The House of Affects Project

Techniques of Optimization in Architectural Design

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The House of Affects is an experimental installation to be part of the PerFormaSpace project pursued at the University of Cambridge, UK (DIGIS) and Goldsmiths College London, U.C.L. (Digital Studios), currently partially funded by Arts&Business East 2006, in collaboration with Econavate, UK who will provide their technical expertise in fabrication using recycled materials. This paper presents project-specific information and theoretical discussion on the design process and the computational methods used to develop advanced adaptive structural components in relationship to behavioral goals, criteria and constraints.

Keywords: Optimization; computational architecture; architectonics; adaptability.

Introduction

The House of Affects project consists of the construction of an interactive audiovisual environment, and its objective is to use several video projections in a dark room; all of which are controlled by means of a positioning device. The host structure for this virtual environment is designed with a set of tools for adaptable structural generation.

This paper focuses mainly on the qualities of the generated space in relation to the design strategy and the operational methods of construction we intended to utilise with our proposal for a novel paradigm of shaping hybrid spaces for responsive moving-image based dramatic narrative with regards to sustainability. The concept of sustainability is used here by means of optimum performance of the proposed structure and material efficiency in construction.

The exhibition environment is conceptualised as a host, the installation as an epiphyte to the host and the behaviour of the visitors as a trigger for emergent associations. An epiphyte is any plant which grows upon another living organism – they are not parasitic upon their hosts, but derive physical support from them (http://www.oed.com: May 2007). The installation is attached to the exhibition environment (host) as an epiphyte, and by doing so it correlates to the field of behaviour framing it as a field of performance. Epiphytes adapt their structural organization, and therefore their form, to their hosts. The flows of pedestrian movements on the exhibition floor are interpreted as guiding forces for responsive organization of the spatially correlated narrative experience.
and as dynamic patterns with performative potential that the structure of the installation seeks to engage with. A detailed analysis of the design enquiries of such an approach is presented elsewhere (Artopoulos and Roudavski, 2006).

Using computer-based techniques and inspired by Nature, it is our will to produce a flexible series of ‘mutants’: developing a system of re-configurable structures that adapt to different exhibition spaces – as epiphytes do. Further analysis of performance-components in praxis, such as human movement and direction of gaze, will inform the way digital design methodologies are adapted to, and around, a unified system.

**Analyses of the project**

Users will be able to navigate between several places presented by the story, and search for narrative content which will in turn be triggered by their movements. By doing so, visual perception and movement relate to each other.

The morphology of the tunnel-like shape was selected for its relation to the concept (i.e. the primordial sense of cavernness that evokes feelings of protection and privacy). For a detailed analysis of the conceptual background of the work see (Artopoulos and Condorcet, 2006). Our design concept stems from ephemeral structures characterised from their qualities of tactability, mobility and privacy such as Yuko Nishimura’s, Paper Tea House. The sheltering image of such a cave construction comprises one of the fundamental forms of human habitation. One enters through cavities in the space emerging from the shape of the installed structure; space being an image of the dwelling, as a symbol of comfort and protection. Being inspired by the work of Fr. Kiesler, the concept was based on shaping space and time-based spatially distributed drama concurrently.

The present position of the visitor in the room, in the present, becomes the centre of the experience, which is realised in the audiovisual performance. The spectator’s relationship with Time, Space and the performance is transformed through a new approach to emotional affect, enabled by digital technology’s creation of the responsive ‘theatre’ and viewing-frame.

**Associative design methodologies**

What follows is a brief presentation of a theoretical perspective on computational processes in architectural design and digital fabrication. The House of Affects represents a proof-of-concept practice based research project focused mainly on the tactics of optimisation utilised during the development of structural components for construction.

With regards to design, the aim was to generate a programmable structural system. The shape was generated through associations of the variables of construction and constrains derived from the characteristics of the site-host (fig. 1). The result is an increase in implicit or explicit relationships, including the possibility of hierarchical structures. In order to do so, we correlated a built form with constraints that derive usually from construction but can also be morphological.

