Performative Compositions / 
Material Behaviour as an Active Agent in Design and Fabrication

Oldouz Moslemian / 2016
Master of Arts Thesis - Aalto University
School of Arts, Design and Architecture - Department of Design
Fashion and Collection Design
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ABSTRACT

While some design practices tend to relegate materiality as a passive constituent of form in the final stages of design, this thesis focuses on the implementation of material behaviour as an active parameter within both the process and the outcome of design. The work considers materials’ inherent dynamic properties as a means to build performative material compositions. As a practice-led research, this thesis involves digital fabrication processes and computational methods to design a kinetic surface system. The project is developed through applied research methods, which refer to the utilisation of prototyping and scientific experiments.

The practical research is presented as three associated case studies that lead to the final production of kinetic structures. The first study examines the production of resilient tri-dimensional surfaces by combining stretch textiles with 3D printing technology. The second case consists of the generation of pneumatic muscles and their integration as actuators into the membranes. The third case study includes the design of assembly and control system of the final kinetic structures.

The theoretical research provides the necessary background information regarding the materials, technologies and procedures employed throughout the scope of this thesis. Furthermore, it provides an in-depth reflection upon the questions raised by the
practical research. It also examines the critical role of material behaviour within digital design processes. Literature and retrospective analysis of the processes are used as sources of information to support the discourse.

Knowledge and expertise from different disciplines are necessary to achieve the objectives of this thesis. The project is a collaboration with Martin Genet, a recent graduate from the Digital Knowledge Department of Ecole Nationale Supérieure d'Architecture Paris-Malaquais. Additionally, the practical research of the thesis is conducted within the premises of ADD Lab (Aalto University Digital Design Laboratory) facilities, as a multidisciplinary project between Aalto University School of Arts, Design and Architecture, and School of Engineering.

The project establishes an experimental strategy that encompasses design, material development and digital fabrication in a holistic research approach. Additionally, the thesis concludes by mapping the importance of understanding and including material information within design processes, while presenting the significant potentials of digital tools in material development. The final outcome of this thesis is presented through an exhibition of the process prototypes and the final kinetic structures.
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INTRODUCTION

OBJECTIVES

This thesis, Performative Compositions, aims to investigate the properties of materials, in particular textiles, as a means to generate performative structures. The optimal objective of this project is to study the development of hybrid experimental textiles with kinetic properties through digital design and fabrication processes. Furthermore, while materiality is reflected upon as a passive medium of form in certain design methods, this thesis focuses on the implementation of textiles’ inherent characteristics and materials’ behaviour as active agents of form. To achieve the objectives of an interactive and adaptive surface, this practice-led research develops a thorough investigation into materials, unveiling their potentials and qualities. The main research questions that guide the progression of this thesis are as follows:
- What are the advantages and challenges of implementing material information within the design process?
- How can digital technologies and fabrication methods affect the design processes in material integration and visa versa?
- What are the potentials of hybrid textiles and their behaviour as active parameters of form in adaptive structures?

The abovementioned questions are studied through an explorative research into digital fabrication methods, various textile constructions and responsive materials, in realising the project’s goal of developing performative structures. This practical research requires a progressive and fluid interaction between physical and digital experimentations, results analysis, prototyping, and design solutions.

Driven by the main goal – here, the achievement of an integrated kinetic system – each new operation is informed by the combination of its preceding stages and the revised design objectives. Therefore, this progression scheme can describe the workflow as iterative. Presented in three associated case studies, the practical research includes production of three-dimensional surfaces by integration of tensile textile structures and 3D printing fabrication methods, production of pneumatic muscle actuators by utilising braided textiles, and lastly, the construction of ‘Performative Compositions’ and their related control systems.

To fabricate such hybrid material systems, the study requires theoretical research and literature reviews to gain the necessary information regarding the materials, technologies and procedures employed throughout the thesis. The written work includes essential descriptions of the incorporated textile mate-
rials such as knits and braids, as well as the background information regarding the fabrication methods such as 3D printing and development of pneumatic actuators and kinetic systems. To provide grounds for the different phases of the project, the literature includes research into examples of recent relevant projects in the realm of design and architecture. Collectively, the process analysis and supporting literature aid the realisation of the project’s provisional outcome. The final results of this thesis are summarised and presented through an exhibition of the process prototypes and the final kinetic structures.

**Motivations**

The subject matter of my master’s thesis project evolved from multiple aspects. Throughout my studies as a textile design student I have always been incredibly fascinated by textile construction techniques and the different materials that can be integrated in their production. Also, topics such as responsive materials, technical and hybrid textiles, and their implementation in different areas of design have always enticed me. Dialogues with mentors and friends involved in other fields of study such as architecture, engineering, and digital fabrication and the comments and perspectives surrounding the realm of textiles and material design sparked intriguing questions.

In particular, exchanging simple and yet inspiring questions such as ‘what constitutes a kinetic and computational design in architecture?’ with queries about ‘what is the difference between a woven and a knit fabric and why do they behave differently?’ and ‘how can we integrate textiles in digital fabrication processes’ with my friend Martin Genet—student from the Digital Knowl—
edge Department of Ecole Nationale Supérieure d'Architecture Paris-Malaquais- resulted in the ambition for a multidisciplinary and collaborative thesis project.

By sharing the initial ideas with my textile design professor Maarit Salolainen, I was encouraged to consult with and propose these concepts to professor Jouni Partanen in the Department of Engineering. It was through their guidance, support and interest in these topics and interdisciplinary work that my thesis partner and I fully committed to this project. Additionally, Aalto University, and its cross-disciplinary approach in education and learning, provided perfect grounds for the initiation of this collaborative master’s thesis.
**Context**

The main ideas and concepts leading to the formulation of this thesis emerged from the literature gathered around materiality, digital fabrication, computational design, and kinetic architecture.

The realm of textile design is tightly bound to the knowledge of materials, understanding the behaviour and integration of materials throughout the design processes. The consistent process of understanding material’s properties and their homogeneous interrelations is commonly achieved by experimentation and accumulation of knowledge through practice. However, limited theoretical literature surrounding the critical role of material behaviour within digital design processes is available in this area of study.

Therefore, the discourse brought by this thesis around material behaviour finds its roots in other design disciplines, particularly architecture. After examining the significance of material behaviour in design within literature and existing research works, this section concludes by aligning the potentials of textiles with the research questions previously stated.

**When Digital turns into Material**

Historically, the first computer-based machine that impacted design in terms of production was the Jacquard loom. Invented by Joseph Marie Jacquard in 1804 (Hobsbawm, 1962: 45), this mechanical loom simplifies the process of manufacturing textiles with complex patterns (Sinclair, 2015).
A century and a half later, numerical control (NC) emerged. Initiated in 1942 by John T. Parsons and Frank Stulen, the research on this automation technology was followed at the Massachusetts Institute of Technology (MIT) by William Pease and James McDonough. In 1959, MIT presents the very first object produced by combining Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM). “The machine can receive information in English, figure out how to make whatever is wanted and teach other machines how to make it” (Ross, 1978: 61).

With the popularisation of personal computers since the late 1970’s, this invention took another dimension. Nowadays, designers can draw and produce parts through a direct workflow from CAD programs to automated manufacturing machines such as 3D printers, CNC routers and more recently industrial robots. Also called File-to-Factory (F2F), this technology facilitates the process of prototyping for designers and introduces the notion of customization.

Any complex form designed on a computer can be turned into a physical object by the same machine, which conceptually allows variation to be achieved. Thus, digital fabrication blurs the contrast between the digital and the physical by translating digital data into material processes.

Yet, as professor and architect Achim Menges states, “whereas the nature of CAM enables difference to be achieved, it is currently used mainly as a means of increasing speed and precision in the production of variation. [...] The accomplishment of economically feasible variation through computer-controlled production and fabrication, by manufacturers and designers
alike, does not by itself lead to strategies of instrumentalising the versatility of differentiated material systems. Nonetheless, the far-reaching potential of CAM technologies is evident once they turn into one of the defining factors of a design approach seeking the synthesis of form-generation and materialisation processes* (Menges, 2011: 203).

According to Menges, digital fabrication and computational design encompass a way greater potential for design by allowing the integration of material information and materialisation within the design process.

**Material as an active agent in design process**

While digital fabrication facilitates the transition from design to materialisation, the full potential of computation can only be reached by a theoretical and practical shift in the relation between design, form and material.

*Because of the primacy of scalar descriptions of geometry emblematic for most contemporary design tools, in the decisive early design stages materiality is usually conceptualised as a mere passive property assigned to geometrically defined elements, and materialisation is implicitly conceived as a secondary process of facilitating a scheme’s realisation within the physical world. Consequently material information is understood as facilitative rather than generative* (Menges, 2012: 17). Menges denounces here the conventional pre-eminence of the definition of form over its subsequent materialisation in contemporary design practices.
Professor and philosopher Manuel DeLanda explains the significance of such a philosophical shift. "In one philosophy, one thinks of form or design as primarily conceptual or cerebral, something to be generated as a pure thought in isolation from the messy world of matter and energy. Once conceived, a design can be given a physical form by simply imposing it on a material substratum, which is taken to be homogeneous, obedient and receptive to the wishes of the designer. [...] The opposite stance may be represented by a philosophy of design in which materials are not inert receptacles for a cerebral form imposed from the outside, but active participants in the genesis of form. This implies the existence of heterogeneous materials, with variable properties and idiosyncrasies, which the designer must respect and make an integral part of the design which it follows, cannot be routinized" (DeLanda, 2001: 132).

Both authors advocate the transition from the traditional top-down approach towards a bottom-up approach, which considers material information as a driver of design. This method would ensure the coherence of an object or the form of an object with the material composing it. In this conceptual reversal, instead of applying a shape onto a passive material, the material itself informs the form.
The Case of Kinetics

Looking into kinetic, in the early nineteen seventies when dynamic spatial design problems were explored in mechanical systems, William Zuk and Roger H. Clark state that "form may change very slowly by evolution, moderately fast by the process of growth and decay, and very fast by internal muscular, hydraulic, or pneumatic action" (Zuk & Clark, 1970).

The case of kinetics in most design disciplines and architecture suffers from a similar conceptual lag concerning the role of materiality. Indeed, only rare projects use material behaviour as a source of movement or deformation. Despite recent advancements in the field of smart and responsive materials, electronics and external mechanism still play a major role in the realisation of kinetic assemblies. A number of research projects that explore the possibilities of active structures already exist. However, most of these entail either tubular structures or faceted surfaces that can only fold over themselves. The same issue exists in the realm of textile and fashion. Rather than focusing on material behaviour, kinetic textiles are mostly developed with the implementation of electronics and other intricate motors and mechanisms.

