PROTOTYPING DYNAMIC ARCHITECTURE
Material properties as design parameters

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ABSTRACT: This paper documents an ongoing research that combines recent developments in the field of Rapid Prototyping Technology for a materialisation of composite pneumatic models. The ability to create three dimensional prints with varying surface materials has the potential to assign the RP model a different role in the design process. The implementation of material performance, configured through CAD driven geometry, allows for an emergence of dynamical models that are freed from conventional representational function.

KEYWORDS: Rapid prototyping, inflatables, performance driven design

RÉSUMÉ : Cet article documente une recherche en cours qui intègre les plus récents développements en matière de technologie de prototypage rapide (PR) pour une matérialisation de modèles pneumatiques composites. La capacité de créer une impression tridimensionnelle à surfaces matérielles amène un nouveau rôle au PR pendant le processus de conception. L’implémentation de la performance matérielle, configurée au travers une géométrie de CAO, permet l’émergence de modèles dynamiques libérés de la fonction représentationnelle conventionnelle.

MOTS-CLÉS : Prototypage rapide
1. PERFORMANCE BASED MATERIALITY

Contemporary techniques of layered fabrication can alter the abilities of designers to engage with the material properties and performance. Increased geometric control, digital production methods and a stronger implementation of material science offer the potential to constitute a new material behaviour of future building components. These processes can be used to address local changes in the building component’s definition that alter material organisation, structural behaviour and performance over time. The material consequences have the potential to change the way we will construct and design buildings.

Rapid prototyping technology evolved in less than 30 years from a proof of concept state towards an elaborated manufacturing technology. Their application in design and manufacturing environments was expanded by decreasing prices for the acquisition of the production facilities and possibilities of contemporary 3D software that required an appropriate technology for the materialization of complex shapes.

Architecture firms as Foster and Partners have a documented output of 4000 RP models a year only in their London office (Peters and De Kestelier 2008). The US army (Gady and Benton 2005) utilizes RP manufacturing (RMS) and Reverse engineering units for the manufacturing of functional near net shape parts up to 30.48cm x 30.48cm x 55.8cm on the battlefield. Until end of March 2005 12.640 individual parts have been produced with the installed Modules.

Recent Technological advancements expand the build size towards larger scaled entities (Mammuth SLA 2008), they enhance the material properties and allow for a multi material composition. The technological limits that are still present today are defined by the build size, build direction and the derivative anisotropic material performance and the non environmental friendly properties of the material.

1.1. Advancements in RP technology

Rapid prototyping, tooling and manufacturing are usually restricted to the use of a single material for the creation of the models and parts. The scope of contemporary materials that are employed for layered fabrication technologies ranges from e.g. Stainless Steel, Titanium-, Aluminium-, Co- and Ni-Alloys, Thermoplastics, ABS plastics, Photopolymers and materials with ABS like properties, flexible rubber-like materials and Quartz sand and plaster.

The Connex500™ (Connex DATA 2008) technology by Objet Geometries Ltd. that was presented to the public at the Euromold Frankfurt in 2007 demonstrated models that could contain different mechanical and physical material properties in a single build.
The machine allowed the simultaneous print from two source model materials and could create a total of 21 interpolated types of digital materials that contain specifically addressable physical properties as e.g. tensile and flexural strength or modulus of elasticity. The technology operates with a steering technology that allows the synchronisation of eight print heads (6 for material and 2 for the support structure) heads with 96 individual nozzles.

The implementation of physical properties shifts the role of the model further away from mere representation towards a manufacturing process. This investigation of a future implementation of RP technology for 1:1 applications seems therefore justified. These innovations can be synchronized with present-day 3D CAD modeling tools that allow the successful implementation of performance data derived from Finite Element Analysis (FEA) or energetic simulation. Since the structural composition of the material is defined through CAD driven volumes that are freed from the usual constraints of manufacturing technologies even interlocking and highly complex geometries are possible. With the aid of digital production tools and analysis methods, a further step is taken to diminish the remoteness between the design concept and its realization.

The paper researches how these recent developments in the field of Rapid Prototyping Technology could be employed for a study on performance based material composition with pneumatic structures.

2. PNEUMATIC STRUCTURES

The paper will investigate an application of multi material Rapid Prototyping technology for pneumatic spatial constructions that can express dynamic form change. Several advantages render an application of RP in the field of Pneumatic dynamical structures interesting.

- The dead load of the material that is employed for the construction of pneumatic structures is negligible compared to conventional structural solutions. This factor enables an analysis of the printed model under rather realistic conditions regarding structural and geometric performance. The
combination of RP with inflatable technologies facilitates the realization of large-scale objects. By fabricating folded skins, the scale of the printed object can be increased significantly by inflating it. Additionally, the effect of all kinds of creased geometries can be studied, depending on the character of the folds. As elasticity becomes a digitally controllable parameter, complex interaction of truly dynamic elements can be realized. The models, which are also conceived as full-scale building parts, blur the concept of a classical element of the architectural practice, the physical model.

