Simulation-Driven Design System

Phototropic Architecture

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Abstract. *This paper presents a design process efficiently involving parametric design, realistic physical simulation and rapid-prototyping fabrication for contextual shape adaptation. This case study focuses on lighting simulation for the specific problem of solar energy harvesting. Inspired by the phototropic mechanism, the ability of plants to grow according to the availability of light, an innovative design technique is defined, taking its root in the morphogenetic design school [Hensel, 2004].*
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Parametric-Simulation in CAD

The introduction of parametric models for design has had a large influence on computer-aided modeling [Shah & Mäntylä, 1995]. This paradigmatic shift has enabled new possibilities to describe relations among geometric parts [Cache, 2004]. Through an under-defined form, it has brought new flexibility in exploring solution spaces, opening the way for mass-customizing and form optimization systems. However, if parametric design has enabled to easily create and explore entire families of designs, the designer is now faced with the difficult task of choosing among a large number of possibilities which ones are in need of further development and, ultimately, construction.

Concurrently, the advent of rapid prototyping techniques and the wider availability of tools has enabled the possibility to integrate design and fabrication methods into a single continuous design process of conceptualization, materialization and fabrication.

Realistic simulations of architectural designs, such as structural analysis, building thermal behavior or lighting simulation, have been proposed to more accurately study a design within its context. If simulation systems typically are in need of precise technical information or expertise in order to provide accurate or meaningful results, recent progress, together with desktop processing power, have provided tools more accessible to the designer, that can be now integrated into a computer-aided design system. Together with a parametric geometrical model, simulation provides a way to characterize the search/choice space by testing and selecting best context adapted parameters. These tools have the ability to provide objective measures that in the end empower the designer to make informed choices in order to meet the architectural program requirements, possibly even leading to the redefinition of the simulation framework itself.

Complementary to parametric techniques, the use of the computer as form generator pioneered by John Frazer [Frazer, 1995], has in recent years presented many examples of form-finding techniques with great tectonic potential; coined as the emerging field of morphogenetic design [Hensel, 2004]. One of the most interesting characteristic of morphogenetic processes is their ability to allow for unprecedented geometrical complexities; another their inherent potential for variability of expression that can be made dependent on contextual parameters.

Design systems that integrate such generative processes with simulations as well as fabrication constraints have been identified as compound models by Oxman [Oxman, 2006]. According to her study, only a few examples integrating a complete system, enabling a true iterative design loop with both generation of form and simulation for evaluation and performance were offered until now.

Through this appearance of powerful simulation techniques together with generative design models, the designer's responsibilities is shifted from practical skills in defining a geometry by iterative enhancement, to new roles in which he interacts, controls and moderates generative mechanisms to achieve meaningful interplay of form and function. Increasingly, the designer finds it necessary to develop digital tool building skills in order to be able to control the implications of the use of software in his design practice.

Structured Geometries

In this research, we draw the difference between *orphaned* and *structured* geometries. An orphaned geometry is a geometrical result obtained from an algorithmic process in which the geometric structure is not preserved. As an example, low-level geometric descriptions sent to graphic accelerated hardware are absolute coordinates of points and faces. As orphaned geometries do not conserve construction properties, they are often poorly editable. The geometrical structure is a description of the relations between geometrical parts, which may be analytical (mathematically described) or hierarchical, based on how pieces are derived from others.

Such geometrical structures cannot be unique. For instance an extrusion may be constructed from one side extruded or from the other. Models consisting of numerous objects imply a multiplication of the available choices, rapidly becoming intractable. The necessary choices implied by this non-uniqueness impose strong constraints on the space of design evolutions. Indeed, the process of describing the model construction is in itself an important part of the design, and its subsequent iterations often mirror the constraints embedded in the original description [Leyton, 2001].

The research presented here bases itself on a geometrical modeling framework taking this consideration into account. Based on the Java programming language, it borrows attributes of the processing.org project. However, instead of focusing on the representation itself, this framework tracks the sequence of steps leading to a geometrical representation. Each of the construction steps may be modified individually, leading to variations of a form keeping similar properties.

