# Integrative Computational Design Methodology for Composite Spacer Fabric Architecture

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*Spacer fabrics are 3D warp-knitted fabrics, which have a volumetric structure. Together with the capacity to differentially stretch and contract, these materials allow three dimensional which is specific to spacer fabrics. The authors present a computational design methodology which enables the generation of form based on these material characteristics and local, regional and global material manipulations. Such a process can not only generate functional surface articulations, but also control the forming of spatial textile geometries. As a resin infused composite structure the spacer fabric can serve as architectural construction and building envelope. This new methodology to develop fibrous and textile morphology is contrary to a traditional hierarchical design process, which is based on a linear strategy from design to implementation. The investigation methods are based on analogue material experimentation and integration of the materials behaviour into a computational design process. Such a feedback process can unfold potential material morphologies and performances of spacer fabric as an architectural material.*

**Keywords:** *Integrative computational design, Fibre composite structure, Spacer fabric, Material Computation, Form Finding*

## INTRODUCTION

The authors present a design and fabrication methodology for a fabric structure composed of 3D warp-knitted fabric, which can be solidified by resin for structural rigidity after the geometry is defined by manipulations. Composite structures utilising fibrous fabrics are already widely used, especially within automotive and ship building industries. This paper proposes a new methodology to develop fibrous and textile morphology and to explore the potential applications in the architectural field.

This research is strongly related to a series of form-finding experiments by Frei Otto. Similar to the Frei Otto experiments, the research started from a series of physical experiments. Both areas of research find the material form as a state of equilibrium of internal resistances and external forces. While most of Frei Otto's form finding processes use abstract model scale material representations to find the global morphology of a system. (Menges 2007); the aim of this research is to explore a design methodology for a specific material. This methodology is based on manipulation of the fabric in order to simulate, design, and fabricate architectural structures. These local, regional, and global manipulations, differ in scale and purpose and are interrelated within the material and global system. In this sense the manipulations do not only generate a surface articulation, but also control the global geometry.

## INTEGRATIVE COMPUTATIONAL PROCESS

Computational tools can extend design possibilities by the integration of structural analysis and digital fabrication criteria. Exchanging information between the physical model and the computational model helps in understanding of the material system, which is related to not only morphology but also to performance. Although, physical experimentation is a good way of intuitively manipulating the material, in order to quickly explore design potentials while abstracting the material system's characteristics and constraints, a computational method is appropriate. This research therefore analyses the material both physically and computationally which can unfold potential material morphologies and performance.

Contrary to a traditional architectural design process, which follows a linear logic from design to implementation, this process has a reciprocal information structure (Figure 1). Even though initial geometry is used as an input to control the architectural

