eifForm: A Generative Structural Design System

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INTRODUCTION

As architecture becomes more technically advanced, there is a growing interest in the use of computer aided synthesis tools to create new geometry and corresponding appropriate structure. The design of free-form structures is challenging since the artistic expressions often do not blend easily with traditional structural systems. Current software provides the means to express and manipulate complex geometry, especially three-dimensional forms, and analyze these forms to assess complex behaviors. While such software has expanded the possibilities for design expression as well as increased the ease of considering many alternatives, these tools are only effective for exploring parameterized concepts often conceived irrespective of behavioral implications.

A recent milestone in structural engineering is the realization of Frank Gehry's design for the Guggenheim museum in Bilbao, Spain. Gehry created a unique form comprised of compound curvilinear surfaces. The shape of the surfaces produced a major challenge for structural engineers to design a framed structure that corresponded to this shape. This challenge was met by using computer tools to digitize cardboard models from which straight-framed sections were created (Iyengar et al, 1998). From design conception to construction, form and structural function were never explicitly considered simultaneously. While the form is unique on the exterior, the structure consists of standard framing that has been angled. However, a more appropriate structure may exist that responds to these new intriguing surfaces.

The focus of this paper is to describe recent development and use of a synthesis system that approaches structural design in a non-conventional way to generate innovative designs. Rather than automating routine structural design tasks, this work aims to provide a means of expanding the current capabilities of structural designers and architects. As free-form structures lie outside the traditional language of structural design it is generally difficult to comprehend their functional attributes. For this reason, generative design of performance driven free-form structures is an area where computational tools have a real opportunity to enhance current design practice.

COMPUTATIONAL APPROACHES TO STRUCTURAL DESIGN

Structural design involves the conception of forms to meet a mixture of behavioral, economic, usage and aesthetic goals. The vast number of possibilities as well as complex tradeoffs among design goals make the task difficult. Computational synthesis approaches that provide assistance beyond current CAD systems have focused on spatial design of structures or configuration for behavioral performance, but not commonly both. For the creation of complex geometric patterns, often used for space frames, structural morphology methods have been developed, for example Formian (Nooshin et al., 1993), based on Formex algebra, and CORELLI (Huyber, 1993), based on polyhedra. Both approaches use an initial shape and rules for geometric transformation to produce uniform patterns that can later be analyzed.

Using explicit domain knowledge in the rules, shape grammars have been used for the generation of architectural layouts such as Palladian villas (Stiny and Mitchell, 1978) and Queen Anne houses (Flemming, 1986). A shape grammar defines a set of allowable shape transformations that in turn can be used to generate a language of spatial designs (Stiny, 1980). The advantage of using a shape grammar as a production system is that the design language defined by the grammar contains both known designs, from which the grammar was derived, and new designs in the same style. Since structural design is both a spatial configuration problem as well as a functional problem, applying a shape grammar to structural design requires a mapping between form and function. Artifact, or functional, grammars have been created to encode functional knowledge within the grammar rules to produce functionally feasible forms (Mitchell, 1994; Fenves and Baker, 1987). Using these approaches, structural form results from functional reasoning.

Increasing the focus of synthesis on structural behavior, structural optimization relies on the assumption that the "best" structural form results solely from functional efficiency. Generally without regard to geometric attributes, optimization methods seek the most efficient form of discrete structures (Bendsoe et al., 1994) or continuous material structures (Chirehdast et al. 1994). While these methods have been successfully applied in the aerospace and automotive industries, for civil structures, structural efficiency is often only one of many design goals. Additionally, current discrete methods rely on being able to formulate the design scenario in terms of support points and point loads posing difficulties for modeling surface based environmental loads. Optimization techniques have however been used successfully for finding efficient forms for shell structures (Robbin, 1996).

STRUCTURAL SHAPE ANNEALING

Shape annealing is a generate-and-test type method that combines a shape grammar (Stiny, 1980) with simulated annealing (Kirkpatrick, 1983) to produce optimally directed designs (Cagan and Mitchell, 1983). Applied to structures (Reddy and Cagan, 1995), the method provides a means of performance driven exploration of structural forms. Design performance is modeled in terms of many competing factors including structural efficiency, economy, usage and aesthetics (Shea, 1997). The result is the generation of complex geometric forms that are not only functionally feasible but also reflect other performance metrics. Both conventional and radical forms can be generated with this method, where radical forms do not contradict behavioral principles but rather follow them. The range of structural classes that could be considered and the adaptability of the structural purpose model create a method suited to exploring rational free-form structures.