The example of the 'Aegis Hyposurface' illustrates the limitations of the conventional conception of dynamic surfaces. This interactive wall is an ornamental dynamic faceted surface mounted on a heavy and rigid steel structure. Developed in 1999 by Mark Goulthorpe and the dECOi office along with a large multi-disciplinary team of architects, engineers, mathematicians and computer programmers, 'Aegis' is driven by a bed of 896 pneumatic
pistons, enabling the formation of dynamic 'terrains' generated by real-time calculations. (Mark Burry, n.d.) As its small separate faces move, the surface seems to change shape. While the parts of the surface mimic a surface behaviour, continuity remains an issue. The application of external mechanisms is challenging in the fabrication of responsive material compositions but also raises a new question: is there an alternative approach for continuous kinetic structures, which actively respond to stimuli without using intricate mechanical systems?

More recently, innovations in the field of materiality introduced the notion of responsiveness, which characterises the property of the so-called 'smart materials' to answer significantly to a stimulus, with the possibility of being controlled, measured, predicted and recorded.

This notion thus led to the ideas of programmable matter and 'responsive architecture', coined by the American computer scientist Nicholas Negroponte, to define a type of hybrid structure that has the ability to alter its form in response to changing conditions (Negroponte, 1975). This evolution is not merely relative to size or motion but concerns energy and the transformation of spatial forms within material substances (Brown, 2003).

In the words of Chin Koi Khoo, Jane Burry and Mark Burry from the Royal Melbourne Institute of Technology (RMIT), "the concept of 'soft kinetic' is a proposal to use the interchange of elasticity and memory in form-changing materials to affect physical transformation and kinesis [...] that offers movement and change in response to material properties rather than changes in mechanical components such as actuated motors and gears" (Khoo et al, 2011: 335-336). The writers further conclude that
"in 'soft kinetic' the transformed surface becomes the actuator itself" (Ibid.).

This review unveiled two fundamental aspects for a new perspective of materiality in design and kinetics. The first concept entails the implementation of material characteristics and properties as active parameters in design. A methodological shift towards a bottom-up approach is therefore needed to integrate this information. The use of parametric design and computational methods will offer the conceptual flexibility required to such objective.

By extension, the second concept suggests the use of materials' behaviour and their heterogeneity as a primary source of deformation. Thus, this thesis will investigate the application of form-changing material systems in order to minimise the use of engines and intricate mechanistic assemblies. Its final objective is to design and produce experimental prototypes of an endogenous system, whose kinetic properties strictly rely on the materials composing it. Therefore, the global movement of a continuous surface would directly depend on the synthesis of its local transformations.

Textiles hold a great potential in regards to both of these concepts. As textiles are compounded materials, they are highly configurable and can exhibit many different properties. Their elemental structure can be designed to control their inherent properties and ultimately their dynamic potential. Also, elasticity seems to be one of their most promising advantages in building kinetic surfaces. Moreover, hybridisation with other materials will be the key to an integrative material system.
METHODOLOGY

To corroborate the critical role of material behaviour, particularly textiles, as an active agent within digital design processes, and to further realize the project’s goals, this thesis is explored through two distinctive approaches. These approaches are comprised of a theoretical and a practical framework.

Theoretical Framework

The theoretical framework accompanying this practice-led research encompasses two main facets of descriptive and analytic writing. As the thesis incorporates several materials, techniques and tools from different disciplines, literature provides the essential background and descriptions regarding the latter. This contextualised information is presented within the case studies and subsequent experiments as supportive material to aid comprehending the terminologies and acquainting with topics related to the process. To avoid excessive stream of information, its content provides fundamental basics and delves into detailed explanations on specific notions.

Additionally, the theoretical discourse addressed in the thesis constructs an in-depth analysis and a critical insight regarding the significance and the outcome of the project. This analytical approach examines and supports the main statements and questions derived from the project. Although there exists abun-
dant technical information concerning textiles, limited theoretical references surrounding the thesis discourse are available. Since the area of investigation is recent, particularly within the realm of textiles, literature found in other design disciplines and retrospective analysis of processes are used to support the discourse. For example, the realm of digital fabrication in architecture presents questions and interests about the relation between materiality, computation and fabrication.

In order to facilitate the information flow, theory is presented in conjunction with the documentation of research processes. Therefore, theory and practice are alternately discussed throughout the thesis to complement one another.

**Practical framework**

The practical research presented in the case studies outline the design strategies and their outcomes. It describes and explains the work and justifies the decisions made throughout the research. The project implements a number of research methods within its course. These include, exploratory research, prototyping and iterative approaches, as well as applied research methodologies.

As mentioned earlier, the design goals require an in-depth material investigation to achieve the functional objective of an adaptive surface. It is important to distinguish the development of the endogenous material system from its implementation as an operational object. Although interrelated, these two intentions play specific roles depending on the phases of the research. The latter is divided into three main stages as follows.
Firstly, tests are conducted to explore material agencies and production techniques. To verify initial concepts, these preliminary explorations investigate various options responding to the material system objective. The goal is to define their capacity for improvement and ultimately their ability to achieve the functional objectives (scale, strength, movement force, price coherence, feasibility).

Secondly, after identifying the legitimate design directions, an extensive empirical research is conducted in the experimental development phase. The primary objectives of the research are to unveil underlying potentials and qualities of the material investigation. This stage is carried out through iterative prototyping to steer production processes and techniques towards consistency and reliability.

Prototypes embody an essential role throughout the research. They offer an important source of information and can be enhanced and refined through iteration (Brown, 2009). As the work concentrates on materiality, prototyping provides an instructive platform to seize the challenges of the production process and to define the parameters influencing the material behaviour. This experimental stage leads to the development of refined fabrication techniques and design strategies, which pave the way for further investigations and the design of the final pieces.

Thirdly, a scientific approach is adopted to further explore qualities unveiled within the experimental investigation. This stage of the research includes a series of methodical tests and analysis that are conducted with the aid of computational methods and digital tools. Some elementary programs are developed to au-
toramize and systematise this portion of the work. These tests aim to extend the control and knowledge surrounding the material compositions in order to attain optimization and performance. The objective is to define the influence of the various parameters over the material behaviour and to ultimately quantify them.

It is important to note that although presented as distinct consecutive research methods, these methodologies are mainly utilised concurrently in the span of the project.

**Research Documentation**

The procedures and progress of work presented within the practical research were documented through various approaches. Prototypes and physical experiments were systematically photographed or digitally filmed depending on the nature of the trial. Furthermore, data related to the physical explorations were recorded through notes and documents and later utilised in comparative studies to evaluate the results. The information was analysed and reported in charts and graphic diagrams. These documents facilitated the understanding of the obstacles, generated new ideas, and offered possible solutions to enhance the design processes.

Questions raised through the different stages of the practical research were documented in a diary form and were further built upon in the theoretical research. Meetings with designers, engineers and academicians were organized for further debate around these questions. The discussions were mainly documented through written notes and voice recording. Collectively,
the gathered literature and information supporting the discourse provided a platform for the theoretical writing.

Collaborative Facet

This thesis is developed in collaboration with Martin Genet, an architecture student from Ecole Nationale Supérieure d'Architecture Paris-Malaquais (ENSAPM). Therefore, elucidating the reasons behind the collaboration, as well as the roles of each individual in the course of the project is pertinent.

As a textile design student, my interests, beyond textile construction techniques and material properties, extend to topics such as responsive and novel materials, innovative fabrication methods, and the potentials in merging the latter. Additionally, recent experiments within the realm of digital fabrication in architecture and the theoretical discourse surrounding materials behaviour and agency have gained my attention. Moreover, Martin Genet, educated under the Digital Knowledge Program at ENSAPM, is interested in conducting explorative projects concerning material performance, digital fabrication and simulation. As friends, the aforementioned topics have raised motivating conversations and queries for us. Therefore, our common interests and the prerequisite of knowledge and expertise within varied areas of design sparked the aspiration to collaborate. With complementary skills, the work responsibilities of our team were shared as follows.

My main responsibilities consisted of material sourcing and research, 3D printing, prototyping, assemblage, testing, and documentation. I performed management tasks such as, scheduling
meetings and meeting undertakings and communicating with industrial companies within the university. Lastly, the writing of the thesis was conducted independently. Martin Genet was responsible for CAD modelling, programming, electronics, and pneumatic system configurations. Therefore, Genet executed the majority of the visual documentation.

Several phases of the project were accomplished in collaboration. The concepts and objectives of the project were developed in co-operation. All design decisions and iterations in the project were made through constant conversation and exchange of ideas. Other mutual responsibilities included tool development, graphics, and production of the final kinetic structures. Furthermore, co-learning can be noted as the paramount reward of this collaboration. For instance, sharing fundamental knowledge of textile materials with Genet facilitated him in understanding challenges and potentials in textile structures and construction. Likewise, learning the principals of digital fabrication, such as 3D printing and CAD modelling, were essential skills for me to fully partake in the project. Moreover, exchange of knowledge allowed thorough discussions and assessments in the course of the project.
INITIAL EXPLORATIONS

As the main objectives of this research project were to investigate the properties of different materials in an attempt to generate performative surfaces, few materials and production techniques were explored at the starting point.

Textile materials were chosen as the fundamental element of the project. Therefore, integration of textile construction, such as knitted and braided textiles, with other materials and the observation of their corresponding behaviours, were the primary aims for the following explorations.
Shape-memory alloys

Shape-Memory Alloy (SMA) wires were investigated for their kinetic characteristics. These nickel-titanium alloys, also known as Nitinol, respond to heat stimuli by a change in shape. SMAs are manufactured in a variety of activation temperatures. Upon heating above the activation temperature, the material structure changes from its relaxed (martensite) state to its activated (austenite) state. (Gu et al, 1998). Below the activation temperature, the material is ductile and can be deformed. If above the activation temperature, the material restores back to its memory-shape. (Figure 0.1)

The memory-shape is a predetermined form that can be initially set in high temperatures (500-600 °C). Shape-setting experiments were conducted using a ceramic kiln. The wire was then placed within the structure of a woven fabric in a martensite state and was heated to reach an austenite state, thus transforming to its memory-shape. During the activation, the SMA wire forces the textile material to follow its deformation. (Figure 0.2)

Electric current can be used to heat up and activate conductive
wires such as shape memory alloys through resistive heating methods. The application of electric current activates the material, providing the possibility of digitally controlling the surfaces. Available in linear form, Nitinol can potentially be used as a yarn in textile construction to develop dynamic surfaces.
However, the material presents a number of challenges. The shape-setting process requires a well-controlled environment with high temperatures. Additionally, SMA only offers unidirectional shape transformation.

Larger scale prototypes would encounter strength limitations and suffer from low reactivity speed. Another complication linked to large-scale prototypes is the high consumption of electrical power.

**Silicon-Based Surfaces**

After recognition of challenges and further study in materials and techniques, it was decided to orient the research towards silicon-based materials and pneumatic actuating systems. The second exploration conducted, as upstream research, was guided with the support of Kari Kääriäinen, Model Maker and Master Craftsman at Aalto University’s Design Factory.