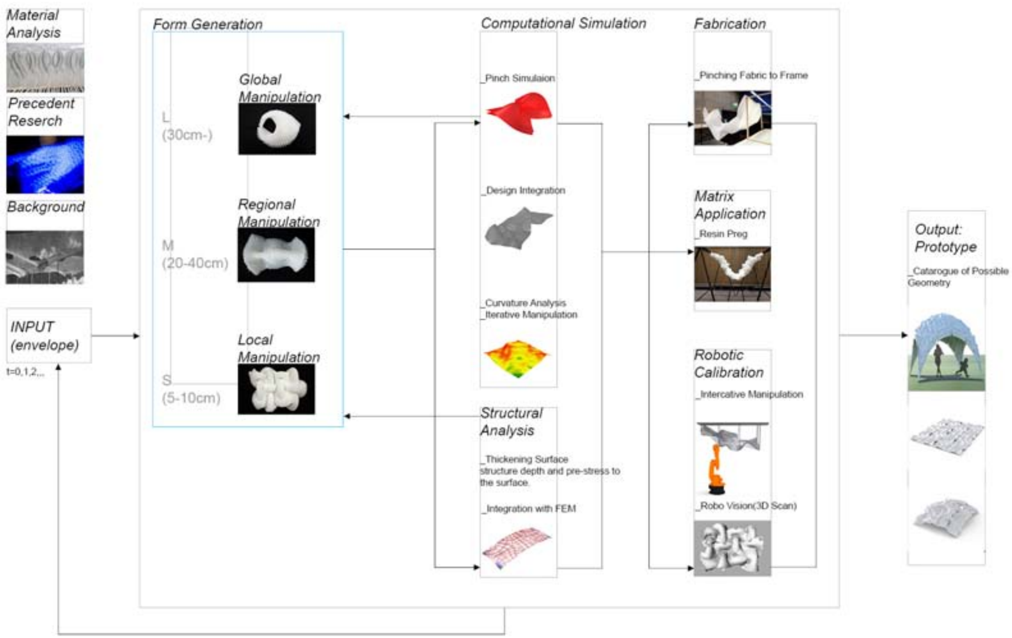


Figure 1
Integrative Computation Design Process

intent and scope, the final geometry emerges after several iterations of the computational tool and fabrication process. The geometry is updated according to integration of the information from physical experiment, computational simulation, structural analysis, and fabrication constraints. As a result, this process can generate architecture which is embedded with more information than conventional architecture.

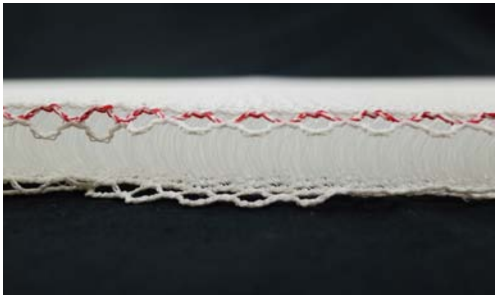

Figure 2
Spacer Fabric

Figure 3
3D Spacer Textile Composites / Nico Reinhardt / 2007-08 HfG Offenbach

## MATERIAL SYSTEM: SPACER FABRIC

The integrative design process is based on a specific material system. By analysing the material characteristics of the spacer fabric carefully, the new potentials of the material system can be unfolded. This creates a bottom-up approach for the architectural design. On the other hand, to become a useful building element the material needs to have scalability. Otherwise, the application is limited to furniture or pavilion scale, even though the system has interesting geometrical or performative aspects. Since this research focuses on elastic and continuous material, dynamic relationships between local and global form can be maintained in the fabrication process. However, the application of textile material is still limited in architectural field mainly because of its structural property. Therefore, the research initially starts to look at spacer fabric which has the scalability because of its property (Figure 2).

The pile, a three dimensional parallel ordered arrangement of monofilaments between the top and bottom mesh of the spacer textile, adds thickness to the fabric structure. In contrast to two dimensional fabrics the strong filaments in the pile provide a relative amount of compressive strength and bending stiffness while the textile remains very lightweight (Knecht 2006). Also, this material has the capacity to differentially stretch and contract through geometric deformation, which offers the possibility to drape the spacer fabric over complex double curved surfaces with no need for seams or cut patterns (Menges 2009). Architectural applications of spacer fabric have already been explored in research at the Department for Form Generation and Materialisation, by the co-author at HfG Offenbach. One example involves the design and fabrication of double-curved furniture, which required five-axis CNC milled moulds. Another example instrumentalizes local form-finding processes in order to differentiate continuous 3D textile glass fibre composite surfaces (Hensel et al 2008) (Figure 3). A series of local manipulations provide structural depth, and create complex emerging surface articulations. Moreover, the spacer textile has variations of weaving pattern, thickness, and elasticity for several usages. Although the majority of spacer fabrics are made from polyester it is possible to manufacture glass fiber spacer fabric. These fabrication parameters allow the production of very thick glass fiber spacer textiles that would be suitable for large scale applications. Based on the methodologies of these precedent researches, and the potential for performative material applications the possibility of using spacer fabric in an architectural proposal is developed, by integrating form generation with structural design and fabrication methods. The novelty of this research is that the combination of local, regional and global manipulations controls the geometry without any formwork.

## PHYSICAL EXPERIMENTS

Through physical prototyping, a catalogue of form-generation strategies for the fabric manipulations was developed for local, regional, and global manipulations. These manipulations are achieved by pinching various points of the spacer fabric and connecting them with plastic cable ties which partially squeezes the textile. This contraction of either the top or bottom mesh results in a bending deformation of the three dimensional fabric structure. First, each manipulation is applied manually. Second, according to the deformation of each pinch, successive manipulation are determined iteratively through a computational tool. Finally, this process shows the relationship between the 2D pattern of pinches and the resulting 3D geometry.

There are three different steps of material manipulations for generating form. First, global system articulation, such as rolling, twisting or hanging, the fabric can be approximately transformed to specific 3D geometry. Second, based on this geometry, the fabric is locally manipulated to further control the surface and increase structural depth. By accumulating locally differentiated manipulations, the spacer fabric can be transformed into complex geometries. The process of physical experimentation and computational simulation are conducted simultaneously as both processes inform each other.