The seed of the form consisted of experimental findings; the experiments operated by associating the initial shape, selected by the designer for its spatial qualities and feelings it evokes to the visitor, to differentiated gradient fields of forces, like gravity, light and operational loads due to its function.

The will to produce an adaptable system that can be effectively installed in different exhibition spaces led us to the development of a component-based structure. The programme of the design and construction was organised strategically in four steps.

Firstly, a system of associated geometric components acted as the generator of the form. The system of associated curves was conceived as the ‘body plan’, from which variations of the spatial configuration would be evolved, through a process that allows for feedback-loops in order to re-inform the system
in accordance to the results of the development procedure (e.g. response to influences and criteria imposed by both the process itself and the designer). A body plan is about the rules that govern the generation of a specific outcome and the interactions between them, in the system; an abstract diagram from which differentiated variations of form will be actualized (DeLanda, 1998). In our case the form was produced from the selected, by the author, design configuration of the system.

Having set up the associations, the issue of geometry rationalisation arose, a tactic which would be critical for the production stage. A modular structure would benefit the way the authors drive the generation of the structural elements with regards to the visual experience of the visitor and the functional needs of the construction itself. In addition, the logistics of the project would be profitable with such a strategy, especially the fabrication and assembly process of the construction allowing for lower costs, given the complexity of the geometry, and the off-site construction of large patches to be assembled into the final structure.

In the second step, the produced shape was analysed by a structural analysis program in nodes (points) and elements (the connecting lines), as a mesh. This approach allowed the optimisation of the topology of the tessellated mesh that described the shape produced in the previous step of the process. The jointed structural elements operated as the parts of a skeleton that could either remain uncovered or be covered with various types of material such as plastic, paper, translucent paper etc. Working with such a structural system allows us to operate each time on re-configurable spatial layouts interrelated with the particularities of the exhibition space that acts as a host to the installation.

Concluding, the architectonic method to be evaluated was that of associating computationally the process of formation of the structure with tactics of functional adaptation.

**From calculating stresses to evoking enclosure-ness**

The generation of a programmable structural system is the third step. The structural system the authors have developed, made use of a skeleton that consisted of tubular elements (paper tubes) and joints. Its synthesis was inspired by the process of bone formation and adaptation. Our aim was to generate structurally customised components for construction – based on performance criteria like load-bearing, strength and weight.

In bony structures, mineralized tissue constitutes the skeleton and therefore acts in a
comparable manner to the structural components of a building. The performance of a bone, though, is efficiently maximized to the highest possible degree, presenting an extraordinary ratio of mass to load-bearing capability. Thus, its shape and internal structure are optimized for efficient distribution of the various stresses it bears in both overall and local level. Cancellous bone structural morphology resembles a complex structure made of rods and plates. The structural elements, the trabeculae, are adapted in density, size and direction according to the local stress environment through a process called bone remodelling. We hereby present a method that applies these principles on architectural truss structures.

In our research project the main interest evolved around architeconics, and so, instead of trying to mimic the bony microstructure, our effort focused on the use of the bone formation process as a role model. The position of the nodes onto the surface (fig. 2), as well as the thickness of the elements of the skeleton (fig. 3) was calculated by the code we developed in MatLab (MathWorks , MA) for structural efficiency. Being influenced by the natural process, the code we produced takes as input the elements’ and the nodes’ coordinates and calculates a new set of optimised values for them having as a criterion the parameters the designer imposes to the program in conjunction to the previously established load distribution in the structure.

Space-trusses are highly efficient lightweight structural systems that can span long distances and be configured in virtually any shape. Previous work on the field includes the research carried out from Army of Clerks with the ‘Self Designed Structures’, which is routed on the concepts of self-organisation and emergent complexities (http://www.armyofclerks.net: May 2007).