The experiment involved fabricating moulds and casting fibre reinforced silicon sheets with integrated air cavities. By inflating the cavities with air pressure, the silicon sheet tends to expand on one side while the other is constrained by the embedded, pre-stretched knit textile. This asymmetry creates a differential strain within the surface and forces it to bend. (Figure 0.3)

Although this material formation held high experimental potential, it contradicted the objective of a lightweight kinetic structure. Moreover, the production of large-scale, silicon-based prototypes required advanced tools and appeared unrealistic within the time frame of the project.
Fig. 0.3 Activation of the Fibre reinforced silicon sheet with air-cavities. (2015)
Top: Deactivated state. Bottom: Activated. 2.5 bars of air pressure in the air channels. 200x250 mm sheet with 3mm diameter cavities.

Overview of Initial Explorations

While the aforementioned trials proved as insightful, they failed to exhibit the expected properties of the envisioned design. The surface structures lacked the desired lightness, three-dimensionality and self-standing characteristics. The production processes were complex and problematic to control thoroughly. Above all, the performance of the textile, as the fundamental element, was not clearly established.
The information obtained through these initial explorations stirred further research and consideration of other fabrication techniques, materials and technologies. These enquiries presented 3D printing as an alternative area of exploration.

3D printing techniques opened a rich investigation field and brought many advantages and interesting challenges onward. Pneumatic actuation proposed a reliable source of strength for the activation of a surface. Nevertheless, it demonstrated necessity for additional research into other kinetic systems and actuators. As a result, these became the primary areas of investigation, which are presented in length throughout the case studies.
A SYNOPSIS OF CASE STUDIES

The process of this design driven project is presented through three case studies that lead to the final production of lightweight kinetic structures through explorative approaches. It is important to note that although presented in sequence, the case studies were conducted simultaneously and are highly interrelated.

Case Study 01- Self-forming Membranes presents an investigation into the development of hybrid surfaces, with the integration of knitted textiles into 3D printing processes, generating these membranes. This case study represents a substantial portion of this thesis work and hence is described in detail.

Case Study 02- Malleable Actuators exhibits the process of developing pneumatic artificial muscles. These actuators are incorporated within the membranes to induce kinetic deformation of the surfaces. As a minimal section of the practical research, the information provided within this case study is less exhaustive.

Case Study 03- Kinetic Structures provides information regarding the design of the structure and control system for the final kinetic prototypes. It includes the description of the structure’s skeleton and connectors, as well as the development of pneumatic and electronic circuits of the control system. For this section, basic descriptive information is gathered and graphics and images are showcased.
The abovementioned studies were all conducted within the Aalto University Digital Design Laboratory (ADD Lab) facilities. (Figure 0.4) Initiated by Aalto University’s School of Engineering and School of Arts, Design and Architecture, the organization participates in research and exploration in the realm of digital design through interdisciplinary collaboration (ADD Lab, n.d.). The ADD Lab faculty have been immensely supportive in offering facilities and space, as well as technical and financial support throughout this project.

Fig. 0.4 ADD Lab Facilities. Aalto University Otaniemi Campus. (2015)
SELF-FORMING MEMBRANES

- Literature Review
- General Process, Technique & Outcome
- Material Selection
- Experimental Development
- Morphology Studies
LITERATURE REVIEW

A Glance into 3D Printing and Textiles

An initial inquiry into the integration of 3D printing in the realm of textiles and fashion exposed the technology in several projects. It is evident that the debut of additive manufacturing (AM) technologies has prompted innovative approaches in merging textile and fashion with digital fabrication. The following examples explore the potential of AM technologies producing complex geometries, intertwined pieces or multi-material parts within a single manufacturing process.

The Dutch designer Iris Van Herpen is known as one of the pioneers of merging additive manufacturing and fashion. Van Herpen presented her first 3D printed fashion piece in the collection ‘Crystallization’—2010. The project was led in collaboration with the London-based conceptual architectural designer Daniel Widrig and the company MGX by Materialise, which were in charge of the manufacturing process (Clarke and Harris, 2012: 198-199; ‘Van Herpen’, 2015). Van Herpen’s piece illustrates the potential of this digital production chain in fabricating intricate and complex three-dimensional forms (Clarke and Harris, 2012: 198-199). (Figure 1.1)

The Amsterdam-based lab Freedom of Creation uses rapid prototyping processes to produce textile-like structures (Quinn,
2010: 50-52). Designed by Jiri Evenhuis and Janne Kyttanen for Freedorn of Creation in 2003, the textile collection is a series of three-dimensional patterns of interlocking forms. Advanced 3D modelling techniques are utilised to generate loosely entwined structures, inspired by woven and knitted textiles, which are produced in a single print process (Quinn, 2010: 50-52, ‘Free-
Textile structures and their construction methods have a large influence in the designer's approach in the production of conforming novel materials through Additive manufacturing. (Figure 1.2)

The 3D Weaver is a project developed by Royal College of Art (RCA) graduate Oluwaseyi Sosanya. The 3D Weaver machine presents a loom designed to weave three-dimensional formations using X, Y and Z coordinates, similarly to the layering process of additive manufacturing. A plotting system passes a yarn around vertical sticks along a specific path at a specific height under computer control ('Sofa Fresh', 2014). The online magazine DeZeen describes Sosanya's design as a machine that "weaves interconnected layers of straight [...] threads and intertwining [...] patterns at different heights, providing the third dimension" ('De-Zeen', 24 June 2014). (Figure 1.3)

Sosanya altered the principle of FDM 3D printing machines to design an innovative fabrication process, which allows genera-

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*Fig. 1.2 3Dprinted interlocking patterns. FOC: Freedom of Creation. (2003)*

*Source: http://www.freedomofcreation.com*
Fig. 1.3 3D Weaver. Oluwaseyi Sosanya. (2014) “This pattern has a comfortable compressive quality and holds similar properties to soft injection foams found in shoe soles.” Source: http://www.sosafresh.com/3d-weaver/

...tion of a variety of patterns with different structural behaviours. Additionally, other materials such as yams are introduced as 3D printing ingredients.

Further reviews of literature and research disclosed a project that has employed 3D printing techniques in generating self-forming surfaces. Published online in late 2014, the investigation was conducted by the research group Programmable Materials within the Self-Assembly Lab directed by Skylar Tibbits at MIT (Cambridge, MA, USA). Programmable Textiles project conducted by Christophe Guberan, Erik Demaine, Carbitex LLC, and Autodesk Inc. provides limited images and a short video, presenting the process of 3D printing on pre-stretched textiles. ("SelfAssem...
bly lab, n.d.) The project displays a transition of materials from two-dimensional to three-dimensional surfaces.

The MIT project provoked motivating thoughts in its methods and the possibility of combining other materials with the 3D printing process. However, there was little literature surrounding this project in assisting with the initial tests and explorations of the thesis. An analogous approach was adopted to further investigate its feasibility and the opportunity to generate a lightweight kinetic structure through integration of actuating systems. (Figure 1.4)

Presented in the following section, a short background into 3D printing provides information regarding the technology employed throughout the project. Subsequently, fundamental background into stretch textiles is delivered to elucidate the choice of fabric materials within the first case study.

Fig. 1.4 Programmable Textile. MIT, Guberan, Demaine, Carbitex, Autodesk. (2014)
Source: http://www.christopheguberan.ch/Stretching-fabric
Additive Manufacturing Background

Additive manufacturing (AM), commonly referred to as 3D printing, is the primary computer-aided manufacturing (CAM) technology utilised within the practical research of this project. AM describes the group of technologies that use additive processes to produce three-dimensional objects from computer aided design (CAD) files. Building these objects generally consists of the incremental deposition of material layers under computer control (Hopkinson, 2010). Each of these layers represents a thin cross-section of the part derived directly from the original CAD file. Typically, AM involves a relatively direct process between CAD and CAM that can be divided in the following steps. First, a solid is drawn employing 3D CAD software. Its geometry is then read by an AM software that generates the successive slices to be printed. Once the machine parameters are defined, the building process can start. After the part is complete, it can be cleaned or post-processed if necessary.

Although the origins of the technology can be traced back to the 1950’s and 1960’s, when the first computer and numerical technologies were developed, the first patents of AM processes were filed in the early 1980’s (Gibson et al., 2010). In 1981, Hideo Kodama of the Nagoya Municipal Industrial Research Institute presented an ‘Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer’ (Kodama, 1981). In his publication, Kodama introduced an experimental machine prototype capable of ‘fabricating a solid model by using liquid photo-hardening polymer in a short time, at low cost, and without excessive manual labor’ (Kodama, 1981: 1770). In 1984, parallel patents describing a similar concept of fabricating a
three-dimensional object by selectively adding material layer by layer were filed by Murutani (Japan), Andre et al. (France), Masters (USA) and Hull (USA). However, Charles W. Hull is generally recognized as the most influential, as he founded 3D Systems Corporation (Gibson et al., 2010). In his patent, US 4575330A, titled “Apparatus for production of three-dimensional objects by stereolithography”, Charles W. Hull defined the process of stereolithography (STL) as a “system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed” (‘Patents’, 1986). (Figure 1.5)
In 1987, his company was the first to commercialise AM technologies with the stereolithography apparatus (SLA) (Wohlers, 2012: 1). Shortly after, in 1989, 3D Systems introduced the STL file format, which translates a 3D solid from any CAD software into the pure description of its external surface (3D Systems Inc., 1989). This format was widely accepted and has become a standard, considering nearly all CAD software can export STL files and most AM systems can recognize those files.

Since 1987, numerous other AM technologies have emerged. While their primary working principles remain similar, the main differences among these technologies concern the type of materials used for printing, the principle under which the layers are created and the bonding method of consecutive layers. In fabricating, they can also differ in terms of precision, printing or print duration and overall quality of the outcome. Today, the principal AM technologies include: Stereolithography (SL), Selective Laser Sintering (SLS), 3D Printing (3DP), Laminated Object Manufacturing (LOM), and Fused Deposition Modelling (FDM) (Hopkinson et al. 2006: 55-80). FDM is the main technology employed throughout this research.

The Machinery Involved

Developed in 1988 by Scott Crump, FDM was first commercialised in 1991 by Stratasys (Wohlers, 2012). This extrusion-based technology uses thermoplastics in filament form. The polymer is melted in a heating chamber and pushed through a nozzle onto the building plate. As it is cooling down the material solidifies and bonds to the previous layer. The extrusion head is carried on a plotting system that allows movement in the horizontal
plane while the platform on which the material is placed indexes in the vertical direction to allow formation of the successive layers. The plotting movement needs to be synchronized with the extrusion rate to ensure smooth and consistent deposition (Gibson et al., 2010).

The FDM principle is rather simple and its implementation inexpensive. Several projects and companies are making efforts to develop affordable 3D printers for home desktop use. Much of this work has been driven by and targeted at early adopter communities, with additional ties to academic and hacker communities.

The two machines used for this research are the CREATR HS from Leapfrog™ and the GIGABOT® from re-3D. These machines target both professional and hobbyist makers as they provide a simple FDM system at an affordable price. They belong to the group of so-called desktop AM systems (Pei, Shen, and Watling, 2015).