## MANIPULATIONS

### *Local Manipulation*

Due to the material continuity, elasticity and stiffness even a single pinch affects the global geometry (Figure 4). The larger the pinch width is, the more deformation both locally and globally. This means the pinch size and directionality are decisive factors for generating form. Pinches with opposing directionalities that are equally distributed on the fabric, such as horizontally and vertically oriented pinches, maintain a thickened local deformation though the effective global deformation of each individual pinch is negated creating a globally flat geometry.

Figure 4
This is a figure

Figure 5
Local Manipulation (multiple pinches)

Based on the pattern which is locally deformed and globally flat, a density difference is applied to the pattern in this experiment. The pattern is manipulated by only pinching the top layer of fabric. The used fabric sheet is 1.4m by 0.5m with a thickness of 1.5cm. The pattern of manipulations is denser in the center than the peripheral area. Thus the amount of deformation in the center part and the peripheral area become gradually different. Because of the variation in density, the overall geometry deforms globally as well (Kuma 2013). This creates an arch like shape, with the top forming the inside of the arch (Figure 5). Although, it supports the self-weight in this scale, it is not rigid enough to keep the geometry at a larger scale. In this sense, manipulations only provide the tendency to define the global geometry though, these accumulated local manipulations have the potential to partially reinforce the geometry in a global model. More decisive manipulations are needed to accurately determine the global geometry.

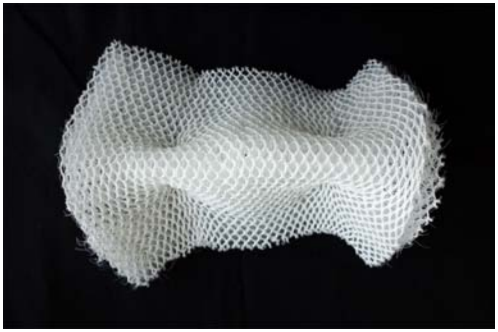

Figure 6
Regional
Manipulation
(single pinch),

Figure 7
Regional
Manipulation
(multiple pinches)

Figure 8
Global
Manipulation
(hanging)

### *Regional Manipulation*

Regional manipulations are controlled by the interaction of multiple local pinches (Figure 6). The fabric between pinches is deformed if the distance between manipulation points is within a range determined by the stiffness of the material. This generates a larger deformation than one which is generated by the individual local manipulations. Therefore, regional manipulation can easily connect the deformations in the global geometry and generate a "flow" of surface articulation (Figure 7). Using this technique of continuous deformation, the curvature can be smoothly controlled. Regional manipulation can also reinforce the global geometry by thickening the surface and distributing weak points to avoid continuous fold lines in the structure.

### *Global Manipulation*

Compared to local and regional manipulation, global manipulations change the geometry dynamically. For example, even one single long-span pinch can deform the entire geometry by connecting strategic points together. Hanging the fabric is also a method of global manipulation. Since spacer fabric has certain weight, the effect of pinching manipulation can be emphasized by gravity (Figure 8). Global manipulation can deform global geometry more efficiently, using fewer manipulations. Consequently, local and regional manipulations are used to modify and reinforce the base geometry crested from global manipulations (Figure 9).

## COMPUTATIONAL SIMULATION

Based on this physical prototyping, the 3D form is simulated using a live physics engine. In this approach, the entire knitted pattern is translated to a system of particles and springs, and the elasticity of the spacer fabric is controlled by variables such as the stiffness and rest length of these springs. In addition, two meshes, consisting of particles and springs for top and bottom layer of the spacer fabric are used to show curvature changes. By applying additional springs to this setup, the geometry is relaxed and the simulation provides the approximate geometry of the manipulation. The relevant variables are determined by comparing physical models with the computational simulation. Likewise, the computational process is tested iteratively to find a way of controlling geometry. According to the output geometry of relaxation, the successive manipulation points are defined by analysing the curvature of mesh in the digital model (Figure 10, 11). By using this simulation tool, pinching patterns can easily be tested computationally to examine the potential deformation in a physical model.