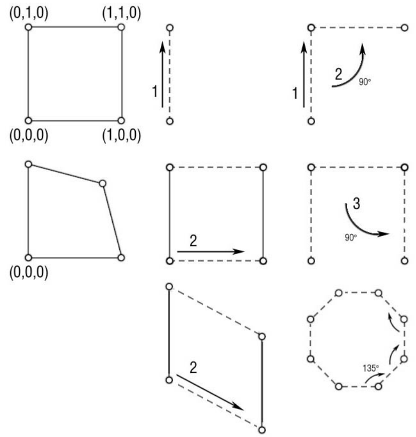

Figure 1
Example of construction choices in structured geometries

The model is thus constructed element after element through the use of transformations. The sequence information is stored within the description and may always be altered at any stage of the construction. In the example of Figure 1, a 2D square is constructed with three different modeling strategies leading to different structured geometries: a sweep from two parallel segments, a face defined by 4 vertices and the space enclosed by a sequence of 4 segments rotated by 90 degree angles. Also shown are the results of simple alterations such as translations or change in rotation on each structure. These examples illustrate how particular choices in the modeling structure may constrain the future development of the design.

Beyond the representation of an architectural geometry, keeping track of the set of transformations that constitutes a form enable to define it ensuring a better correspondence with real construction strategies. For example, constraining the geometry to the reuse of a small set of transformations will greatly ease the planning of the construction, by defining at design time how each pieces may be assembled together. As well as model construction, the integration of design techniques should be present at any stage of the design process, being dependent on the nature of the project itself.

The present project furthers work on Computer Assisted Design (CAD) by implementing design approach based on programming as a reflexive practice [Schön, 1983] where expression of geometrical relationships are used to improve the geometrical description by keeping track of construction processes to achieve a form rather than a geometrical result.

Phototropism and Morphogenesis

The ability of plants to induce changes in their development to adapt to their context can be seen in the phenomenon of phototropism, i.e. their ability to grow toward a source of light and away from their neighbors through the help of differential growth. In a bio-inspired approach, the case study presented here sets out to explore an application of this phenomenon in an architectural context. This is implemented through an integrated system using a radiation simulation to reproduce a lighting context for a phototropic adaptation. This paper thus defines and investigates a morphogenerative context-driven design system including generation, fabrication and simulation refinement.

Phototropism in Plants

The phenomenon of phototropism was firstly unveiled by Charles Darwin and his son Francis in 1881. It was already known that young grass seedlings illuminated on one side with blue light could bend towards the light. However, by covering the tip of the coleoptile with foil, Darwin could suppress the bending [Taiz & Zeiger, 2006]. This bending actually happens through differential growth: inhibition of growth on the illuminated side of the plant and promotion on the non-illuminated side. However the bending is situated several millimeters below the tip and some signaling across the tip had thus to be involved. This led in 1926 to the discovery by Frits W. Went of Auxin, a plant hormone responsible for tropism behaviours such as gravitropism - growth in response to gravity - and thigmotropism - growth with respect to touch, enabling for instance roots to grow around obstacles. Auxin is actually ubiquitously involved in typical plant developmental phenomenon such as phyllotaxy, apical dominance and many others.

This ability to grow in the direction of light enable the plant to explore its environment in order to discover better sites and orientation for photosynthesis. The cost of growing towards better positioning may then be compensated by added carbohydrates productivity.

Approach

The main hypothesis explored by this study is the idea that stimulating the growth of an architectural form through the availability of solar energy leads to the generation of form with efficient solar power harvesting characteristics. In order to do so, a parametric geometric growth process is interfaced with a solar radiosity simulation to estimate the available solar power on the whole geometry. Growth is stimulated where power is stronger, leading at the same time to a change in morphology dependent on the context, and to an increase in the efficiency of the design. By automatically modifying its geometry according to the availability of solar power, the design adopts a form that mirrors the solar lighting context.

Unfolding Surfaces

In this design context, the structured geometry proposed for this application is constrained by the advent of a new generation of solar photovoltaic panels that are highly flexible. This technology is produced in various widths and lengths, and consists in very light-weight material. Therefore the geometry consist in a deformation through folding of a lamellar plate whose length is much larger than its width.

As the simulations are surface-based, we must define rules to produce regular surfaces. In this case, we define a system constrained in such a way to produce only unfolding surfaces. Also, with a limited set of different lengths on both sides of the surface, angles are introduced which allow the form to be folded in space. In order to constrain the fabrication to a limited set of folding possibilities, a set of basic transformations is defined, which consist in:

1. a modular translation T_A which forms the base of a set $\{T_i\}$ of three translations: $\{T_A, T_{2A}, T_{3A}\}$
2. a set of translations $\{R_i\}$ based on a single angle $\alpha > 0 : \{R_{-2\alpha}, R_{-\alpha}, R_0, R_\alpha, R_{2\alpha}\}$

These transformations are combined in order to generate two parallel paths from which a surface is swept. Starting from two 3D points as origin and two direction vectors, one element T_i from the set of translations is applied on one path and another - possibly the same one - is applied on the other. The choice of T_i is constrained such that the difference Δ of path length between the two paths cannot exceed a given value λA with λ being an integer. Each direction vector is then rotated by some R_i around an axis that goes through the two points just created. Figure 2 present a schematic view of the construction. Repeating this process defines a growth mechanism, whose simple definition results in a structured geometry constrained to use a minimal set of different elements.