In contrast to other AM machines, which feature an optimized process of printing, this type of FDM technology allows for flexibility of use. Indeed, the 3D printing programs dedicated to these types of printers allow for a high level of customizability in controlling the printing process. The variation of parameters has a significant impact on the quality of the printed part. The successions of machine operations are calculated based on the model by the slicing tool of the 3D printing software. The material of each layer is deposited along a linear path defined by the slicing tool. The composition of a layer is a combination of the outer shell (perimeter) and the inner filling (infill).
3D printing has a number of production advantages such as accessibility, reasonable cost, and control in fabrication procedures. Additionally, the process allows production of complex geometries through assortment of materials available for printing as well as integration of multiple materials within a single process.

Knits & Stretch Textiles

Textiles are generally categorized based on their production methods. Weaving, felting, lacemaking, braiding and knitting are among the numerous techniques applied to produce textiles using yarns and fibres.

In his book Knitting Technology: A Comprehensive Handbook and Practical Guide, David J Spencer, classifies the mechanical production of textiles using yarns into three principal categories; interweaving, intertwining and interlooping. Interweaving refers to the crossing of two sets of yarns in vertical (warp) and horizontal (weft) directions that results in the generation of a woven fabric. (Figure 1.6a) Intertwining, applied in techniques such as braiding and knotting, refers to the intersection and twisting of yarns at different angles (Spencer, 2001: 2). Braided structures will be further explained within case study two, as they are the main textile material investigated within the latter.

The third method describes the principals behind the production of knitted textiles. "Interlooping consists of forming yarn(s) into loops, each of which is typically only released after a succeeding loop has been formed and intermeshed with it so that a secure ground loop structure is achieved" (Spencer, 2001: 3). (Figure
1.6b) The tensile properties and structure of knitted structures, employed within the first case study, play a predominant role in the results achieved through the research. Therefore, it is essential to provide background information regarding the material and the underlying production technology.

The term knitting, traced back to the mid-sixteenth century (Spencer, 2001: 7), is a fabrication technique that uses consecutive process of intermeshing loops of yarn(s) to create a textile structure by hand or machine (Sinclair, 2015; Kadolph, 2014; Anburnani, 2006). Knitted fabrics are mainly produced through two main methods of weft knitting and warp knitting.

Weft knitting (Figure 1.7a) is noted as the initial method of generating knitted structures, first by hand and later by the introduction of the stocking hand frame in 1589 by William Lee ‘of Calverton in Nottinghamshire’ (Spencer, 2001: 7-9). In this method, one continuous yarn is used to create horizontal loops and
Fig. 1.7a (top) Weft-knitting principle. Fig. 1.7b (bottom) Warp-Knitting principle. Source: ‘Knitting Technology’, David J. Spencer. (2001)
the internmeshing of loops take place on a crosswise or circular manner (Anbumani, 2006).

Warp knitting, (Figure 1.7b) first presented by Crane and Porter in 1769, was never a hand-manipulated technique (Spencer, 2001, p. 12). In this fabric forming technique, the ends of numerous yarns are used to create vertical loops, with a lateral internmeshing of these loops a basis is formed (Anbumani, 2006).

Numerous properties are taken into consideration in production and final application of both knitted and woven textiles. These include deformation, stretch properties, recovery properties, dimensional recovery, creasing, thickness and compression, air permeability, liquid transfer qualities and comfort (Cook, 2011: 37-47). These properties are explained and examined in detail in the book Advances in Knitting Technology edited by K. F. Au. However, the most important quality within the process of this case study is the tensile strength of the knitted textiles that is reliant on both the material composition and the structure of the fabric.

Knitted textiles were used in this case study due to their capability to stretch far more than woven textiles. The stretch quality of these fabrics is due to both their structure and the material composition of the textile. A simple method of comparing the tensile properties of a knit fabric with a woven textile is to assume the two fabrics are made of the same material. The structure of a plain knitted textile, as previously explained, consists of loops. With the application of force, the curvature of the loops changes, which results in the deformation of material. Due to the more open structure of knitted fabrics compared to woven textiles,
SELF-FORMING MEMBRANES

with the application of greater force, yarn interchange can take place within the material (Cook, 2011:38-39). Thus, “moving yarn segments from the vertical sides of the loops into the tops and bottoms of the loops”. This allows for the stretch of 15-20% before any force is applied on to the yarn itself for stretching (Ibid.).

The deformation mechanism of a plain weave textile is completely different. In the woven textile, the yarns pass over and under one another in a wavelike pattern. This undulating pattern is referred to as crimp. When force is applied, the textile can only change form between 3-5% before the crimp effect is removed and the yarns are straightened (Cook, 2011: 38).

As mentioned earlier, yarn properties play another important role in the tensile characteristics of knit textiles. Knitted textiles, particularly the industrially produced fabrics, require “relatively fine, smooth, strong yarn[s] with good elastic recovery properties” (Spencer, 2001: 4).

The development of synthetic fibres such as Elastane, wildly known by their commercial names Lycra® and Doralastan®, have played a significant role in the knitting industry. Invented in 1937 in Germany, Elastane is “a fibre composed of at least 85% by mass of a segmented polyurethane which, if stretched to three times its unstretched length, rapidly reverts substantially to the unstretched length when the tension is removed” (BISFA, 2009: 11).

The extreme elasticity properties, tension capacity, and durability have made the material a great candidate within the knitting industry. Elastane intensifies shape retention and supports the
deformation properties of a knitted fabric structure. When an elastic material is deformed due to an external force, it experiences internal resistance to the deformation and restores to its original state if the external force is no longer applied. Further developments in technology and materials have led to significant advances within the realm of textile and indeed the knitting industry.
The three-dimensional surfaces developed within the first case study of this thesis are produced by 3D printing on tensile textiles. By printing a thin frame of plastic onto a pre-stretched fabric, this hybrid composition results in a self-forming and resilient surface. The general production process of these membranes can be divided into three main operations. (Figure 1.8)

Initially, an elastic textile is stretched around a metal frame. The framed tensile fabric is then placed on the plate of a 3D printer. Next, a defined geometry designed with the aid of 3D Modelling programs such as Rhinoceros, is printed on the surface of the pre-stretched textile. After the printing process is completed and the frame is removed from the 3D printer plate, the surface is released by cutting the excess fabric surrounding the printed area.

As the textile is released from the metal frame, its tension force is transmitted to the printed plastic geometry. Conjointly, the plastic frame constrains the textile from fully recovering its relaxed state. Originally printed flat, the plastic frame bends under the tensile force of the fabric. As a result, the prototype takes a three-dimensional shape, corresponding to the balance between the rigidity of the plastic frame and the tensile strength of the textile. The final stable form of the prototype draws the equilibrium state between these two interacting forces.
This process produces lightweight, flexible and resilient three-dimensional surfaces. (Figure 1.9) The outcome of this hybrid material composition relies on various factors such as the type of textile and its tension, the thermoplastic material properties, as well as the geometry of the printed frame. Therefore, it is essential to understand the influence of these parameters in order to enhance the control over the prototypes’ structures and properties. The practical research conducted through this case study concentrates on testing, observing and analysing the behaviour and performance of different combinations of these agents. The following chapter presents an in-depth description of the investigation processes and provides the necessary background knowledge to understand these research enquiries.

Fig. 1.8 Left General Process of 3D printing on textiles. (2015)
Stretching the textile, printing on the surface of textile, releasing the printed geometry

Fig. 1.9 Self-forming released geometries. (2015)
Preliminary Observations

To verify the feasibility of the production process, an initial "blind" test was conducted, which exposed the main challenges at stake. This experiment was conducted on the CREATR HS 3D printer from Leapfrog™. (Figure 1.10)

A knit textile was manually stretched on the printer platform. Then, a 4x4 square grid was printed directly on the surface of the fabric using Polylactic Acid (PLA). The result revealed two main issues. Firstly, the plastic frame displayed a weak adherence to the fabric. Secondly, the rigidity of the printed part prevented the fabric to initiate its deformation. It was evident that numerous tests and adjustments were necessary to achieve successful results.

![Figure 1.10](image1.png)

*Fig. 1.10* The initial blind test results. (2015) 4x4 square grid 3Dprinted on stretched knit textile with PLA filament
At this early stage of research, a set of experiments explored a selection of few polymers with different stretch fabrics. The objective was to find the most suitable materials for this fabrication process. Because material properties and composite quality were considered as the main focus, geometry remained constant in comparing the materials and their behaviour. This experiment was also conducted on the CREATR HS 3D Printer from Leapfrog™. Fabrics were cut to the same size (200mm x 250mm), and stretched over the printer platform. Filaments were used to print on all selected textiles. The nozzle temperature was the single parameter of the machine setup that varied throughout the tests, due to the requirement of matching each plastic's melting point specification. The outcome of this test facilitated the selection of few materials to employ throughout the case study.

Henceforth, various explorations were carried out to identify the different parameters involved in the production and to also determine a respective influence over the outcome. In order to execute constructive experiments, the observed obstacles were systematically isolated and examined within the tests. A detailed documentation routine was adopted to draw comparison and analyse the outcomes. Analysis and information gathered throughout the experiments provided insight for enhanced production of the final membranes.
MATERIAL SELECTION

Thermoplastic Filaments

As mentioned earlier, a large variety of thermoplastics in filament form are available for FDM 3D printers. They demonstrate different mechanical properties and imply specific printing parameters. As well as their conformity with the machine, the filament’s characteristics were brought into light by the conducted tests. (Figure 2.4)

Conformity with the machinery proved to be a difficult aspect to anticipate and yet presented a key factor in the filament selection. For instance, polycarbonate (PC) seemed a promising candidate with high strength and flexibility properties. However, polycarbonate demands a high printing temperature from 270°C up to 310°C (’Taulman3D’, n.d.), while the printer at hand could merely reach up to 250°C.

Presumably, nylon would hold notable potentials for its integration into stretched textiles and features suitable mechanical properties. Nylon is an extremely strong and durable material, and represents appropriate flexibility attributes similar to polycarbonate. Nevertheless, nylon filaments require demanding handling and process. They are highly sensible to humidity, light and are environmentally unfriendly. While the recommended printing temperature of 242°C by to the manufacturer (Ibid.)
could be reached by the printer's hot end, this temperature setting revealed insufficient while sampling. Consequently and despite several attempts, the tests displayed poor intra-layer and inter-layer adhesion. Once more, the machine setup was considered the principal cause of these failures, since it could not address the needs of an appropriate print with the material.

Among the multiple flexible filaments available on the market, few were tested during the research: Flexifil, Crystalflex and NinjaFlex. The implementation of these materials provided two issues due to their flexibility. Firstly, their softness conflicted with the extrusion-based system of the 3D printer, causing feeding inconsistency. Indeed, a small gap between the feeding wheel and the heating chamber caused the filament to bend under the pressure before it melted. Once bent, the filament stopped extruding and jammed within the gap. Despite this mechanical problem, some of the tests with Flexifil succeeded and offered appropriate prints and a suitable binding to the fabric. However, the second issue was related to the membrane's behaviour. The samples deformed quite drastically due to the softness of the plastic frame and lacked resilience. This material was then considered too flexible for the intended use, but its malleability drew interesting potentials for other applications. For example, it could be applied in clothing or combined with other polymers in multi-material prints.