For discrete structures, the shape grammar represents the relation between form and function through the specification of allowable shape transformations. Implemented structural grammars include planar trusses, shown in Figure 1, and an extension to single-layer space frames, applied in Figure 4. One way of employing the rules is to hand select and apply them to generate known designs for the modeled structural class; for example the generation of a Warren truss (Figure 1). But, when transformations are applied iteratively in random order at random locations in the design, the set of transformations define infinite languages of structural shapes.

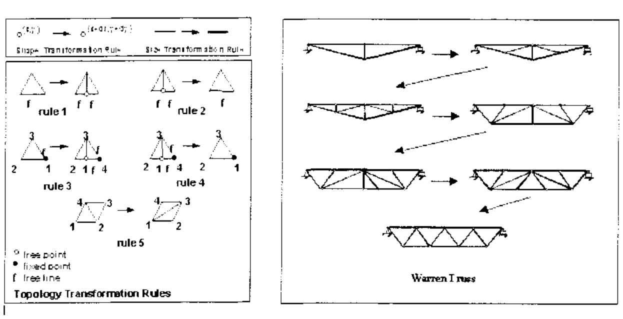

Fig. 1. Planar truss grammar (Shea and Cagan, 1999) and generation of a standard truss design

The process of structural shape annealing is not modeled after a conventional design process. Rather than using a predefined sequence for applying transformations, the method applies near randomly selected rules in near randomly selected locations. This allows innovative designs to evolve from a series of design transformations in response to the modeled design intent. To focus the search, rather than just randomly exploring the design space, the method uses control techniques for rule selection, rule application as well as design selection. The required input, which will be discussed further in Section 4, and basic method steps are shown in Figure 2. The design task is formulated in terms of an initial design, which models the support points and loading, specifications, constraints and design objectives, which combine to define a performance metric. Given an initial design, it is first analyzed for structural behavior using the finite element method. Based on the analysis and the defined design objectives, a performance metric is calculated. A grammar rule is then selected based on past performance using a dynamic rule selection technique. The selected rule is matched to each shape in the current design where it applies and a random match among these is selected. The rule is then applied at the selected location thus transforming the initial design to a new design that is then analyzed and its cost is calculated. A decision is then made based on the relative performance of the two designs as to whether the new design is accepted or rejected. While a better design is always accepted there is a possibility that a worse design may be accepted based on a probability function. Continuing the process, a rule from the shape grammar is applied to the selected structure creating a new design and the process continues iteratively until either a fixed number of iterations has been reached or transformations no longer lead to significant design improvement.

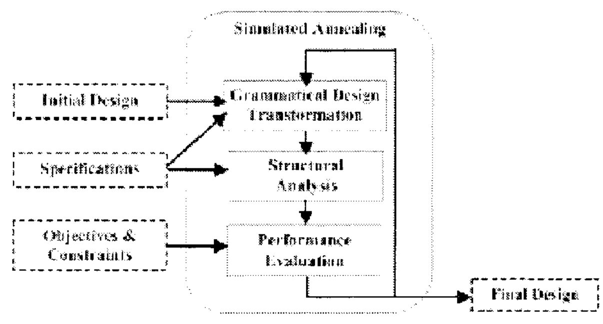

Fig. 2. Overview of structural shape annealing

To illustrate the method a standard situation of designing planar roof trusses is shown (Figure 3). Given an initial design with two fixed supports and three load points, all colinear, a lightweight structure was generated and is shown in Figure 3 (left). However, since this structure proved too deep due to regulations, a constraint was placed on depth producing the heavier but more conventional structure shown in Figure 3 (right). Note that the addition of only one constraint resulted in the generation of the bowed Warren truss. Additional studies of limiting the sizing to standard cross-sections, increasing the number of load points and considering asymmetric designs can be found in Shea and Cagan (1999). It was found that since the performance of these structures was measured purely in terms of structural mass, symmetric designs would only occur when symmetry was clearly superior or constrained.

Fig. 3. Novel and conventional designs generated for a roof truss scenario (Shea and Cagan, 1999)

USING EIFFORM

eifForm is an experimental system based on the structural shape annealing method described previously. Since eifForm supports the design of innovative structures by searching a constrained space of alternative forms, structural design must be formulated as a search problem. Effective use of the system involves expression of design intent through geometric, structural behavior and search models as well as visualization and interpretation of generated designs towards realization. The following descriptions illustrate ways in which the tool has been engaged to explore architectural applications as well as issues related to this process that have come to light through experimentation.