In detail, the process started with the segmentation of the geometry, output from the parametric modeling stage, into elements. In a process similar to meshing, the surfaces produced by the modeling were tessellated in triangles (the function operated with Delauny triangulation), which constitute the segments of our geometry. Finite Element Method operates on a set of points (called ‘Nodes’) which connected create a grid (called ‘Mesh’). The material and structural properties which define the behaviour of the structure under load are embedded in the mesh as variables. The higher the density of the mesh in nodes the greater is the accuracy of the dynamic simulation. The mesh acts like a woven thread in that all nodes are inter-connected. From every node a mesh element extends to each of the adjacent nodes. More information on Finite Element Methods can be found in (Zienkiewicz, O. C, Taylor, R. L. and Zhu, 2005).

At that stage, considering the method of analysis we chose to operate with, we made the critical assumption that the component of the structure is the finite element for the calculations. We proceeded by utilising the structural analysis software to optimise the topology of the nodes on the surface to apply transformation tools on the mesh of the surface for optimised force distribution, constrained to be conformed to the original shape. Thus, the first process of optimisation in our design method occurred at the level of the shape topology, with criteria such as the dimensions of the components, the density of triangles, the local curvature of the shape and the distribution of forces across the structure.

The second process of optimisation operated at the level of local adaptability for the components. The recalculated coordinates of the nodes were used as input to the custom-made Finite Element code Analysis written in MatLab. We calculated the stresses on the edge of each triangle and replaced the triangular planar surfaces with a truss structure (e.g. a system of linear elements, in our case tubes, joined together with nodes). By integrating a set of operational variables to the code, to control and drive the calculations, we provided ourselves with a layered tool of computational tactics in architectural design for generating a dataset of values to describe the geometry.
Sustainability through optimisation

The structural optimisation stage consisted of two phases. At first, we applied initial values to the diameters of the truss elements as well as set up the boundary conditions. Then, we provided the code with input values indicating the location of the expected temporal forces (i.e. a human body leaning or seating on the structure, in the designated areas) in order for the program to incorporate additional flows of forces to the system, apart from those produced by body weights (gravity) onto the structure itself, which were dependent to the geometrical characteristics, the material properties and the structural performance of the latter. The program calculated concurrently the diameters (fig. 3) of the struts aiming to the minimisation of a) tensile stresses for each element loaded in tension, and b) buckling forces for each element loaded in compression, due to gravity and additional forces, as imposed by the designers. In order to do so, the code operated on a range of selected from us values for the parameters describing the structural elements of the construction, such as thickness, size, structural performance, material and geometrical properties of the paper tube.

The program runs in loops, with the number of iterations being inserted as input by the designer or until the algorithm converges – the range of difference of the calculated values between consecutive loops reaches an acceptability threshold. This is the selection point; when the system falls in equilibrium the values under calculation are optimised. Such a process is well known among engineers developing tactics of optimisation in fields like structural engineering, aerodynamics, signal processing etc. Essentially, the process of optimisation is about trying to locate the optimal combination of a set of given geometric, structural and material parameters within a defined group of associated constraints to achieve maximum performance. In order to do so, one has to utilise a dynamic simulation consisting of four main phases. First is the modeling of the geometry which will be modified after the system starts looping. Second is the generation of the mesh, the efficient definition of which is very important for the performance of the simulation. Then the phase of calculation follows, and the first circle of operation ends with the analysis of the solution. Thereafter, the system recalculates the performance of the generated figures after having updated the variables iteratively.

Tactics-wise, a critical point in the method we followed was the utilisation of Integer Linear Programming. An Integer linear programming problem is when the unknown variables are all required to be integers. In contrast to linear programming, integer programming is used in many practical situations when the operator is restricted by bounded variables.

The advantages of such a tactic can be found at the level of logistics for the construction in a real-life scenario. By applying a range of preset tube sizes and limits, for the calculated by the code values of the adapted diameters, the program selected the fittest figure. Hence, the designer can insert to the program specific values for the diameters of the paper tubes found on the market, and the code will produce only precise values for the adapted diameters.