Major modifications of the printer in mechanical parts, electronics and software were required to meet the expectations of printing with PC, nylon or flexible filaments. Although the problems were identified, upgrading the machine appeared fairly expensive and unproductive at this stage of research. Additionally,
higher printing temperatures also induce higher risk of burning the fabric.

These examples clearly illustrate the role played by the printer and the imposed limitations over the choice of materials, and filaments in particular. Therefore, these first tests ruled out some choices based on the stability of the printing process. However, drawing eminently conclusions upon these results would be misguided. It is important to note that interesting materials rejected at this point could lead to future investigations at a more advanced stage of the research.

Polyactic Acid (PLA) and Acrylonitril Butadiene Styrene (ABS) filaments proved to be most practical for several reasons. PLA and ABS are the most commonly used plastics in FDM technologies; these filaments offered stable results within the production process. Additionally, the formations appeared resilient, relatively malleable and aesthetically pleasing. 3D printing with PLA is generally considered more convenient than ABS due to lower printing temperature and less warping issues – common condition caused by quicker cooling rate of the plastic at the edges of the print compared to the inner sections. After further sampling, ABS was preferable to PLA by comparing their respective outcomes based on the following reasons.

ABS appeared to be less brittle than PLA and offered more stable results when repeating the prints. Another major advantage of ABS was its bending properties and elastic behaviour. In material science, an elastic deformation is a reversible change in form, referring to the material’s property, returning to its original shape after the force is removed (Ashby, 2011: 4–5). On the other
Fig. 1.11 Example of material selection tests. (2015)
ROW 1: Weft-knitted (88% Polyamide-15% Lycra)- PLA filament
ROW 2: Tricot Knit (88% Polyamide-12% Lycra)- Nylon filament
ROW 3: Tricot Knit (88% Polyamide-12% Lycra)- NinjaFlex filament
ROW 4: Warp-knitted (92% Polyester-8% Lycra)- ABS filament
hand, PLA presented ductile properties that referred to plastic deformation. Plasticity describes an irreversible change of form in response to applied forces (ibid.). The elasticity of ABS allowed for the production of resilient membranes that could be later transformed into dynamic surfaces; a production that was one of the main objectives of the thesis. Therefore, although further tests were realized with PLA, ABS was chosen for the final prototypes at a larger scale.

Tensile Textiles

The information provided within the Knits and Stretch Textiles section, clarifies the reasons behind the selection of knitted textiles rather than woven textiles within this case study. However, as stretch textiles feature diverse structures and material compositions that influence their behaviour, the type of knitted fabrics employed were decided based on the conducted tests. These consisted of the tensile strength of the textile in deforming the printed plastic frame and the quality of the binding with the filament material.

The examined fabrics entailed diverse tensile strength and structural density. They also provided a variety of results when printed on with different filaments. (Figure 1.11)

The higher density knits with higher percentage of Elastane (88% Polyamide-15% Lycra), offered greater tensile strength. Consequently, their force generated severe deformations in the printed thermoplastic filaments that generated undesirable fabric creases inside their frames. Additionally their structural density prevented feasible binding between the textile and the filament.
Although more open in structure, some knit fabrics exhibited minimal binding quality compared to other tested textiles. It is safe to simulate that this lack of binding is affected by the textile's low tensile strength. While the stretched textile is reverting back to its relaxed state, it shows insufficient strength in deforming the plastic and is released of the frame.

A thin tricot knit (88% Polyamide-12% Lycra) presented sufficient strength in forcing deformation on the plastic filaments, and held feasible binding with them. Observations revealed that the structure of this knit fabric, compared to other tested textiles, allowed for better penetration of molten filament plastic within its permeable structure. This tricot knit, in combination with PLA or ABS filament was employed in most subsequent tests conducted on the Leapfrog™.

As the project aimed at producing larger scale samples for morphology tests and final prototype production, initial tests on the GIGABOT® were also conducted with the tricot fabric and ABS thermoplastic filament. However, these tests were challenging as the tricot demonstrated lack of tensile strength in deformation of larger frames. Through further iterations in the frame height and width, three-dimensional forms were acquired, but lacked the resilience and aesthetic measures envisioned.

Research into stronger open-mesh knit structures presented Powernet warp-knit fabric as a potential solution. Composed of 77% Polyamide and 23% Elastane, this knit structure is firm and holds high tensile strength. Its permeable structure allows for improved binding between the textile and the filament. It contains enough force to deform the plastic frame in larger scale
and generates resilient, uniform and aesthetically pleasant surfaces.

It is important to note that all the abovementioned knitted textiles are commercially available materials and are not produced by hand. Generating knit textiles with variable materials and structures did not deem practical within the timeframe of the project. However, testing the latter techniques provides an exciting area of research ahead.

Although relatively successful, the material selection tests and further experiments revealed a number of challenging and important issues such as stretch ratio, binding, and print parameters that needed to be taken into account and resolved to enhance the overall outcome quality.
EXPERIMENTAL DEVELOPMENT

Stretch Ratio

The tensile strength of the knit fabric plays a critical role in the deformation of the printed geometry. Stretch ratio is the proportional extension of the textile around the metal frame. The deformation of the plastic print relies on the force applied by the fabric, which directly depends on the stretch ratio. Therefore, avoiding manual processes was considered essential to control the stretch ratio and the consequent deformations.

During the printing processes, the fabric pieces were cut to the same size, and the printing was carried out on the face side of the textile. However, the stretch ratio was inconsistent. As Encyclopaedia Britannica describes, the stretch ratio also known as extension ratio is the “difference between extended and initial lengths divided by the initial length” (Encyclopaedia Britannica, n.d.). This stretch ratio irregularity was due to the malleability of the textiles and inconstant physical power employed during the stretching process.

Another issue raised due to manual stretching was the oblique grain of the knit textile. The direction of course and wale of the material, were kept consistent with the X and Y axes of the printer. However, with manual stretching it was difficult to keep the course and wale straight and parallel to the border of the frame.
Therefore, enhanced control of the process required development of an alternative technique for stretching.

Pantograph also known as Scissor Mechanism provided the most suitable, low cost, and customisable solution. The mechanism was built by assembling laser cut 7mm Plexiglass pieces, using screws as pivots. (Figure 1.12) The main difficulty was to design the gripping system to hold the fabric while stretching. Clamping or pinching the fabric required a complex mechanism. Therefore, jagged discs were employed to hold dense knits and sharpened screws were used with an open-mesh textile (Powernet).

The pantograph provided enhanced control in the stretching procedure. The fabric stretched evenly and the extension ratio parameter was regulated. This contributed to the consistency of the output.

**Binding**

Naturally, the quality of the bond between the polymer and the textile represented the fundamental challenge of the fabrication process.
A loose binding refers to the failure of the plastic to properly adhere and integrate within the textile structure. Defective binding induces unstable results such as inconsistent deformations and prototype fragility. From past experience built along the experiments, the binding quality was not merely related to the type of plastic used and was also greatly dependent on the printing parameters and the structure of the knit fabric. (Figure 1.13)

This issue was tackled through multiple approaches. Gluing seemed to be the simplest solution to this problem. This technique was excluded for a number of reasons. The glue hardens both the printed plastic and the textile and alters their material properties. Its dispersion is difficult to control and leaves undesirable marks on the surfaces. Most importantly, it disassociates with the objectives of the production process and eliminated the necessity of the printing process on fabric. The frame can be produced separately and glued onto the textile. The aim of the methods employed within this case study were to develop hy-

![Fig. 1.13 Close-up of binding during printing process. (2015)](ABS filament printed with close contact and dispersion rate on Powernet knit)
brid materials that were generated through combined processes and refrained from material assembly techniques.

At the early stages of the research Acetone was used in a secondary process to reinforce the binding. Acetone is a solvent commonly used to polish 3D printed ABS parts. The chemical was applied on the frame through the textile; partially dissolving the plastic’s back surface. Pressure was then applied, forcing the softened plastic to further penetrate into the structure of the textile. Although effective, this technique caused irregularities and seemed to affect ABS properties.

To avoid secondary processes, the focus was shifted on enhancing the quality of the bond between the plastic and textile directly upon printing. Advancement in the integration of molten filament into the structure of the knit textile provided the maximum binding results within the processes.

As mentioned earlier, this mechanical bond is improved through permeable textile structures. An open mesh fabric is preferable for penetration of the molten plastic within yarns of its structure. Additionally, the plastic’s viscosity and extrusion measures during printing processes help distribution of sufficient plastic material within the textile’s structure. These arrangements can be altered within the machine’s print parameters. Employing plastics with permeable knits provided an effective outcome in smaller scale printing methods. However, the binding between

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**Fig. 1.14** Double sided printing process on GIGABOT. (2015)
Bottom half of design printed on platform. Then, framed tensile fabric placed on the first stage of print. Lastly, another half of design printed on the fabric, clamping the two sides.
experimental development
the two materials lacked adequate strength in the final production of prototypes at a larger scale.

Double sided printing process was developed as the final and most effective approach to the bonding obstacle. This technique consists of clamping the textile between two layers of printed plastic. Presented in Figure 1.14, it involves three stages in the production process. Firstly, the bottom part is directly printed on the plate of the printer. Secondly, the pre-stretched textile is placed on top of the print. Thirdly, the top part is printed onto the surface of the fabric. Ideally the molten plastic of the top print penetrates the textile structure and bonds with the bottom print.
This process results in a highly effective mechanical binding that secures the textile within the frame. (Figure 1.15)

**Print Parameters**

The printing parameters entailed the customization and control of the machine setup and printer’s software program to improve the overall quality of the prototypes. The main parameters include print speed, printing temperature, bed temperature, material extrusion rate, and Z-axis height. The latter are controlled within the printer’s software program.

For instance, adjustment of the printer’s Z-axis height was one of the key factors in the machine setup. Overly low Z-axis could result in burning the fabric due to contact with the hot-end of the printing nozzle, while high Z-axis would result in weak binding between the plastic and the textile. Conjointly, print speed and material extrusion rate played a significant role in the binding quality. While printing on the fabric, higher extrusion rate allows more plastic to be pushed into the textile structure, therefore creating a stronger bond. Slower printing reduces the risk of irregularities in material deposition. Experimentation and documentation of these parameters throughout the research was essential to understand their influence and adjust them accordingly. (Figure 1.16)

The control over the fabrication process provided the necessary platform to investigate the relation between frame geometry, plastic stiffness, tensile force and textile properties in terms of morphology.
The technical development of the fabrication processes provided the necessary platform to further investigate these membranes in terms of morphology.