As a generative tool, the system lends itself to a complete digital design process starting from site selection from a digital topography map through design generation and selection to using CAD/CAM interfaces for making prototypes. This process requires user interaction on all levels as well as iterative design generation to explore the space of possibilities for a design scenario. The end result can be structures that would not have been conceived otherwise and further understanding of relations between performance and free-form structures. Similar to using any computational system involving some level of automation, e.g. analysis and rendering algorithms, proper modeling will lead to more effective use.

DESIGN INTENT

Design intent is formulated in terms of both geometric and behavior models of the design task as well as through search parameters. First, a geometric model is defined as relations among points, lines, shapes and surface(s), if working in 3D, to provide a starting point for the algorithm (Figure 4). While the specification of points and lines is always necessary so that the structure can be analyzed, the specification of shapes identifies allowable regions of shape transformation. The starting points of the geometry can also be specified by outlining a polygonal boundary of support locations, perhaps chosen from a digital topography map. In this case, lines, shapes and surfaces are not specified allowing the algorithm to invent a free-form structure. But, the designer has less means of control and the outcome may not be as suited to the design intent. Varying surface equations, for instance the height of the dome in Figure 4, is also a means of design transformation.

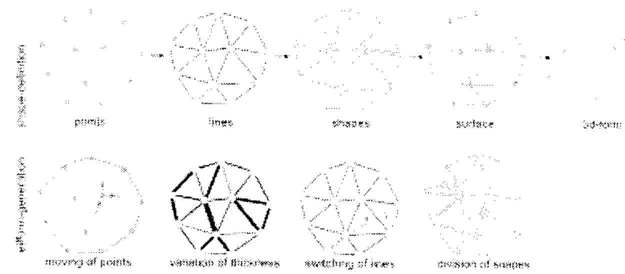

Fig 4. Geometric models and design transformation (adapted from DSoF, Fall 1999)

Design intent is also modeled through specification of structural parameters that interpret the geometric model as a structural system. Currently, spatial forms are always interpreted as truss structures. Parameters similar to those involved in a conventional truss design task, such as material properties and member shape (bar, tube, box, etc) as well as acceptable limits on stress, buckling and displacement are also defined. A performance model is specified, as noted previously, as a function of both geometric and behavioral models. The overall performance of a design is calculated as a weighted summation of defined metrics where the weights reflect tradeoffs among objectives (Shea and Cagan, 1997). For the generation of structural solutions, structural mass is always one of the performance goals. For further details on modeling can be found in Shea (1999).

Modeling design intent is not always a simple task. Exploration of the system capabilities resulted in studies of applications involving difficult topographic design scenarios, complex programs and asymmetric modular structures. In an initial study, eifForm was used to generate designs for enclosing a space defined by a polygonal non-planar boundary created by points taken from a digital map. A complex program was also explored that involved generating a structure to support a system of non-planar platforms. For this scenario, it was found that the system was more effective when the program was decomposed into smaller problems that could be designed separately while maintaining common connections. Further constraints placed on design transformations can also be used to model design intent (Shea and Cagan, 1999b).

DESIGN GENERATION

While specifying structural parameters is standard to exploring structural design tasks, formulating the problem as search may be new. Within the constraints of the previous model, generation is controlled through selection of rule sets.

definition of key search parameters, and specification of design objectives. Search parameters include process attributes such as how many new members can be generated and how long the process should run. These are functions of problem size as well as computational resources. While a full understanding of the process is not necessary, insight about how to manipulate the search parameters is beneficial. The system can initially be used to generate conceptual stimuli leading to further search refinement to generate structural solutions.

For example, eifForm was used to explore the design of asymmetric modular structures (Figure 5). Since the structures generated often contain intricate geometry and complex joints, innovative structural modules combine the aesthetic advantage of an asymmetric structure with the practicality of a modular system. An interwoven surface was generated for one module by a system called MoSS (Testa et al., 2000), which was explored in parallel with eifForm, suggesting the possibility of generating structural systems where there is no longer a clear division between surface and structure. This example also illustrates the potential impact advanced CAD tools can have on facilitating the design of creative structural solutions. Further investigation is underway to transform this concept into a structural system.

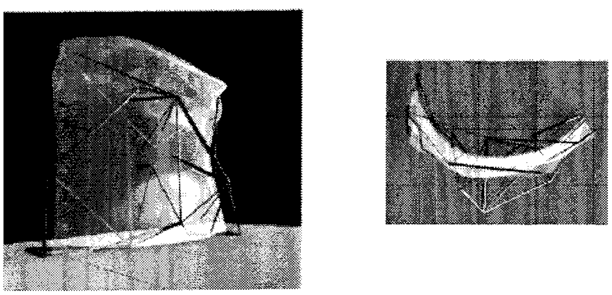

Fig. 5. Conceptual designs for modular systems (Yeung, DSoF)

Following from the illustration of design intent models in Figure 4, a number of free-form designs were generated as structural solutions to enclosing a circular space considering specified point loads and self-weight. The designs shown in Figure 6 illustrate different structural responses to changes in performance metrics. The design in Figure 6 (left) was generated as a lightweight option while the design in Figure 6 (right) is a response to further design goals of minimizing surface area, maximizing enclosure space and creating a uniform subdivision of the space.

