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Tension-actuated textiles for architectural applications

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Abstract

This paper discusses the formal characteristics and architectural potential of tension-actuated textiles. Specifically, it shows how dynamic 3D surface geometries may be generated by printing rigid 2D patterns onto pre-stretched fabric. The resulting surfaces have aesthetic and structural properties similar to adaptive skins found in nature and, if scaled up, could bring a new degree of softness and responsivity to the built environment.

The hybridized textiles presented herein exhibit complex double-curvature. The final shapes are affected by many variables including material elasticity, bending resistance and ambient temperature. However, in all cases, the principal factor is the initial 2D print-pattern itself, where even small variations can result in drastically different surface curvatures. Through an extensive physical prototyping process, the causal link between 2D-input and 3D-output geometry was explored and several designs were developed with performative qualities such as incidental bending and snap-buckling.

The practical implications of the proposed shape-making technique are far-reaching. Along with CNC knitting, the method is among only a few fabrication techniques capable of generating complex surface curvature without the need for molds, formwork or manual labor. Since input patterns may be adjusted without incurring additional tooling costs, the

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process is highly controlled and customizable. For these reasons, the process promises to be competitive with traditional fabrication techniques – offering new and exciting opportunities for design and manufacturing in the coming years.

Keywords: Smart Textile, 3d Printing, 4d Printing, Programmable Materials, Self-Assembly, Smart Facade, Shading, Biomimicry

1. Project introduction

The findings presented in this paper are drawn from a 14-month interdisciplinary project conducted by students enrolled at the *Alta Scuola Politecnica* in Milan, Italy. The project started from the premise that buildings account for an outsized proportion of energy consumption in the world today and do not adequately safeguard the wellbeing of occupants. These shortcomings are largely attributable to underperforming building envelopes that fail to properly regulate the flow of heat and light from the outdoors. Smart materials and control systems provide opportunities for better performing building envelopes. Indeed, many of today's state-of-the-art facades perform quite well. But, like works of art, they tend to be expensive, singular designs for premium new buildings. To have a more widespread impact, façade solutions must remain economical and applicable to a variety of existing, underperforming buildings.

With these considerations in mind, the team proposed the use of a lightweight 'second-skin' to improve the aesthetic and environmental performance of ageing glass curtain-walls. Such a system would block excess heat gain and visual glare, while optimizing natural daylight and views. Textiles are an ideal material for such applications, as they are highly customizable in terms of size, color and translucency. However, the surface geometry of soft, woven textiles can be difficult and costly to control, involving complex cut patterns and structural frameworks. Therefore, it was deemed necessary to explore new means of shape-making wherein planar surfaces acquire three-dimensionality autonomously, without extensive tooling or labor.

The proposed manufacturing process is situated at the intersection of digital fabrication and smart materials. It leverages the inherent elasticity of textile as an actuator, capable of inducing physical transformations. By depositing a pattern of rigid material onto the textile when outstretched, the textile's elasticity is selectively inhibited, causing non-uniform yet predictable surface deformation. This permits extremely complex 3D curvatures to be achieved with the application of simple 2D patterns [fig. 1].

The project builds upon the work of scholars in the emerging field of programmable materials (Yao, 2015). The prototyping process has been tested at several institutions with objectives ranging from the mathematical (Guseinov, 2017) to the aesthetic (Co-de-it, 2017). This project is unique in placing emphasis on large-scale, real-world building applications, arguing that the use of smart textiles with an economic shape-making process could be a game-changing innovation in the world of high-performance building facades.

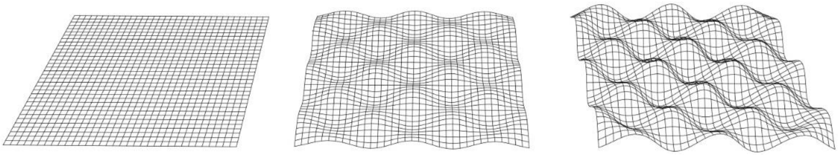

Figure 1: Prescribed deformations of plane from 2D to 3D.

2. Performative Skins

Building envelopes are increasingly seen as active systems meant to regulate environmental flows. They absorb daylight, block excess heat, shed water, filter pollutants and so forth. In short, they are expected to perform many of the same tasks as living skins found in nature, which respond to their environments in adaptive, resource efficient ways. There is much to be gained, therefore, in developing new building skin concepts with an eye toward the natural world, emulating its material intelligence wherever possible.