Most manufacturing processes, particularly AM processes, consist of creating a physical model that corresponds to the explicit definition of a geometrical model, in this case a CAD model. The outcome represents a comparatively accurate material version of the desired geometry. Here instead, the final morphology is not explicitly stated in the 3D model and the material behaviour plays an active role within the formation process.

Since the plastic frame is printed on a pre-stretched fabric, the membrane contains an energy potential that is expressed when the fabric is released. As the flat printed pattern evolves towards a three-dimensional shape, the deformation of the membrane expresses its implicit – rather than explicit – form. In fact, this hybrid system is programmed by the complex interaction of frame geometry, plastic properties, tensile force and textile properties. Furthermore, the interactions from which these forms emerge are far from describing a linear behaviour, which makes them hardly predictable.

This section describes the explorations conducted in expanding comprehension and control over the material morphogenesis,
predominantly by investigating the correlation between the frame pattern and the membrane's stable form. The following technical information was elaborated with the aid of Martin Genet.

To roughly simplify the role of the membrane's two essential components, the tensile force and the frame stiffness determined the amount of deformation while the frame's geometry influenced the orientation, in other words its morphology.

**Textile Behaviour**

The force applied by the fabric on the frame, proportionally depends on its tensile stiffness and the stretch ratio. Naturally, these two factors work hand in hand as a multiplier of deformation, meaning that the greater the stiffness and stretch ratio, the larger the deformation. Although in most cases the tensile force is considered uniform within the whole textile's surface, some knit structures can present anisotropic stretch properties, resulting in different tensile strength along the course and the wale directions. If so, the membranes would exhibit asymmetrical deformations.

Once the fabric is released, the deformation of the surface occurs instantly. The membrane seems to adopt a stable state in a matter of seconds. According to the observations, the optimal deformation is usually attained within 24 to 48 hours after the release. Over time, the constant stress applied by the fabric onto the plastic induces a creep effect. Here, the creep describes the deformation of a solid under constant load or constraint in time (Ashby et al., 2014: 330). Figure 117 illustrates the extent of
Fig. 1.17 Illustration of the creep effect over a month (2015)
8x8 square grids printed a month apart. (ABS plastic with Powernet fabric)

the surface deformation due to this phenomenon by comparing two identically fabricated 8x8 Square geometries, printed a month apart. Over time the plastic looses some of its elasticity and slowly deforms under the continuous tensile force of the textile.

After a few weeks, some PLA pieces seemed to have deformed plastically, while ABS responded more elastically. As earlier mentioned, if the textile is too strong and implies excessive deformation, the fabric’s surface may pleat.

This factor did not affect our final prototypes production. However, deeper control of this issue would be necessary in future developments as it has a great impact on the durability of the element.
Automated Geometry Generation

The frame geometry is the most modifiable parameter, and has the most significant impact on the membrane’s morphology. In order to keep a record of the geometry attributes and facilitate the documentation work, an automated method was developed for the generation of the frame’s 3D models.

This involved programming a parametric model through Grasshopper. (Figure 1.18) This plug-in of the 3D modelling software Rhinoceros, provides a visual interface for programming within the software.

By connecting values and functions, one can build an associative model in which the parameters are flexible. Therefore, when values of these variables change, the model updates accordingly to the system logic. By extension, this tool allows for the automation of a series of tasks within the computational model.
The developed parametric model requires input parameters as follows:

- single lines 2D drawing of the desired frame
- height and width of the outside perimeter and the inside frames if necessary
- inside and outside fillet radii
- name of the design.

Once all these parameters are defined, the script models the frame accordingly and offers to export:

- STL file format of the geometry for 3D Printing
- Rhino model file as a backup
- Excel File containing all the input parameters information along with the overall dimensions and the date of the export.

Henceforth, information on all the exported geometries is saved within the same file, which provides an efficient tool for documentation and comparison of the tests.

Presented in Figure 1.19, a collection of geometric calibration batch tests were produced through implementing this parametric model program. This test consists of a matrix of sixteen printed squares combined with four different width and four different height variables, which exhibit the influence of the variation of the frame’s geometry in the membranes deformation.

Fig. 1.19 p. 70 to 73 - Parametric Squares. Geometric Calibration Batch Test. (2015)
16 squares showing all the combinations of different parameters in frame’s width (5, 10, 15, 20mm) and height (0.3, 0.6, 0.9, 1.2mm). Base dimensions: 150mm x 150mm (central line of the frame)
Variable Frame stiffness

The frame’s bending stiffness is influenced both by the section of the frame and the plastic properties. Increasing the print’s height or width both results in a stiffer frame. Nevertheless, these two parameters imply their own specific visual and structural impact on the outcome. For example, a wider frame offers more binding surface area but might be aesthetically dissatisfactory.

Frame’s stiffness variability offers endless possibilities in the control of local and global deformations. Since multi-material printing was neither available on the Leapfrog™ nor on the GIGABOT®, variable frame stiffness was more conveniently achieved by varying the frame’s section. Two sets of samples were produced to illustrate this potential.

In the first experiment, The Wings, two rectangles of identical size were printed on the same fabric; one with higher frame section in the middle of the longer sides, the other with higher frame section on the shorter sides. The first rectangle deforms
mainly at its extremities, while the second one bends in the middle. This experiment presents the impact of the frame’s stiffness variability in local deformations. (Figure 1.20)

On the other hand, the second test titled ‘Directional Curves’, (Figure 1.21) showcases the impact on the global deformations. In this experiment, two 8x8 square network surfaces of the same size were fabricated.

The first geometry was printed with 0.3 mm additional height along the parallel lines of the Y-axis. In this sample the deformation of the Y-axis is constrained, resulting in consecutive sine wave morphology. The behaviour of this membrane visibly differs from that of the square grid with unified print height. (Figure 1.22) The second grid surface is printed with a 0.3 height difference in a staircase pattern. Although similar to that of unified height grid print, the deformation in this sample is highly contained and less evident. (Figure 1.23)

*Fig. 1.21 Directional Curves. Height Differential on a grid surface. (2015)*

*Left: Extra height on straight lines. Right: Extra height in angle lines.*
Fig. 1.22 & Fig. 1.23 Directional Curves. Height Differential on a grid surface. (2015)
Top: Extra height on straight lines. Bottom: Extra height in angle lines.
Pattern prints collection

In addition to abovementioned investigations, numerous patterns and geometries were generated implementing the Automated Geometry Generation parametric model program and were printed throughout the research process. The categories of these samples consist are presented as follow.

Basic Geometries

The four samples presented under this category consist of repeated symmetrical geometries of the ‘Square’, ‘Hexagon’, ‘Triangle’, and the ‘Glassworks’ grid patterns. The deformations of these patterns are mirrored on the opposite sides of the membrane.

Similar to the sine wave, these membranes represent a repeated wavelength. Each wavelength is a section of the same surface pattern. Therefore, these morphologies exhibit a homogeneous surface effect, rather than a global deformation. Due to these geometries, each membrane is highly resilient, stable and uniform in structure. (Figure 1.25 to 1.28)

Fig. 1.24 to 1.28 Print Collection - Basic Geometries. (2015)
(Order of presentation: 8x8 Square Grid, Hexagon Grid, Triangle Grid, Glassworks Pattern)
Approximative dimensions: 500mmx500mm; white ABS printed on white Powernet.
Floating Patterns

The following two membranes, ‘Buttons’ and ‘Bars’, present repetition of disconnected shapes. These samples maintain flexible textile behaviour and generate surface relief effects. While the ‘Bar’ surface displays an organized relief effect, in the gradient print ‘Buttons’, the affect is more visible in sections that the edges of the printed circles are closer to one another. It is evident that the lack of rigidity in these samples is due to the separation of the printed geometries. These samples showcase potential in production of fashion-oriented textiles. (Figure 1.29 to 1.31)

*Fig. 1.29 to 1.31* Print Collection - Floating Patterns. (2015)
(Order of presentation: Buttons, Bars) Approximative dimensions: 400mmx400mm; black ABS printed on black Powernet.
Parallel Strokes

‘Stripe’ and ‘Swerve’ surfaces embody parallel linear geometries. As both samples are constrained in one direction, they adopt forms with resilience in one axis, while the other axis retains springiness and high elasticity. The deformation of the ‘Stripe’ gradient sample is symmetric and the generated curvature is uniformed. The ‘Surf Line’ design, due to the variations in the lines shape and width, adopts an irregular wavelike morphology. (Figure 1.32 to 1.34)

Fig. 1.32 to 1.34 Print Collection - Parallel Strokes (2015)
(Order of presentation: Stripe, Swerve) Approximative dimensions: 450mmx350mm, black ABS printed on black Powernet.
Asymmetrical Shapes

3D printed irregular samples ‘Shattered’ and ‘Organic’ further reveal the potential of boundless morphologies that can be generated through integration of this production process. In comparison to the Basic Geometric surfaces with mirrored and homogeneous surface effects, these two samples effectively expose global deformations. Due to their asymmetrical design, the curvature of a single frame’s line can accumulate in the same direction as its neighbouring contours, which leads to a larger global deformation.

It is interesting to note that the angled multisided forms in the ‘Shattered’ design tend to initiate smaller localized breaks within the global deformation. As the design of the ‘Organic’ is composed of smoother continuous lines, it adopts a global deformation out of smooth swells in different directions. (Figure 1.35 to 1.37)

*Fig. 1.35 to 1.37 Print Collection - Asymmetrical Shapes, (2015)*
(Order of presentation: Shattered, Organic) Approximative dimensions: 450mmx450mm; black ABS printed on black Powernet.
The various samples produced display a large panel of possible forms and provide valuable insight for a better awareness of the causal relationship between frame geometry and membrane shape. Yet it is evidently impracticable to assume the result of any given construction by experience. In order to predict the behaviour of the self-forming membranes, the elaboration of an advanced simulation is required. The following section describes the first steps made towards simulation and explains the associated challenges and potentials.

**Geometrical Simulation and Digital Analysis**

In geometrical terms, the membrane’s formation responds to the equation of a decreasing area within a constant perimeter. The inner tension of the fabric applies forces on the frame in the plane XY. However, this planar stress implies deformation within the Z-axis comparable to buckling which characterises the bending moment within a column caused by an axial force. This can probably be explained by the fact that the frame’s section is wide (in XY) but relatively thin in (Z), which entails that the frame is more likely to bend in the XZ and YZ planes rather than in XY. In other words, the oddity of this equation means in-plane forces induce out-of-plane reactions.

As a case study, the deformation of a square frame was simulated via Grasshopper. (Figure 1.38) The textile is represented by a flat mesh, which tries to shrink in all directions. On the other

**Fig. 1.38** Simulated deformation of a square frame under tensile strains. (2015) Programmed with Grasshopper+Kangaroo. Color code: the gradient from red to blue represents the local strain within the fabric. Blue means that the fibers are stretched, and red means that they are relaxed.
hand, the frame is modelled as a three-dimensional mesh with an inner structure that tries to restrict any local change of size. As this simulation is purely geometric and deductive, if the frame is flat or its height is equal on both sides of the fabric mesh, no deformation would occur outside the XY plane. Only an external force in the Z-axis would initiate the envisioned formation process. However an volumetric frame generates the expected deformation without any external disturbances, and approximates the physical prototype very well. Although this simulation showed satisfying results and potentials, the developed model revealed to be impractical and poorly versatile. Indeed, while the main purpose of the simulation is to predict the behaviour of any frame geometry, changing the latter requires an extensive volume of research.