VISUALIZATION AND INTERPRETATION

The system breaks away from conventional structural design to consider new alternatives that are most often non-intuitive. For achieving novel structural solutions, results should be interpreted with respect to the formulated model. While with some results it is rather clear what the model defines other generated designs are more subtle. In the design shown in Figure 7 (left) the performance model did not reflect structural efficiency while the design shown in Figure 7 (right) illustrates the difficulty of determining where the support locations were modeled, which are not shown in the rendering. Structural understanding of generated structures is best achieved through reflection on the analysis. These ambiguities have highlighted the need for further investigation into visualization techniques that make performance models, including structural behavior, transparent to the designer. Appropriate interpretation is as important when generating conceptual designs as with structural solutions since it enhances understanding of the relation between the defined models and the underlying method and could result in more effective use.

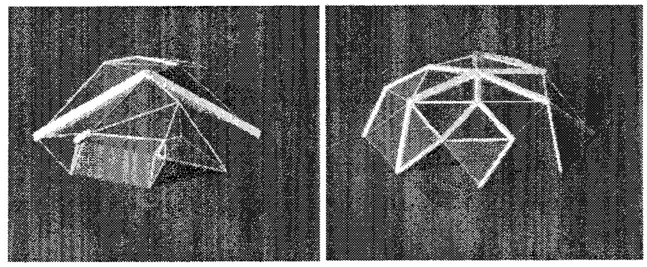

Fig. 6. Structural domes (Shea and Cagan, 1997)

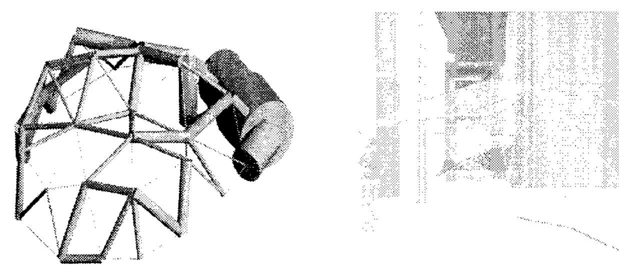

Fig. 7. Interpreting results (Hunneyball, Liao and Guma, DSoF)

REALIZATION

Realization of the complex designs generated by eifForm prompted investigations into appropriate detail design of complex joints and attachment of covering materials. Current manufacturing techniques make it possible to consider building structures that use many different section sizes and member lengths. However, the use of intricate joint angles and different sized members entering any one joint poses a difficulty for further detailed design. If three-dimensional structures are generated and covering is desired, surface material can be modeled as contributing to dead load. But, determining where and how to attach the material to the structure remain up to detail design. For instance, this issue arose in the design shown in Figure 7 (right). Studies of transforming generated designs into realizable structures is necessary though and can lead to the placement of additional constraints on geometric design transformations during generation.

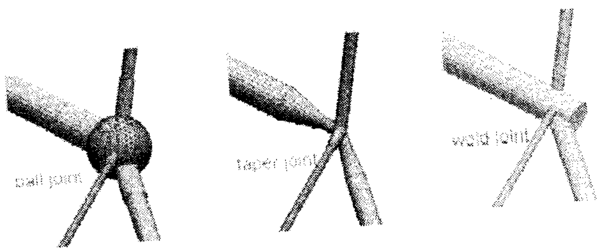

Fig. 8. Study of possibilities for intricate joints (Hunneyball, DSoF)

CONCLUSIONS

eifForm is based on the structural shape annealing method that enables the generation of innovative structural forms as responses to articulated performance. Engaging eifForm to create purposeful structures requires specification of design intent through both spatial and behavioral models as well as appropriate search model parameters. A certain level of experience and structural understanding is needed to effectively model design intent in this manner and make appropriate interpretations of the results. It is anticipated that through a collaborative networked environment qualitative descriptions of design intent could be translated into quantitative models using distributed knowledge and synthesis sources. Further development will focus on making the system models and method assumptions transparent to encourage use of the system for creating both conceptual designs and structural solutions. It is aimed that with further use, issues of form, function, material and scale in relation to changing manufacturing and construction capabilities can be explored to further our understanding of new structural forms.

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