2.1. Living skins

The living skins of plants and animals are case studies in good design, with physical characteristics that have been proven and improved over millions of evolutionary cycles. Human builders have long borrowed from nature's catalog – either *directly* through the use of animal hides and plant fibers, or *indirectly* through the simulation of organic materials and systems. But the extent of biomimicry in architecture should not be overstated; today's buildings have more in common with the solid, inanimate confines of a cave than they do with the soft, dynamic skins of living organisms. Most buildings remain square and static.

In contrast, plant and animal skins are often characterized by (a) complex double-curvature and (b) softness and/or movement [fig. 2]. Curvature helps in achieving structural stability with minimal material input, while range-of-motion allows for better adaptability and resilience to changing environmental conditions. If buildings were not limited by manufacturing constraints and tradition, they might acquire these same shape characteristics, which are so effective and widespread in the natural world.

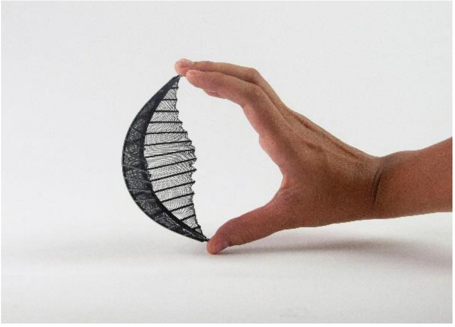

Figure 2: A prototype designed to replicate the shape and movement of the Bird of Paradise plant.

2.2. Technological skins

Textiles are perhaps the building material best suited to simulate the performance of living skins. They share many shape characteristics with plant and animal surfaces, including the capacity for softness, movement and double-curvature. This is by no means an accident as the first textiles were developed specifically as substitutes for animal hides in building and clothing applications. Textiles met and exceeded the performance requirements of earlier materials, while also being *economical, scalable* and *customizable*.

This biomimicry success story is considered one of the first examples of human 'technology' (Postrel, 2015). Time and again, textiles have been a driver of innovation – kicking off the Industrial Revolution with mechanized production and anticipating the Digital Age with binary punch cards. The future of smart buildings and dynamic building facades may very well be propelled by the next big breakthrough in the textile industry.

2.3. Programmable materials

It is popular today to talk about *smartness*, which in the age of smartphones is often associated with digital technologies and processing power. Search '*smart textiles'* online and the top image results will inevitably feature digital circuitry. Yet, smartness goes far beyond the digital. Indeed, in the natural world, smartness is manifest in the physical shape and structure of organic materials; it is baked into the biology of living things.

The emerging field of *programmable materials* borrows this natural logic, embedding smartness into the composition of materials themselves (Yao, 214). A 'programmed' assembly is one that responds directly to external stimuli in a predictable and desirable way. Textiles, being highly customizable and kinetic, are an ideal medium for this type of material programming. So rather than resembling circuit boards, the *smart textiles* of the future are likely to be as dynamic and life-like as living skins.

3. The Shape-making Method

While it may be advantageous to emulate the high-performance surface geometries found in nature, economic and manufacturing constraints have largely precluded the idea. Today's methods of replicating organic shapes are complex and costly, typically involving custom molds. Complex forms are certainly achievable, but high tooling costs lead to shape-standardization and loss of variety. A new shape-making method, leveraging recent innovations in smart textiles and digital fabrication, could change all of this. The following sections describe the prototyping process and offer observations about the resulting forms.

3.1. Prototyping process

Prototypes were produced by printing rigid thermoplastic onto flat, pre-stretched fabric [fig. 3]. The design input is a 2D pattern, which is bonded to the fabric layer, locking the fibers in their outstretched position. When the fabric swatch is released from its frame, the printed areas remain elongated, resisting both compression and bending. Meanwhile, the unprinted areas of textile contract, causing distortion of the entire plane.

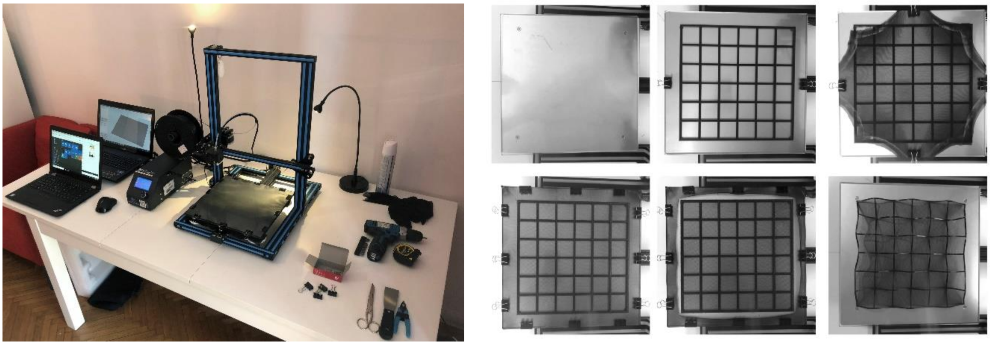

Figure 3: The Creality CR-10 3D-printer used by the team and six main steps of the fabrication process: (a) clean and pre-heat bed; (b) print lower layers; (c) stretch and clip fabric; (d) print upper layers; (e) cut away excess material; (f) remove part from printer bed and allow 3D deformation to occur.

