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A practical generative design method☆

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ABSTRACT

A generative CAD based design exploration method is proposed. It is suitable for complex multi-criteria design problems where important performance criteria are uncomputable. The method is based on building a genotype of the design within a history based parametric CAD system and then, varying its parameters randomly within pre-defined limits to generate a set of distinctive designs. The generated designs are then filtered through various constraint envelopes representing geometric viability, manufacturability, cost and other performance related constraints, thus reducing the vast design space into a smaller viable design space represented by a set of distinctive designs. These designs may then be further developed by the designer. The proposed generative design method makes minimal imposition on the designer's work process and maintains both flexibility and fluidity that is required for creative design exploration. Its ability to work seamlessly with current CAD based design practices from early conceptual to detailed design is demonstrated. The design philosophy behind this generative method and the key steps involved in its implementation are presented with examples.

1. Introduction

The design of complex artifacts such as buildings or products requires designers to explore multiple alternatives. Currently, most of this exploration happens at the conceptual stage of design with the aid of pencil and paper. CAD is rarely used at this stage of the design process. In its current form, it is a tool of implementation and increasingly a tool of analysis that is most useful at the later stages of the design process. But at this stage, all the important commitments have already been made and significant improvements cannot be made. Can CAD be used in the early stages of design to help designers explore design possibilities?

Generative design is largely about this. Though little known amongst engineers, generative design is now seen to be at the cusp of going main stream in architecture. Leading global architectural practices have embraced it [1]. It is now taught in most architecture programs, especially at Masters Level. Generative design is now enabling architects to explore thousands of design possibilities within CAD environments. Despite the lack of a clear definition and formal methods for its implementation, its significance is now widely recognized by architects and design researchers [2]. Proposed in this paper is a particular implementation of generative design on top of history based parametric CAD systems.

The main objective of the proposed method is to assist human designers to explore a larger range of design possibilities than what is manually possible for the class of problems outlined in Section 1.1. It is a designer driven design process. It is structured to stimulate the designer's creativity by guiding the designer through viable design spaces constrained by performance criteria. The proposition is also practical rather than theoretical in that, it is designed with practical considerations in mind and is implemented with minimum overheads on existing design processes.

1.1. Types of design problems that are suitable for generative design

Design problems may be broadly categorized as routine and creative design problems. While advances in design automation are gradually replacing the first category of design problems with fully or semi-automated design procedures, the second category of '*creative design problems*' remains elusive. This is mainly due to the inherent complexities that are attributed to the multiplicity of design objectives, the contradictory and unquantifiable nature of some of these objectives, the lack of complete domain knowledge and the vastness of design space. The combination of these issues makes it virtually impossible to automate or procedurize conceptual design—which remains securely in the hands of expert designers, beyond the reach of computational processes.

The unquantifiable nature of key design parameters introduces a particular problem in the design process—subjectivity. Aesthetic issues are a prime example of this. It differs from designer to designer. The design outcome will therefore depend on subjective choices made by the designer, reflecting the designer's intensions and taste. The proposed method is able to support this category of design activity as it relies on the designer's subjective evaluation in driving the design direction. Architecture, product design, game design and animation design clearly belong to this category.

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The proposed method is not suitable for most engineering problems where most of the key performances are computable, or for design problems where it is possible to map between problem space and solution space. Genetic Algorithms (discussed in Section 2.1) is more suitable for this class of design problems.

1.2. Stages of application

Many types of automated design exploration methods are available for late stage design. In this stage, important aspects of the designs are already established and exploration is carried out within narrow bounds to improve specific performances. This is referred to as design optimization. Generative design on the other hand, can operate at the conceptual stages of design, where the design is still under formulation. The ability to explore design variations at the early stages of design can produce far more beneficial results, than optimizing it within narrow means at the final stages of design. Most CAD packages now support analytical and optimization tools that are used extensively for late stage design. While the proposed method can be used for design optimization, its primary value is in its use in early stage design where CAD is currently rarely used. It is mostly useful at a stage where the design intentions have been clarified and where basic form has emerged, marking the last stage that is prior to the use of CAD, where design possibilities in terms of geometric variations are still under consideration.

Despite many methods proposed by researchers for the use of CAD in early stage conceptual design, CAD is still mostly used in the final stages of design. Decades of research and proposals made by academic researchers for structured conceptual design processes have not met with success [3] in terms of industry adaptation. There are many conceptual and implementational challenges that prevent the use of CAD in early stage design. These issues are discussed next.