In future research, the simulation of these formations will need the development of a robust mathematical model. The latter would then allow quantifying forces and predicting precisely the outcome morphologies. Within this process, comparing the result of the simulation with the one of fabrication becomes highly informative. 3D scanning the prototype would then constitute a useful feedback in order to validate and refine the theoretical model.

**Digital Image Correlation**

A test of digitalization of the formation process was realized by using the technique of Digital Image Correlation (DIC), under the supervision of professor Sven Bossuyt, Department of Engineering Design and Production, Aalto University. This procedure consists of tracking and mapping displacements through pattern
matching in digital images (Bossuyt, 2013). The setup involves two high-resolution cameras, the software and DIC algorithm, as well as the thin pattern coated film. The film was applied directly onto the membrane before releasing the fabric. The formation process was then recorded for 24 hours. (Figure 1.39)

Fig. 1.39 Digital Image Correlation. (2015) (with Sven Bossuyt)
Top left: Strain map in both directions. Top right: Height map. Bottom: Pattern applied on membrane.
This technique constructs a temporal map of the strains and deformations within the membrane in all directions.

Ultimately, conducting this research forward would result in the ability to program the membrane’s morphology by the integrative understanding of material behaviour. For instance, designing a software interface for direct simulation could become an interesting tool; as the user designs the frame, the simulation automatically displays the result. The work could also lead to a generative form-finding program, which would calculate solutions that fit a certain form. Thus, further collaboration with the Mathematics and Mechanical Engineering departments are envisaged.

Collaboration has also been conducted with Walter Götsch, Fashion and Collection Design Bachelors student at Aalto University. Walter Götsch has been interested in futuristic and conceptual fashion collections and exploration into the potential future textile trends during his studies. Within this joint effort, self-forming membranes were incorporated in a fashion piece, as part of Götsch’s futuristic fashion collection ZÅZ. This fashion piece and a number of prototypes were presented in the Fashionology Exhibition during the inNORDICvision conference in August 2015, at BOZAR, Centre for Fine Arts, Brussels. (Figure 1.40)

The central inquiry of this research phase was to understand the material's role within the development processes. As textile and plastic are both active agents in these hybrid formations, the analysis of their reaction contributed in clarifying the role of their characteristics within this process. The material information and behaviour informed the design processes and it was through material observations and iterations of prototypes that the final objects were designed and produced.

Over thirty self-forming membranes with similar shape and parameters were produced for tests and integration within the final kinetic structure. The identical results achieved through this production, further solidifies the feasibility of this production process. This explorative research has introduced many possibilities for further investigations.
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Literature Review
Primary Explorations
An Integrative Kinetic Membrane
Bending Muscles Fabrication
LITERATURE REVIEW

A GLANCE INTO KINETICS AND TEXTILES

Throughout this case study, the project focused on the development of an actuating system for the self-forming membranes. As the objective of the project is to devise surfaces that would possess kinetic capacity, the following section presents a selection of work in the area of ‘smart’ textiles and responsive materials.

‘One Hundred and Eleven,’ Hussein Chalayan’s collection of Spring/Summer 2007, is among one of the most renowned kinetic collections in the realm of fashion (Figure 2.1). Celebrating Swarovski company’s 111th birthday, and in collaboration with designer and engineer Moritz Waldemeyer, Chalayan, elaborate integration of mechanical components extend the boundaries of design in fashion pieces. The pieces, ‘elegantly gliding through
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Fig. 2.1 One Hundred and Eleven. Hussein Chalayan. (2007)
Source: Digital Visions for Fashion and Textiles, p. 115

...a series of fluid movements,... change form while presenting the metamorphosis of fashion in time (Clarke and Harris, 2012: 114-115). Moritz Waldermeyer reflects on the challenges of the project by stating that “the real challenge lay in keeping the integrated technology lightweight yet strong enough to manoeuvre different fabrics and material” (Clarke and Harris, 2012: 115).

Investigations into pneumatic kinetic designs in the realm of fashion and textiles exposed the project 'Walking City'. Designed in 2006 by Canadian designer Ying Gao, this project includes a collection of three interactive dresses. The hidden pneumatic assemblies incorporated within these garments transform the outlines of the dresses. The Japanese origami style pleats of the pieces respond to different external stimuli such as sound and the proximity of an audience through integrated sensors ('Ying Gao', n.d.). (Figure 2.2)
The abovementioned projects, take great advantage of the extensive potential of textile constructions in the integration of other materials and technologies within their structures. However, reflecting upon the Waldemeyer’s statement and Gao’s pieces, the textile materials of these garments are positioned as a passive medium. In these examples and numerous other kinetic and responsive textile projects, textile materials act in compliance with the integrated technologies and their inherent behaviour is not fully explored and taken into account.

Today, the subjects of kinetics and material behaviours are extensively examined amidst the field of architecture. Textile materials
are, as well, implemented in a number of projects investigating the aforementioned topics. Designed in 2008 at the Centre for Information Technology and Architecture (CITA), ‘Slow Furl’ (Figure 2.3) is a room-size, shape shifting installation responding to the presence of its inhabitants. The textile, acting as a skin, is embroidered with active patches responding to touch and unifies the mechanical movement of the underlying dynamic armature (Clarke and Harris, 2012: 117-118; ‘CITA’, 2008). Once again, the inherent behaviour of the textile structure does not influence and merely follows mechanical compartments.

Further research into kinetic assemblies devoted to the impact of material behaviour disclosed two principally similar projects.
the ‘Hygroscope: Meteorosensitive Morphology’-2012 and the ‘HygroSkin: Meteorosensitive Pavilion’-2013, conducted in the Institute for Computational Design (ICD), Stuttgart. (Figure 2.4) In these projects, architect and professor Achim Menges, in collaboration with Oliver David Krieg and Steffen Reichert have developed responsive structures through examining the hygroscopic behaviour of wood fibres. Hygroscopic attributes of wood, commonly considered a deficiency in design and technology, is its ability to attract water molecules from the environment’
(Menges and Reichert, 2015: 68), which leads to a change in its dimensions and form (Ibid.). These structures change morphology through environmental humidity fluctuations, bearing no supplementary "mechanical or electrical equipment [...]", as the performance of sensing, actuating and responding is integrated" (Menges and Reichert, 2015: 68) within the molecular structure of the cellulose material. (Menges and Reichert, 2015: 66-73; ‘achirmngen’, 2012)

Research led by Achim Menges, is purely driven by material behaviour and the inherent properties of the material in its deformation. This project is noteworthy in relation to the goals of this thesis. Similarly, the kinetic actuation developed for this project takes into account textile characteristics and properties as active agents of form, to achieve the project’s performative goals.
PNEUMATIC ARTIFICIAL MUSCLES

The original kinetic considerations aimed at embedding an actuator within the printed frame of the membrane to force the surface to deform once again and recover its shape. Due to its resilience, the membrane returns to its three-dimensional formation after the force is removed. This was envisioned by rigidifying the frame’s borders with air pressure. As mentioned in the Preliminary Explorations, initial tests conducted with air pressure passing through silicon tube-lines proved to be effective.

To verify the practicality of pneumatic actuation, a silicon tube was placed directly on the frame of the membrane to generate surface deformation. As the plastic frames are malleable, the objective was to find a solution for them to temporarily lose their flexibility. The implementation of a sole silicon tube revealed to be inadequate in gaining stiffness and relaxation in the membrane. In fact, the tube required constraining by another means in order to redistribute the air pressure equally across its length and to generate bending stiffness. Further research into air pressure employed as an activation method, presented artificial muscles as a stimulating and practical area of research.

A Pneumatic Artificial Muscle (PAM) also known as McKibben muscle is an actuator that converts air pressure into pulling force (Wickramatunge and Leephakpreeda, 2010: 188). Similar to that of a biological muscle, this actuator stiffens and shortens when triggered. Originally invented by Richard H Gaylord in 1958, the design was popularized by Joseph L. McKibben in early 1960s (Tondu, 2012: 225).
The PAM actuators can be easily constructed and consist of two basic elements. The muscle is constructed of an inner cylindrical elastomer such as silicon tubing that is covered by an outer cylindrical braided material. One end of the muscle is sealed and the other is used as an air inlet (Tondu, 2012: 225; Davis and Caldwell, 2006: 359). Consequent to application of air pressure, the internal silicon tubing radius expands, and transfers its force upon the outer shell. In response, the non-extensibility of the braided mesh causes its yarns to slide, expand radially, and shorten in length. Therefore, the actuator contracts and produces a pulling force, while maintaining the cylindrical shape of the muscle. (Figure 2.5)

The performance of these muscles is reliant on different factors in material selection. These parameters include thickness and elasticity of the inner bladder (tubing), as well as the structure and material composition of the braided mesh. Some of the main advantages of these actuators are their low weight and compliance, relatively high power and low manufacturing cost. Industrial companies have devised and offered adaptations of the McKibben muscle. These include the ‘Fluidic Muscle MAS / DMSP’ designed by Festo company (‘Festo’, n.d.) and ‘Digit Muscle’ developed by the Shadow Robot Group (Greenhill, 1993: 29-30). PAMs belong to the field of soft-robotics and have a wide range of applications in bio-robotics, mechatronics, and industrial robots.
Fig. 2.5 Schematic representation of the PAM working principle. (2015)
Top: The muscle is deactivated. Middle: Air pressure enters the inner tube and apply a normal force to its surface, extending its radius. Consequently, the braid angle of the sleeve (θ) changes forcing the length to shorten from \( L \) to \( L' \). Bottom: The muscle attained its maximal contraction.
BRAIDED TEXTILES

Here, the basic background of textile braiding techniques offers grounds for deeper understanding of the material's structural behaviour within artificial muscle actuators.

The braiding technique involves the intersection of yarns in bias angles (Spencer, 2001: 2). (Figure 2.6) Braided structures are constructed through entwining three or more yarns to create an integral structure. The pigtail hair plait can be referred to as the

Fig. 1

Fig. 2

Fig. 3

Fig. 2.6 Super-elastic alloy braid structure. Gene Samson (2001)
Source: European Patents. EP0806596 B1
elemental example of braiding. The German Industrial Standard DIN 60000 has defined braids as “two or three-dimensional fabrics with even thread density and closed fabric appearance whose braiding threads cross each other in diagonal direction to the selvedge” (DIN 60000, 1969).