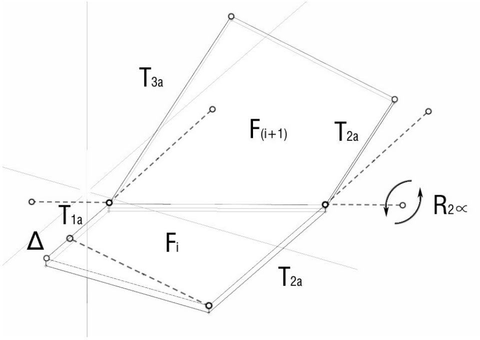

Figure 2
Structured geometry for unfolding sheets.

Simulation Driven Growth

The geometry defined above is then interfaced with the Radiance software, an open source physically realistic radiosity software commonly used in architectural lighting rendering [Ward & Shakespeare, 1998]. Previous research has shown how this tool can be used to evaluate the annual energy radiating on a given model [Cheng et al, 2006].

Using annual sky models including the sun path and reflections by the sky vault, this method is able to extract the effects of model geometry and orientation on its potential for solar energy. Interactions between the incident irradiation and the model, such as mutual shadowing or inter-reflections, are estimated using a ray-tracing method, whose physical accuracy has already been proven in several studies [Ward & Shakespeare, 1998]. The simulation computes irradiance in [W/m2] by positioning virtual pyranometers in front of all external surfaces of the model. These measurement points are evenly placed in order to insure constant resolution in sampling [Compagnon, 2002].

At each step of the growth process, the annual energy is computed for all possible growth candidates as defined by the structured geometry. The element presenting the highest annual irradiation is then chosen for the final growth. By repeating this process the geometry performs a local search, in the manner of a plant in its surrounding environment.

It is important here to emphasize the fact that the growth rule itself is deeply embedded in the structured geometry and the relative ease of description follows from the formal representation of the geometry. As defined, the growth process happening in simulation may then easily be translated in scale prototypes with the help of rapid-prototyping tools.

Sample Contexts

Context 1: single growth

In Figure 3 is presented the growth sequence of a folded element. It is clear that the local search is able to orient the developable sheet towards maximal gathering of energy.

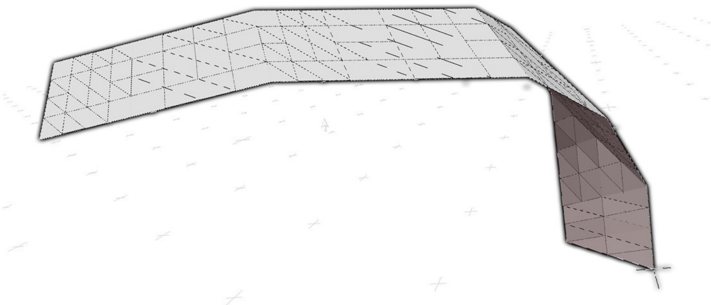

Figure 3
Single growth.process.

Context 2: competitive growth

Figure 4 represents the result of growing several folded sheets in competition with each other using the same growth rule. As a result, sheets avoid each other in their search for energy. The resulting process is of particular interest for defining complex geometries. Figure 5 presents the same growth process with a constant rotation applied at each step. In this case, a simple variation in the growth rule translates itself in drastic changes on the resulting geometry.

Future Works

If concerns on oil supply has already had an impact on architectural practice at the time of the 70es oil crisis [Borasi & Zardini, 2007], growing concerns on global warming will certainly drive an even more decisive change. Sustainability will inevitably be more and more part of the specifications of an architectural project. It is therefore of great importance to address the different ways in which these concerns can be integrated in the CAD/CAM framework, with the aim of ingraining sustainability deeper in the design. To this extent, the paper suggests to step away from the resulting model itself to encompass its architectural and energetic context.