1.3. Difficulties in supporting conceptual design in CAD

There is a noticeable tendency amongst most engineering design researchers in viewing creative design as a somewhat inefficient and haphazard process. Many methods have been proposed to eliminate this haphazardness by imposing a '*rational*' structure to it. These efforts remain largely unsuccessful [4,3] primarily because formalized processes "*impede the thinking effort by an invasive framework*" [4]. Freedom to create, modify and discard seem to be of paramount importance in design. Guidon explains why top-down breakdown is problematic for conceptual design [5] and shows structured approached to be fundamentally unsuitable for conceptual design. The haphazardness noticed by many researchers is claimed by Guidon to be "*the natural consequences of the ill-structuredness of problems in the early stages of design*" [5]. Perhaps, this haphazardness should be viewed as a positive indications of a creative process; where new learning and understanding of the problem and solution space emerging out of the exploration process, is altering the course of search. The lack of it, on the other hand may indicate that both the problem space, solution space and the relationship between the two is well understood, effectively disqualifying it as a creative design problem.

In addition to the difficulties in automating conceptual design, there are other reasons why CAD remains unsuitable for conceptual design.

1. At the conceptual stage, vague concepts and forms have to be considered and represented. CAD in its current form is unsuitable for representing vague concepts.
2. Designs are developed based on reactions to previously generated concepts. CAD does not provide the creative stimulation that designers derive from the process such as hand sketching [6].
3. Design is an iterative process of searching the design problem space as well as the solution space [7]. Designs and solutions co-evolve [8], during the design process.
4. Many possibilities are considered and most of them are discarded at the early stages of design. In this context, designers need to represent a wide range of concepts efficiently. They are, therefore reluctant to invest the additional effort required to represent such concepts in CAD.

There are also other cognitive, epistemological, methodological and computational issues that prevent the use of CAD in conceptual stages of design [3].

1.3.1. The centrality of emergence

Recent research [9,10] in design processes has identified emergence as the key driver of early stage design exploration. In creative design processes, the direction of design exploration is dependent on and is directed by the result of previous explorations—which is the key characteristic of emergence. Creative design is based on reflection, reaction, critique and inspiration being drawn from the process itself. Design exploration is very much dependant on the designer's internal representation and understanding of the design problem and potential solutions to it. Oxman defines '*conceptual emergence*' as a search for '*The fit between visual images stored in the designer's mental image memory and the way the designer maps these images into a formal–configurational Schema*' [10]. She has experimentally verified the existence of high level cognitive structures such as visual schemas and prototypes that help designers think visually. Conceptual design therefore relies heavily on the ability of the designer to identify emergent values. The designer relies on experience and understanding to identify emergent solutions to the design problem despite the vague and unresolved state of early stage design solutions. In other words, the designer's understanding is used to identify promising prospects within the vast expanse of search space. The designer's creative imagination is relied upon here, to complete the missing aspects of the incomplete propositions.

1.3.2. The role of sketching

Sketching is central to most creative design processes. It seems to trigger creative thought processes in exploring emergent concepts [11]. The main use of sketching during conceptual design has been found to be the stimulation of the designer's creative imagination. "*the designer does not represent images held in the mind, as is often the case in lay sketching, but creates visual displays which help induce images of the entity that is being designed*" [6, 12]. "*Drawn shapes play a critical role not only in representing a design concept but also in allowing the designer to re-interpret them to develop new ideas. In the conceptual and creative aspects of design, this re-interpretation of what has been drawn appears to play an important role*" [13]. Sketching seems to play a dual role in stimulating the creative process with emergent concepts while helping the designer refine the generated concepts. Production of design ideas depend heavily on this interaction with conceptual sketches [12]. Sketching also facilitates what is now known as "*visual reasoning*". CAD based conceptual design is deprived of these qualities [13].

1.3.3. The chaotic nature of design processes

Conceptual design development is a process where many threads of possibilities are developed in parallel. These concepts are then abandoned or re-combined until a satisfactory scheme emerges out of the exercise. Often, this exploration is directed by the outcomes of previous explorations [12]. One of the key challenges in the generative design process is to facilitate the fluidity of this chaotic process. Sketching seems to be the preferred