grammatically correct designs are permissible, thus making grammatical correctness a further factor in evolution.

3.6 Origine – A Generative Design Tool for Form Exploration

While CATIA is extremely powerful, its dependence on system-defined entities (objects) and tree-structure definition limits the design's ability to transcend limitations of structure in dramatic or geometrically unforeseen ways. Therefore, a radically different approach to the storage, representation and construction of design data had to be taken.

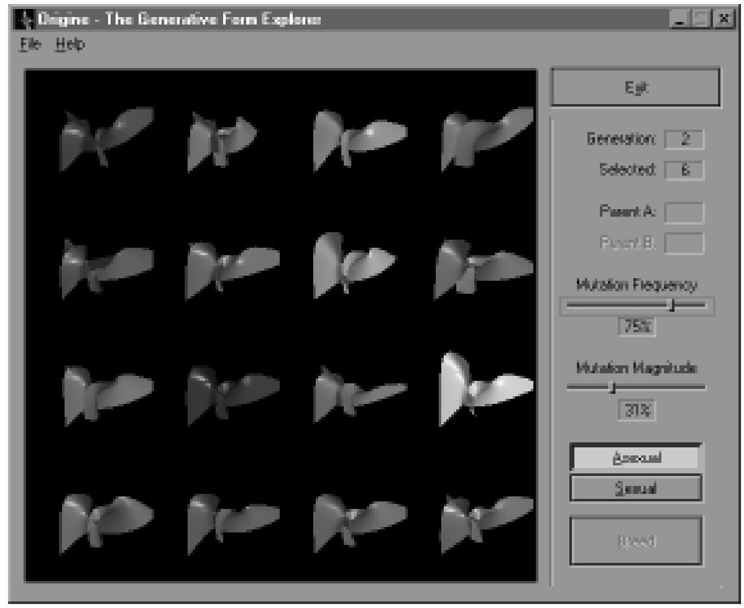


Figure 6. Origine – The Generative Form Explorer.

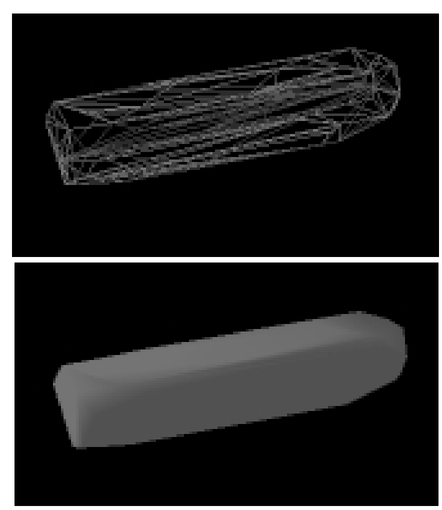
In our case, it consisted in understanding the design as a single complex volume, which was determined by a given set of points in space. Thus, the door handle object is treated as a *topological* surface, which is defined by a *point-cloud* of surface points. The system evolves the spatial location of individual points, and then places a *skin* over the point-cloud to create a volume. Figure 6 shows the tool we developed, named Origine, showing a family of related shapes during an evolution sequence.

Geometrically, the system employs a Convex Hull algorithm (O'Rourke 1998) to create a surface volume from the given set of points (Figures 7, 8). This presents obvious limitations given that this algorithm does not generate complex non-convex volumes. We hope to improve on this in future by implementing more advantageous algorithms based on spatial proximity and the spatial relations of points, such as the Hoppe or Crust algorithms.

4 Conclusions

The task of integrating Parametric and Evolutionary Design with Mass-Customization efficiently requires considerable computing expertise, time as well as a commitment to determining feasible form generation and production methods. The discourse on how to best encode a tactile, three-dimensional form and manipulate the resulting data is equally if not more of philosophical nature than technical. Furthermore, geometric and parametric manipulation methods have a fundamental influence on the nature of the resulting forms. Maintaining full flexibility becomes a technically demanding issue, and increases computational development time greatly. In our case, we determined a simple, if effective, generation method in order to achieve tangible results within the project's time frame.

At the time of writing of this paper, the project is still ongoing, and it is hoped that the final results of the work described will be published at a later date. Additional work is required both to the parametric user interfaces and the geometric description of complex 3D forms within Origine. However, feedback from colleagues and students is very promising, in particular with regards to the fundamental idea of using sophisticated computational methods to support a simple goal: to sustain intuition in creating individual, customized objects using automated manufacturing technologies.



Figures 7,8. Convex Hull for generating closed volumes.

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