Figure 9
Global Manipulation + Regional Manipulation

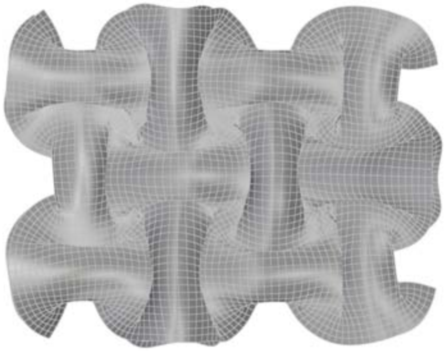

Figure 10
Computational Simulation of Spacer Textile by Physics Engine (local manipulation)

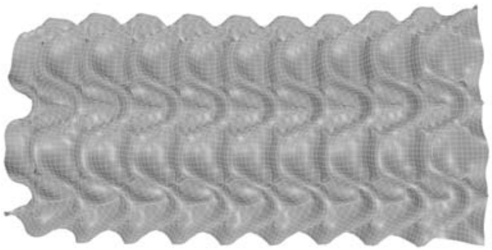

Figure 11
Computational Simulation of Spacer Textile by Physics Engine (regional manipulation)

## STRUCTURAL INTEGRATION

In addition to this form generation system, structural analysis is utilized in the design system, and integrated with form generation to calibrate the structural contribution of both the overall curvature and the local undulations resulting from local textile gathering (Menges 2009). First, the physical model shows how the local undulated pattern contributes to the global geometry by using load case tests. Subsequently, it is analysed by computational tools using a finite element method (FEM). Generally, based on principal moment lines and force flow lines, the fabric can be reinforced by differentiated pinching patterns.

## FABRICATION

### *Robotic Integration*

The fabrication process incorporates existing fibrous composite technology and digital fabrication methods. For added speed and accuracy, the hand pinching manipulation can be replaced by the 6 axis robotic arm in the fabrication process. In this developing scenario, a series of fabric manipulations are applied robotically and interactively. For example, the robot finds the successive pinching points on the complex surface by using a 3D scanning and image processing method (Figure 12). 3D Scanning data is then analyzed computationally. Iteratively, a comparison between the in-process geometric state of fabric and guide geometry is utilized to detect the area with the highest deviation in terms of the curvature. Subsequently, the necessary manipulation is calculated for this area and is applied to the fabric either in a manual process, a robotically assisted process, or in a potentially fully automated robotic fabrication process (Figure 13). This iterative process is repeated until the fabric is transformed into a form within a specific range of deviation from the guide geometry. This adaptive robotic process can increase speed, tolerance and redundancy of fabrication.

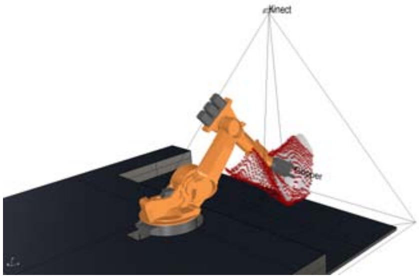


Figure 12
Robotic Manipulation integrated with 3D scanning

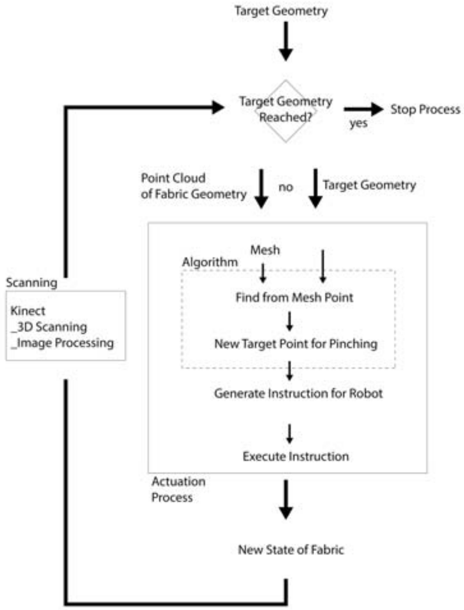


Figure 13
Information Flow for Robotic Fabrication

### *Matrix Application*

Spacer fabrics can be infused with resin and solidified into the controlled geometry. This can be done either before or after adding the manipulations. Currently the resin is applied in a manual process during the physical experiments. Potentially the fabrics can be pre-impregnated with resin before applying the manipulations and stored at cold temperatures, slowing the catalyzation process. After the resin infusion, the fabric finds it form through several steps of manipulations. Subsequently the resin in the fabric can be cured by controlling the temperature or by treating with UV-light.Alternatively the soft and flexible haptic nature of the material can locally be maintained through selective resin infusion. This allows for the integration of interior design features and structural design.