- The model doesn’t rely on a hierarchical structural system composed of differently articulate load-bearing systems, but on a dynamic interaction of self-stiffening members. The spatial arrangement defines the performance domain of the overall structure that is the further articulated by the discrete configuration of the local expansion skins behaviour.
- Elastic inflatable structures have been rarely applied in building construction. The reason may be found in the change of stiffness, which occurs with varying loads and therefore a lack of reliability. The most widespread industrial structural application for elastic pneumatic elements can be found in car tyres. Among others, the success of the system can be found in two qualities: the more rigid tyre limits the soft inflatable tube. The whole system is redundant. The technology of printing different materials allows for a more sophisticated distribution of limiters. Redundancy will be given by the over-all design of the investigated structures.

The paper investigates the design of two pneumatic systems. It starts with a test of a pneumatic knot for a space filling structure. The second experiment investigates a performative pneumatic tubular system. Both test geometries were designed to allow performance based continuous form change. Additionally will the paper introduce a parametrically driven system for a gradient material distribution that could be integrated into the performing skins to steer material behaviour.

2.1. Knots

The first chapter develops a spatial array of pneumatic knots. The design for a space grid can be developed with the help of a soap bubble structure, known as Kelvin Structure. The bitruncated cubic honeycomb is a space filling tessellation in three-dimensional space. It was developed in 1887 by Lord Kelvin following his investigation on how space could be partitioned into cells of equal volume with the least area of surface between them. The space grid is organized by a three dimensional array of truncated octahedrons. The arrayed knots with double curved surfaces were adapted to the octahedral structure.

The initial expansion parts of the membrane surface received physical properties that were correlated with the stress distribution that derived from the initial curvature. The membrane tensions of an air supported dome struc-
ture under the surface loading of internal pressure can be indicated by the expression (Dent 1971)\(^1\):

\[ T = \frac{(\Pi \times R)}{2} \]

With \( T \)=surface curvature; \( R \)=Radius; \( \Pi \)=Inner membrane tension

**FIGURE 1. KELVIN STRUCTURE WITH TRUNCATED OCTAHEDRAS (WIKIPEDIA 09).**

Accordingly the centre parts of the expansion surface were equipped with an elastic material that was encircled by two surfaces of varying flexibility. The first version of the knot contained individual air intake nozzles and two types of joint systems for attachment of the neighbouring knots. The individual pressure levels of each node would drive adjustable areas of surface expansion that would be correlated with a performative quality of the overall structure.

**FIGURE 2. KNOT WITH DIFFERENT ASSIGNED DIGITAL MATERIALS.**

The first condition for a successful structural application thus is fulfilled by the reinforcing parts or limiters, which are built up by less elastic material. These parts also act as a tensile net, a common system in building construction to reinforce inflatable structures and to manipulate their form (as in Herzog 1976).

**FIGURE 3. SPATIAL ARRAY OF KNOT ELEMENT.**

The second condition will be given by the Space Structure itself, which can be read as a cluster of at least three layers of structural elements. The Kelvin structure embeds one orthogonal grid onto another shifted orthogonal grid. This principle has been applied before in a series of experiments by the authors (Figure 6 and Sommer 2008). Three layers of knots will thus define two opposing exterior and one inner grid. According to the pressure difference of corresponding exterior knots a curvature can be forced upon the over-all structure. As the two layers would not form a rigid system, the inner layer will be used for stiffening, if inflated after a transformation has being processed locally.
Seen globally, the structure should behave redundant; if one part weakens other parts take over. Locally, each knot derives its rigidity from the integrated reinforcement network. The soft parts, however, fulfill a third function. They enable to close or tighten the skin, offering different states of porosity. Not only formal qualities, but also qualities of light and ventilation can thus be controlled.

**FIGURE 6.** 3D PRINT OF KNOT WITH DIFFERENT ASSIGNED DIGITAL MATERIALS.

The first test print delivered a series of insights on geometric and material constraints that impact the following designs of the structure.
- The geometric accuracy of the printed geometries is important, to prevent minimal capillary gaps. This appearing problem can be solved in two ways, either through a mathematical description of the surface or a change in the knots morphology.

**FIGURE 7. MESH MODEL OF SCHWARZ-P SURFACE (POLTHIER 2005).**

An alternative solution that has been studied by the authors is the alteration of the overall morphology of the knot geometry. The geometry of the inflation areas of the knot were hereby geometrically defined through inscribed spheres that were divided in four neighbouring surfaces. The inflation process would then mirror the convex curvature of the membrane in a smooth expansion process with tangential edge conditions into an increasingly concave form. This solution relies on a spherical solid with an accurate mathematical description.