Through the course of the study, different fabrics and plastic filaments were used. The best results were achieved with an elasticized tulle net, sandwiched between multiple layers of TPU flex-filament. Fabrics were stretched bi-laterally to about 150% of their original dimensions and deposited plastic patterns were permitted to cool before removal from the machine. The nozzle temperature and height were fine-tuned to achieve as strong a plastic bond as possible without inadvertently damaging the textile.

3.2. Shape characteristics

After having optimized the process, a *catalog of shapes* was printed using consistent materials and print-settings. By holding these variables constant, it was possible to identify how variation in the 2D print patterns impacts 3D form. The following observations were made:

- The interplay between elongation and contraction generates complex, non-developable, Gaussian curvature, but not simple one-dimensional bending.
- Patterns with more plastic toward the center (e.g. an 'X') result in 'dome-shapes' with positive Gaussian curvature; whereas patterns with more plastic toward the perimeter (e.g. an 'O') result in 'saddle-shapes' with negative Gaussian curvature [fig.04].
- Depending on the print pattern, the resulting parts will have two or more states of structural equilibrium. When an adequate force is applied, the surface 'pops' from one state of equilibrium to another in a process called snap-buckling.
- Two main pattern logics were used for the plastic deposition: linear elements (ribs) and rasterized gradients of dots (tiles) [fig.05]. While tiles are a more nuanced method of generating curvature, they offer no bending resistance and collapse like a limp sock. Ribs, on the other hand, serve as a built-in structural frame that helps to maintains form.
- Though a formal distinct exists, the surfaces produced in this method have much in common with *developable surfaces*. Both geometric families achieve 3D shape from 2D planer input; both achieve overall structural stability despite being locally thin.
- Folding is possible and may even be self-induced, resulting in origami-like assemblies.

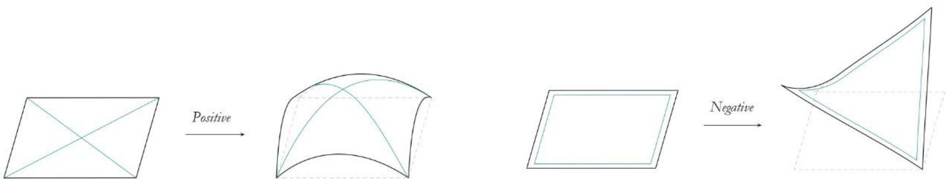

Figure 4: The shape of structure applied determines the final shape of the 3d form

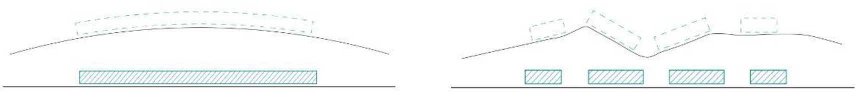

Figure 5: The pattern typology of the print pattern (ribs or tiles) affects bending resistance

3.3. Software applications

Though not strictly necessary to achieve quality results, software may be used during the design process both as a predictive visualization tool and as a generator of pattern. Shape prediction is the most valuable and computationally challenging of these functions, as the software must account for many physical variables at play like material stiffness, fabric tensioning and ambient temperature. This study made use of the Kangaroo plugin for the NURBS modeling software Rhinoceros 3D. While Kangaroo and similar physics-modelers give an indication of what is possible, they remain cumbersome and error-prone for non-expert users.

Software may also be used to 'reverse engineer' from the desired 3D output to an unrolled 2D input pattern. Two projects cited by this paper focus entirely on this problem. The first contribution, CurveUps by scholars at IST Austria, proposes a custom algorithmic approach (Guseinov, 2017). The second contribution, Self-Forming Structures by Nervous Systems, proposes the use of a surface-unwrapping tool used in the game design industry called Boundary First Flattening (Sawhney, 2017). The idea is to 'unwrap' the 3D surface onto a flat plane and identify the zones of minimum and maximum distortion. The distortion map generated by the unwrapping tool is then used to create a corresponding rasterized pattern that can be printed (Fields, 2018).