## ARCHITECTURAL APPLICATION

The potential in this fibrous spacer fabric reinforcing process is the development of a self-supporting enclosed structure without use of extensive formwork in which there are many architectural applications. New architectural tectonics can be generated with complex spatial arrangements utilizing the specific character of spacer fabric (Figure 14, 15) . The emerging surface articulations can be instrumentalized to modulate performative criteria such as structural reinforcement, acoustics and thermal regulation. Especially the characteristic soft light conditions and reciprocal relation between structural depth and light transmission have the potential to create stunning interior qualities. As a building envelope in particular, this new fibrous design methodology explores an architectural potential to create a weatherproof, habitable space in a large scale.

Figure 14
Prototype_A Structure by Spacer Fabric

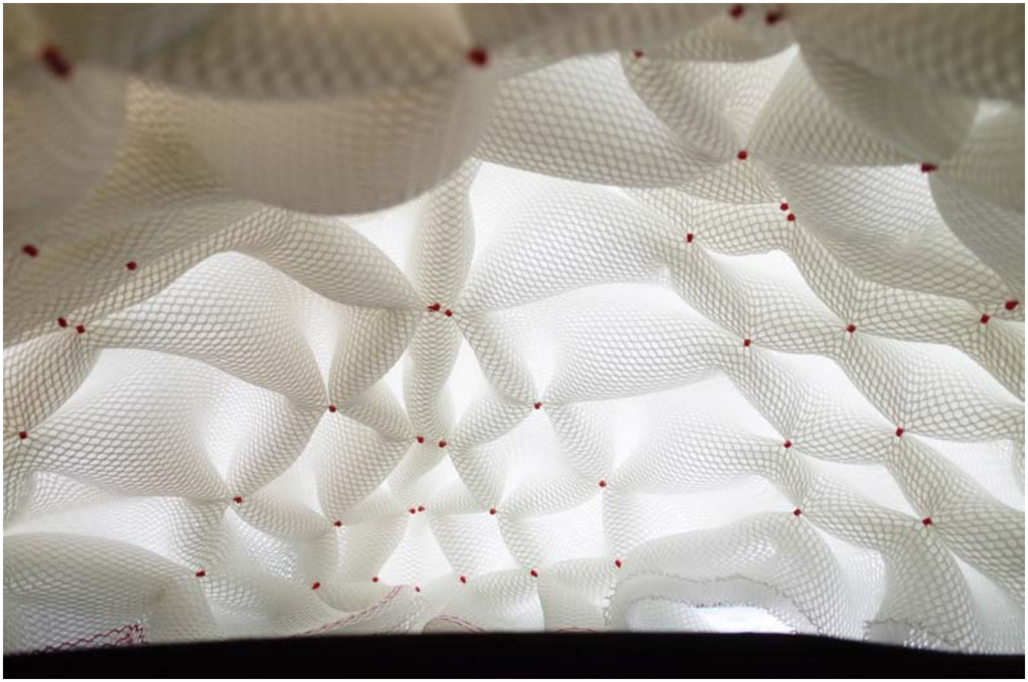

Figure 15
Prototype_B Space by Spacer Fabric

## CONCLUSION

The research demonstrates the potential design methodology of spacer fabric architecture by integrating physical prototyping, computational simulation and automated fabrication processes. Further research will focus on fabrication of a 1:1 demonstrator and the development of a fully automated fabrication process. Since the manufacturer of spacer fabric has limitations for material sizes that can be produced, modularity of elements for larger scale applications and on-site assembly may be considered. The robotic fabrication process could potentially produce mass-customised components, which will be assembled, for various architectural demands.

Full control over the fabrics production parameters and their integration into the computational design process could expand the material systems capacity. This could allow variations in the materials forming behavior through gradual transitions in mesh size and variable stiffness through controlled monofilament density. The possibility to fabricate customized multi-material spacer fabric would allow local enhancement and integration various material performances, such as structural reinforcement, light transmission and insulation properties. This could also apply for the integration of soft electronics into the fabric.

Further fabric customization could not only include material variations but also allow individual fiber arrangements within multi-axial spacer fabrics. Such a material would enable further structural differentiation through anisotropic fiber reinforcements and achieve a higher degree of material efficiency.

This architectural design and fabrication methodology could combine the soft and light appearance of textiles, increased functional integration and highly efficient lightweight construction into novel atmospheric and performative tectonics in architectural design.

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