The fourth stage, still outstanding, the fabrication of the components to be assembled, when combined with the parametrically designed structure (fig. 4) reveals the full potential of such an approach. The selection of paper tubes as the structural component (fig. 3) grants us the flexibility of using a cheap, lightweight, replaceable element for construction. With the support of Apsley Paper Trail Mills innovative sustainable construction materials made of recycled paper will be used for construction.

The use of an architectonic unit, such as the paper tube, for associated functional (locating the ‘seating’ areas) and structural (adapted diameter as the resultant of tension/compression values) purposes, while at the same time holding its own materiality (recycled paper), and acting as a distinct monad of form (tubular), portrays the intention of the author for operating architecture as a variable continuum of associations.
The above method of computational architectural design provides the designer with a process of production for rapid manufacturing of a component-based structure which incorporates the flexibility to re-configure the design in accordance to differentiated criteria, such as direction of vision and light permeability (fig. 4) or energy efficiency criteria, parametrically connected to the structural performance of the system (i.e. minimal use of material to maximise the efficiency of the design).

Figure 2
Detail of the transformation operation on the position (coordinates) of the nodes on the surface. The arrows on the nodes point out the calculated tangential direction of each node. In this way, the form remains constraint, whereas the structure is ‘grown’ in conjunction with the geometrical and material properties. Hence, the structural performance is optimized.

Figure 3
The second process of optimization operated at the level of local adaptability of the components. The calculated coordinates of the nodes were used as input to the Finite Element code developed for the purposes of our project. Then, the program runs in loops to calculate the fittest values for the diameters of the components (tubular elements) according to a range of parameters and limits inserted by the designer, as a means of operational control of the computational process.
Synthesis in Computationally Intensive Architectural Design Methods

The generation of the structure required a development environment able to support complex geometries, computationally intensive processes – including dynamic simulation – and flexible automation tools. Based on these requirements, the tactics of design consisted of a production line with the synergy of several programs and custom-made tools. Namely, Generative Components for Bentley’s Microstation Suite was used for the associative design of the underlying geometry of the shape (a parametric technique capable of supporting versioning and prototype breeding) (fig. 2). Abaqus for Dassault’s Catia was utilized for the structural analysis stage, in association with custom-made Finite Element Analysis code in MatLab for the generation of the components (fig. 4).

The fabrication stage of the design relied on the programmable environment of Rhinoceros 3D (which was also used for the validation of the surfaces). Finally, Dassault’s Virtuools program for Real-Time 3d Virtual Environments was selected for visualization purposes and the validation of the User-Space Interfacing.

Techniques of optimisation in architectural design

Architecture’s logical next step should be the creation of generative, feedback-based, computational tools that support the evolution of forms and structures,
nonetheless respecting a network of co-effecting criteria. The power of such tools stems from the control via parametric processes (e.g. integrated variables) they allow to the architect-user.

The need for a sound knowledge of issues of optimization and performance, as well as the thorough understanding of the role the operational variables have in the process, was illustrated in this paper. Optimisation techniques were applied twice in the designing process (from shape to fabrication). The design process is presented in detail elsewhere (Artopoulos, 2007). The first optimization occurred at the level of transforming – for efficiency – the topology of the surface mesh (consisted of nodes and their connectivity elements) (fig. 2). The second phase involved the computationally generated diameters for the elements (replaced by paper tubes in the construction) adapted to the material properties for structural performance and material efficiency (fig. 3).

The concept of optimization could have been pursued in other stages of the design process as well, such as the controllable fenestration of the translucent membranes, designed to be fixed onto each triangle of the structure, associated to the projections and the isovistas of the visitor to the space, but that is for future developments of the project. Such an approach would have been in the right direction towards a multi-level optimization, a method which is closer to that of architectural design, because of the complexity of the latter in contradicting variables and constraints. Such a model might allow architects to have an insight on the methods followed by disciplines traditionally associated to computation, such as mathematics or engineering.

References


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