4. Process Fundamentals

There were many practical considerations to understand and overcome during the prototyping process to achieve clear results. However, the scientific value of the project goes beyond the specific equipment or settings being used. This section focuses on the fundamental aspects of the shape-making process that are valid regardless of fabrication process or scale. These principles represent the conceptual groundwork on which real-world innovation may be built.

4.1. Developability

One fundamental aspect of the process is the *2D-to-3D* transformation. In contrast to *developable surfaces* like origami that assume three-dimensionality through bending and folding alone, the hybridized surfaces assume their shape through a process of planar distortion. Furthermore, the transformation is *self-actuated* by intrinsic material properties like elasticity and/or environmental stimuli like heat. There is no need for external/manual manipulation other than removing the assembled part from the machine.

4.2. Patterning

Structural patterning is the principal variable governing the shape and stability of the final form. The pattern determines the location and extent of surface distortion, which in turn determines the location and extent of curvature. Distortion is a relative variable, meaning that what happens in any given zone is dependent on what happens in neighboring zones. If the entire surface is distorted equally, it will remain flat. Surface curvature results from distortion differentials, mathematically defined by the input pattern.

Structural patterning may also affect the assembly's overall bending resistance. A rasterized non-continuous 'dot' pattern will generate surface distortion and curvature but will not resist bending. In contrast, a linear 'ribbed' pattern may resist bending and, in doing so, will provide greater overall stability. Structural patterns with more continuity ensure more continuous curvature and fewer inflection/buckling points [fig. 6].

4.3. Hybridization

The final form is a composite of two or more input materials. These may be referred to as *surface* and *structure* respectively. In the context of this study, *surface* may be thought of as a thin, flexible membrane that acts in tension. Whereas, *structure* is a relatively solid deposited material forming a pattern that acts in compression and, at times, also bending. A third material, such as a *coating*, may be introduced to augment the performance of the final assembly [fig. 7].

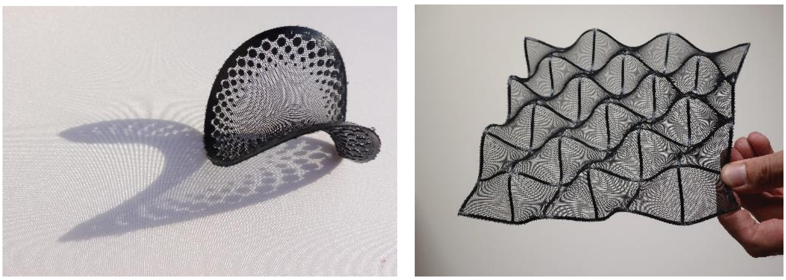

Figure 6: Patterning variation in (a) a singular, circular form and (b) a repeating, square grid.

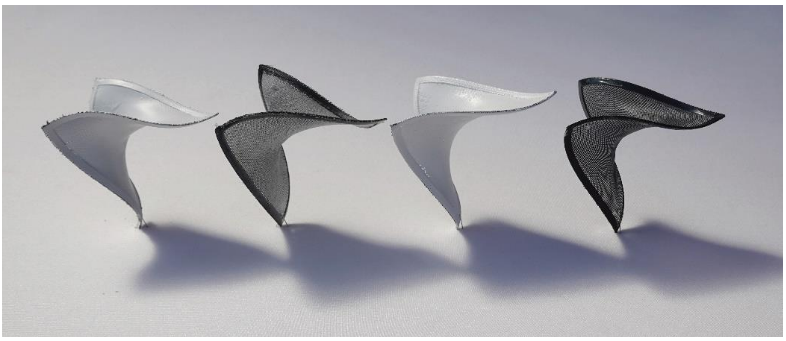

Figure 7: Four 'Hypar' structures generated by the interplay between surface and structure. Each has been treated with a different coating, affecting aesthetic and performance characteristics.

4.4. Typologies

The prototypes presented in this paper are composed of an *active* surface and a *passive* structure. But this may not always be the case. In fact, there are at least three distinct material typologies, each involving a different self-actuation process:

(1) *Pre-stretching* is the method described earlier in this paper. It involves stretching a surface and bonding it with a more rigid structure. The hybridized surface is actuated by the contraction of the surface when it is released from its frame.

(2) *Post-contraction* is a method wherein structure is bonded to an unstressed surface material, possibly a thin-film polymer that can be contracted through a chemical or mechanical process. The hybridized surface is actuated by the contraction of the surface when exposed to a reaction agent (chemical, heat, etc.).

(3) *Post-stretching* is a method differing from the previous two approaches in that the structure itself elongates after being bonded with the elastic surface. The hybridized surface is actuated by the elongation of the structure when exposed to a reaction agent (pneumatics, heat, etc.).