**FIGURE 8. SPATIAL STRUCTURE WITH SPHERICAL EXPANSION AREAS.**

2. The initial saddle was modelled as a patch surface defined by six edge lines. The software delivered only a very good approximation of the edge conditions but not a geometrically precise result. Due to this inaccuracies, that were further amplified through the surface offsets, capillary gaps were created that materialised in the printing process as cuts. These cuts interfere with the idea of a pneumatic component for obvious reasons.
3. This surface generation process is not defined through form-giving rail lines that are used to configure a dependant surface configuration but relies on a mathematical description of the surface itself. The surface therefore doesn’t contain any edge lines that are usually sensitive in the surface offset process.
Material thickness of the layered surfaces has to be rather sturdy to prevent cracks. The tendency to form these cracks is further enhanced by the brittleness of some of the print materials. The layer thickness of the skin influences the required air pressure level for the inflation.

Material tear resistance is highly dependent on the build direction. The evolving material shows anisotropic behavior. An analysis of the print out model clearly exposed the different material properties ranging from stiff to different degrees of elasticity.

2.1.1. Gradient Skin Material

The first test created material differentiation through clearly separated areas of different elastic properties in the skin surface. In the printing process it became visible that the border between different material areas was vulnerable against tearing and could potentially affect the air tight properties of the material.

**FIGURE 9. GRADIENT MATERIAL DISTRIBUTION.**
In order to avoid these critical edge conditions of neighbouring materials the areas with increased stiffness requirements were embedded in an elastic base material to ensure air tight seams. Exemplary performance diagrams were then used to guide the material distribution that was geometrically described by parametric modelling software. The remaining five available materials (beside the base material) that gradually decrease in their elasticity could then be addressed to specific zones of structural requirements. This possibility of a computer driven assignment of a local material behaviour allows complex material specification.

**FIGURE 10. FUNCTIONAL GRADIENT MATERIAL DISTRIBUTION (BARRY 2004).**

Similar technologies of a subtle change between different materials can be seen in aeronautical developments of combustion chamber coatings. These Contemporary Functional Gradiant Materials FGM (Holmes and Mc Kechnie 2004) were employed to prevent materials with differences in thermal expansion to shear apart and eventually leading to separation and flaking.

**FIGURE 11. MATERIAL DISTRIBUTION DIAGRAM (HOLMES AND MCKECHNIE 2001).**
2.2. Tubes

Given the anisotropic behavior of the printed material, a tubular structure, in itself anisotropic, seems to be more promising for our further investigations. The membrane tensions of an air supported cylindrical structure can be indicated by the expression

\[ T = \left( \frac{\pi R}{2} \right) \text{ in the direction of the axis (given hemispherical caps)} \]

With \( T = \text{surface curvature}; R = \text{Radius}; \pi = \text{Inner membrane tension} \)

Given the right orientation of the elements during production, the material strength can be fully utilised.

**FIGURE 12. LAYER OF TUBES, REVEALING THE STRUCTURE OF THE “GRADIENT MATERIAL”**.
We propose to build a cluster or at least one layer of inflatable tubes, which performs according to the “gradient” material property of their skins.

Each tube can be pressurized individually. If all are fully inflated, we expect them to equalize the effect of the different material grades and to meet each other’s neighbour. Fully decompressed, the structure will reveal the hidden gradient pattern, which has been implemented by the RP print. Again this pattern can be the result of a surface study, which is an understandable and convenient way to define the desired properties. There is an infinite range of continuously variable states in between inflation and decompression. The diversity of possible patterns is once more enhanced by the possibility to assign each tube a different inner pressure. The structure thus can be become an interactive building part.

3. CONCLUSION

The surface studies technique seems promising in its implementation of parametric design software and material diversity.

As stated before, was the material weakness that could be witnessed so far highly dependent on the quality, composition of the geometry and the build direction of the geometry. Given the current technology, today and quite likely in the future, it will be necessary to consider the production process, as it always did influence the conception of products.

To combine inflatable structures with the RP technology introduces dynamic qualities to highly customised building parts. The quality of the structural performance, the appearance, the transparency and the permeability of such parts can be changed continuously. These changes reveal and exploit the digital structure in a unique way. Rapid Prototyping thus is used not anymore as “proto” typing, but becomes a production method in its own, which leads to complete new applications in building construction.

Looking at the development of Rapid Prototyping technology from its earliest phase in the late 1970ies to its first commercial application in the late 1980ies and to the diversity in print materials we encounter today, we can expect to leave behind the usual scope of a model’s scale. The impact of this material integration will leave its traces in the applications, concepts and processes of design creation.

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REFERENCES

Connex500 Digital Material Data Sheets, Digital Material, 25 Sep. 2008  


Gady, Amsrd-Tar-N/ Ms 255, Benton R., 2005, Subtractive Manufacturing on the Battlefield with MPH, Standardization and Part Standardization and Management Committee San Diego, CA, November 16, 1 Sep. 2008  


< http://en.wikipedia.org/wiki/Weaire-Phelan_structure >

< www.architecturalgeometry.at/aag08/poster/sommerb.pdf >