In this context, instead of directly controlling the form, the designer's intervention lies in the definition of the structure of the geometry according to the problem premises, in morphological evolutionary rules acting on that geometrical structure, in the parameters taken into account in simulating the real context and in the constrains derived from the fabrication methods. This results in the design of a process, whose parameters may be either induced

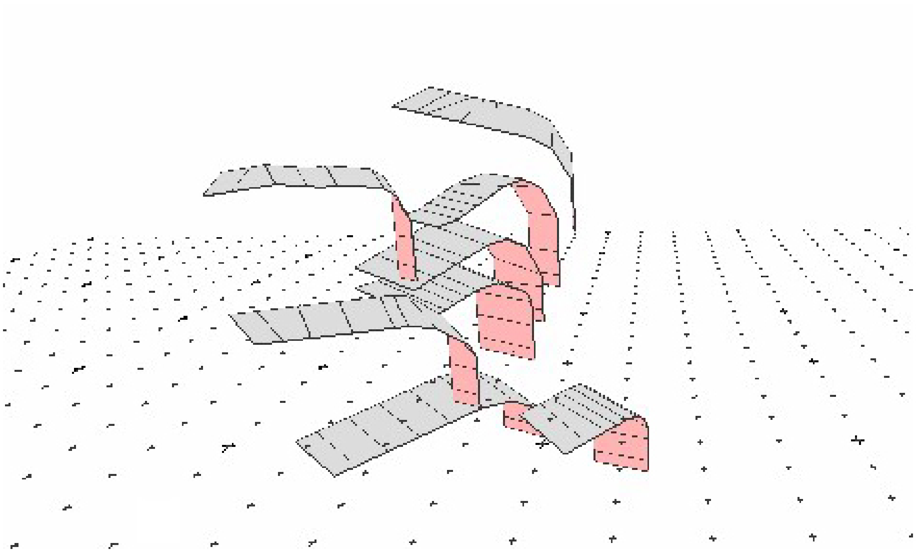

Figure 4
Growth process in a competitive context.

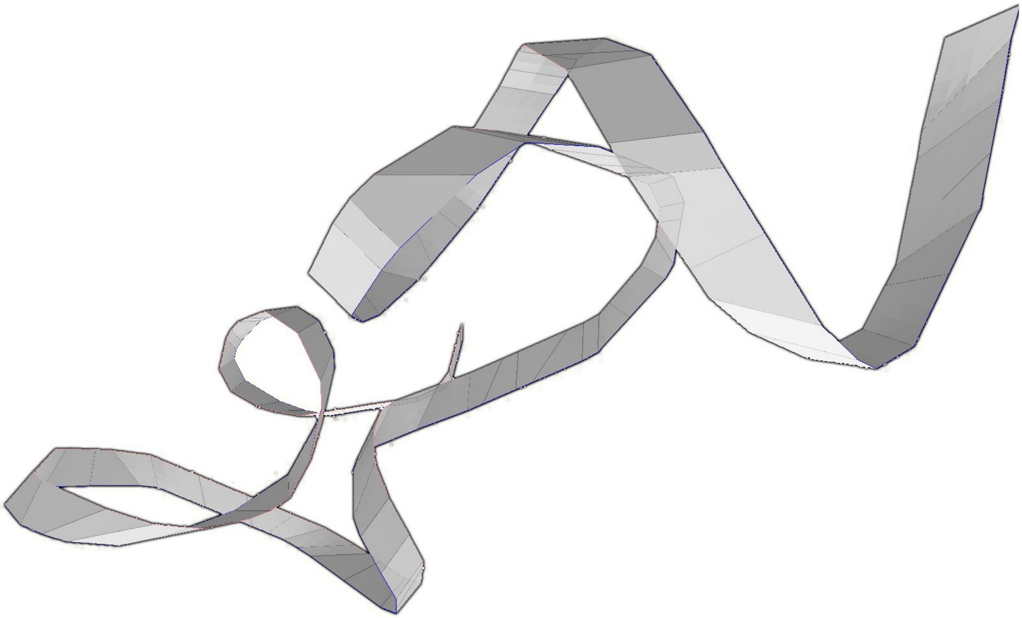

Figure 5
Growth process with constant rotation.

by considering the final realization of the architectural object or through subjective interpretation of the designer. Instead of representing obstacles to creativity, constraints are transformed into starting points for further exploration.

As of developments of the research, we will explore more deeply the design implications of the presented work and pursue the integration of additional realistic simulations such as structural or thermal behaviour to account for additional constrains.

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