5. Market Viability

The proposed shape-making method could significantly impact many disciplines, from fashion to interior design and beyond. It points toward a future where softness and variation are as widespread in the built environment as in the natural world; where engineered materials are as responsive as living skins. The viability of the idea is a function of both feasibility and value: *how can programmed textiles be produced at scale? and will their end-value outweigh costs?*

5.1. Scaling up

There are several manufacturing techniques that might be used to replicate the team's prototyping process efficiently at a larger scale. These include large-format 3D-printing, laser cutting and CNC weaving/knitting – digital processes that offer pattern variation at no extra cost. The machinery need not be complicated. For example, the structural material could be deposited with a simple 2D 'plotter' onto moving sheets of stretched fabric. The hybridized surface could then be collected onto a roll, shipped to construction sites and deployed with reduced overall material, transportation and installation costs. An analogous process could occur in reverse to efficiently remove and recycle the textiles at the end of their optimal lifespan.

The success of these manufacturing and recycling processes depends largely on the selection of appropriate materials. Many textile surfaces already exist for building applications, including some that are fully reusable (technical nutrients) or fully biodegradable (biological nutrients).

It is critical, however, that the chosen *surface* material have enough elasticity to generate and retain the desired surface deformation. Furthermore, the *structural* material should be easily formable into the desired pattern and securely bondable to the selected surface through chemical and/or mechanical means. A third material, such as a spray-on coating, may be used to improve structural performance, protect from the elements and/or reduce flammability [fig. 7]. The long-term durability of these assemblies need not be a major constraint, provided they are situated within healthy economic and environmental ecosystems. The ephemerality of the engineered skin, as with living ones, may be the key to sustained performance and appropriateness in cities as urban and climactic conditions rapidly change.

In today's economy, companies specializing in smart textile materials are distinct from those specializing in additive manufacturing. The realization of high-performance 3D-printed-textiles requires the merger of competencies and equipment of these two fields. If and when this occurs, the production of tension-actuated textiles could be as affordable as screen-printing is today.

5.2. Value proposition

Hybridized textiles could be used to wrap buildings in a second-skin, improving façade appearance and performance. The textile would be tuned to site-specific needs, offering different degrees of shading, daylighting, views and urban-identity. The low-cost and versatility of such a system makes it suitable for ageing buildings, which are among the lowest performers in cities today. In this case, the fabric layer could easily be attached to existing buildings with a modular, lightweight structural system like scaffolding. Through a case study in the Porta Nuova district of Milan, designs were developed and evaluated with regard to stakeholder needs and requirements [fig. 8]. Environmental and visual simulations show that when shaped correctly, even a thin layer of textile can significantly reduce energy consumption and improve human comfort, which creates value for building occupants and owners alike.

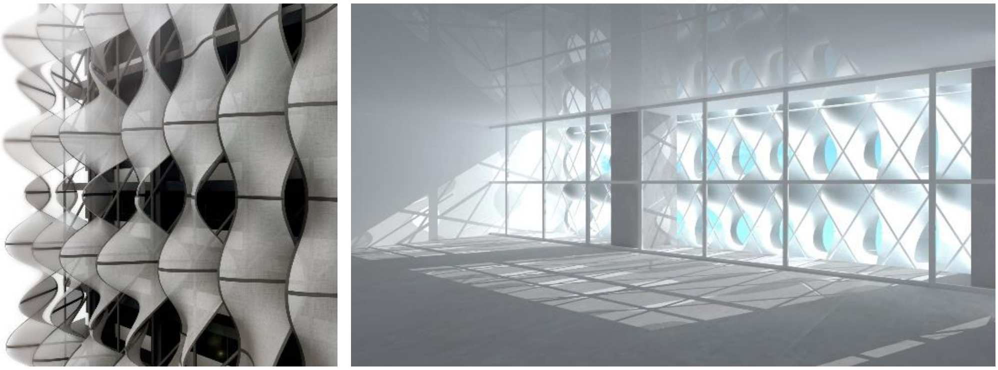

Figure 8: Rendered exterior and interior views of an office building with an undulating textile second skin.

5.3. Final remarks

One might question the logic of wrapping buildings in textile, opting instead for more traditional and durable building materials like stone and glass. But textiles are in fact one of the oldest and most technological of building materials. What they lack in longevity, they make up for in adaptability – a quality they share with the living skins of plants and animals.

If people change their clothes daily and animals change skins/coats through the course of the year, why don't building envelopes change too? For centuries, the performance of buildings has been limited by material and manufacturing constraints. The introduction of an innovative new fabrication method for textiles could overturn this paradigm and change the look and feel of cities in the years to come.

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