Patented in Manchester, England in 1748, Maypole Braiding Machine is the first braiding apparatus (Branscomb and Beale, 2013: 12). These machines produce cylindrical braided textiles identified as two-dimensional or biaxial braids. The yarns in these braids are only positioned in the circumferential direction of the tube and there are no yarns in the radial direction, which is the through-thickness direction (Wulffhorst and Gries, 2006).

Two-dimensional braids can be flat, tubular or contain other geometrical cross-sections. On the other hand, the yarns within three-dimensional braids move throughout the thickness of the structure and generate solid formations such as rods and I-beams (Branscomb and Beale, 2013; Sontag et al., 2015). The book Advances in 3D Textiles clarifies that “The definition of 2D and 3D braids is independent of the actual geometry of the structure but depends on the braided structure itself” (Sontag et al., 2015: 154).

A wide variety of braided meshes with different diameters, materials and yarn thicknesses are currently available in the market. Biaxial braids, employed within this research phase, are the most common two-dimensional braided structures. Similar to woven and knitted textiles, braids are produced in different patterns, referring to the order of their interlacement with the adjacent yarn (Branscomb and Beale, 2013: 14).
One of the vital factors in the performance of McKibben muscle is the braid structure. The braid functions as a restraining layer to prevent over-inflation of the inner bladder. When activated, by providing opposing forces, the braid converts the radial expansion of the inner tube into contraction and generates actuation (Davis and Caldwell, 2006: 359).

A significant factor, related to the braid structure, is the "angle formed between the longitudinal axis of the mesh and the mesh fibres" (‘softroboticstoolkit’, n.d.). The lower angle braids would allow for higher contraction before reaching their neutral 54° degree angle, which is known as the degree that prevents the braid’s structure from further "axial contraction or radial expansion" (ibid.).

Yarn material employed in the construction of the braid is another agent affecting the behaviour of the pneumatic muscle. A varying extent of friction is caused between the braid yarns while sliding upon one another. Braids are available in a variety of materials such as carbon fibre, fiberglass, and Polyethylene terephthalate (PET). Examined in detail throughout the practical framework of this case study and as an instance, the smooth surface of PET monofilament results in higher slippage between the yarns and consequently generates less friction.
During the initial phases of this case study, a variety of pneumatic muscles were produced and tested. The process consisted of examining inner bladders made of different materials and radii diameter such as latex balloons and silicon tubes. In general, silicon tubing is sturdier than latex and is available in a variety of diameter and wall-thickness sizes. Therefore, silicon-based tubes were preferred over the latex-based materials. Tubes with higher wall-thickness require more air pressure for diameter expansion. The muscle’s reaction can become less efficient as the thickness of the tube counters the force pressure. Yet, tubes with lower wall-thicknesses can rupture under the force. Consequently, tests were conducted to select the most suitable tube material.
Braided meshes in a range of structures, materials and diameters were used to cover the tubes. Due to lower cost and availability, fiberglass and PET braids were investigated. The actuators were developed with the constant length of 200mm. Figure 2.7 presents the components used to produce a pneumatic muscle and the making process. After the assembly, a compressor was used to apply air pressure into the enclosed tube. The activation of the different material combinations tests are displayed in Figure 2.8.

Fig. 2.7 Making Process of PAMs (2015)
Silicon tubing (ID: 7mm - OD: 10mm), Fibreglass 45° braided single threads sleeve. First, the tube is clogged and attached to a plastic connector. The sleeve is then put on the tube and secured with zip-ties.

Fig. 2.8 Activation tests of different PAM constructions (2015)
**SAMPLE #1**

- **Inner Tube Material:** Latex
- **Inner Tube Diameter:** 5mm
- **Outer Mesh Diameter:** 5mm
- **Outer Mesh Material:** PET 45° braided

**Specifications:**
- **Relaxed Length:** 160mm
- **Contracted Length:** 120mm
- **Maximum Contraction Ratio:** 25%
- **Effective Pressure Range:** 0 - 0.1 MPa

**SAMPLE #2**

- **Inner Tube Material:** Silicone
- **Inner Tube Diameter:** 3mm - 4mm
- **Outer Mesh Diameter:** 5mm
- **Outer Mesh Material:** PET 45° braided

**Specifications:**
- **Relaxed Length:** 170mm
- **Contracted Length:** 140mm
- **Maximum Contraction Ratio:** 18%
- **Effective Pressure Range:** 0.2 - 0.4 MPa

**SAMPLE #3**

- **Inner Tube Material:** Silicone
- **Inner Tube Diameter:** 7mm - 10mm
- **Outer Mesh Diameter:** 10mm
- **Outer Mesh Material:** PET 45° braided

**Specifications:**
- **Relaxed Length:** 170mm
- **Contracted Length:** 150mm
- **Maximum Contraction Ratio:** 23.5%
- **Effective Pressure Range:** 0.1 - 0.4 MPa

**SAMPLE #4**

- **Inner Tube Material:** Silicone
- **Inner Tube Diameter:** 7mm - 10mm
- **Outer Mesh Diameter:** 10mm
- **Outer Mesh Material:** FiberGlass 45°

**Specifications:**
- **Relaxed Length:** 170mm
- **Contracted Length:** 140mm
- **Maximum Contraction Ratio:** 18%
- **Effective Pressure Range:** 0.05 - 0.4 MPa
The graph on Figure 2.9 presents the contraction rate of different constructed muscles according to air pressure. This chart facilitated the measurement of the average air pressure necessary for activation of the actuators; it also provided a selection of muscles with the quickest contraction response. Although in some tests the air pressure was pushed up to 6 bars, nearly all muscles reached maximum contraction within 4 to 4.5 bars of pressure.

Beyond 5 bars muscle failure was observed. The principal cause of failure mostly relied on the assembly complications rather than a material collapse. The main challenge of the pneumatic artificial muscle was securing its components together, so that the actuator would successfully withstand air pressure and avoid leakage.
In general, the tests revealed high strength and contraction rates in the muscles. The advantage of the system with air pressure is its scalability. The force is relative to the section of the muscle. In other words, the larger the volume of the muscle, the greater the generated force.

Due to their linearity, one of the first assembly ideas provoked by PAMs was the interlacement of these actuators. Muscles were woven and braided in small formations and were then activated to observe their behaviour. (Figure 2.10)

Although not related to their integration within the self-forming membranes, this small test presented great potential for future explorations. As the order and volume of airflow in each muscle can be controlled separately through different air channels,

*Fig. 2.10* Braided and Woven PAMs Prototypes. (2015)
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A variety of formations is possible within an interlaced structure. After analysis of the PAM viability and behaviour, further experiments were conducted to integrate the actuating system within the self-forming membranes.

Muscles and Membranes

To pursue the objectives of developing kinetic surfaces several assembly tests were realised. The purpose of incorporating muscles and membranes is to generate a reciprocal behaviour.

Fig. 2.11 Activation of a first kinetic prototype. (2015) Assemblage of PAMs with membranes. Dim. 220x220x140 mm.
Investigations were conducted to observe the muscles ability to initiate deformation in the membrane and the ability of the membrane to recover its original form in a deactivated state. It is important to note that the pneumatic artificial muscles were mostly tested on samples of the selected membrane as the final surfaces for the kinetic structure.

In the first group of tests the muscle ends were attached to the membranes in several configurations. Although responsive, the linear contraction of PAM only generated larger curvature in the membranes and failed to reverse or revoke the surfaces deformation. In these tests the actuators operated as separate elements, which contradicted the aim of producing an endogenous hybrid system. (Figure 2.11)
AN INTEGRATIVE KINETIC MEMBRANE

Due to their compliance, PAMs can bend and follow form in their relaxed state. Taking advantage of this behaviour, the subsequent approach involved the direct attachment of actuators to the plastic frame of the three-dimensional membranes.

Originally, zip ties were used to fasten the muscle at the backside of the plastic frame. This assembly method delivered contradictory results. The muscle, nevertheless, performed as an independent element and contraction of muscle between the secured points generated wave-like effects in the membrane. This test triggered the idea of attaching the muscle along the full length of the plastic frame.
Glue was used to secure the muscle to the membrane. This process presented successful deformation of membrane and provided an important insight into the procedure. The glue used to fix the muscle to the membrane played an additional major role. It prevented contraction of the glued side of the sleeve by constraining the braided mesh yarn’s movement in the area. Placed on the external side of the curvature, when activated, the muscle inverted the curvature of the frame’s border. (Figure 2.12) The diagrams on Figure 2.13 clarify the behaviour of a muscle attached to the membrane.

Glued muscles to the membrane delivered the appropriate
Fig. 2.13 Schematic representation of the PAM working principle. (2015)
Top: The muscle is deactivated. Middle: Air pressure enters the inner tube and apply a normal force to its surface, extending its radius. Consequently, the braid angle of the sleeve (θ) changes forcing the length to shorten from L to L’. Bottom: The muscle attained its maximal contraction.
deformation in the membrane. The actuation system offered adequate strength in deforming the membrane, while the membrane proved ample resilience in returning to its original form. However, similarly to the binding mechanism of membranes, gluing was not a satisfactory solution to the process. The challenge was resolved through generation of an alternative fabrication system presented in the following section.
BENDING MUSCLES FABRICATION

3D printing on Muscles

Analogous to the 3D printed geometries on the membranes as constraining frames, printing on muscles appeared a viable solution to block the contraction of braided mesh along the length of the muscle.

The initial tests of 3D printing on muscles were conducted on the Leapfrog™ printer. This process required designing a secure casing for the pneumatic muscle on the printer. Initially, an elementary foam board housing was used for this purpose. The pneumatic muscle was secured within the casing and placed on a predetermined position on the platform of the 3D printer. The machine setup was altered to meet the height and position of the muscle. A strip of plastic was then printed on the muscle.
Materials and Patterns

Filaments such as ABS, PLA, and nylon were tested for printing. These tests revealed two main specifications for successful outcomes. The first requirement was for the printed muscle to maintain adequate flexibility in bending while deactivated. The integration of a rigid actuator to the membrane was problematic, as it stiffened the membrane before activation. The durability of the printed strip was the second requisite. The plastic print had to retain a strong binding with the braided sleeving and bend without releasing or cracking.

The issue of flexibility was originally approached through printing discontinuous and zigzag strip patterns on the muscles. (Figure 2.14 & 2.15) These patterns offered adequate flexibility. However, due to their minimal printing surface area, they lacked durability and adhesion to the braided sleeve. The continuous, flexible printed strip proved as the most suitable option to tackle these discrepancies.

![Image of printed patterns](image)

**Fig. 2.14** Primary test of 3D Printing for Bending PAMs. (2015)
Flexible PLA was employed within the subsequent tests. This filament demonstrated sufficient malleability and durable bonding with the braided mesh. In the CAD model developed for the production of final pneumatic artificial muscles, were fabricated for integration onto the self-forming membranes. Pins were designed and added to the initial strip design to facilitate the assembly of the two elements. The influence of material and structure of the braided tube was also taken into consideration. The polyethylene terephthalate (PET) braided sleeveings were selected, as they presented the highest bonding and flexibility rate among the tested braids.
The Twisted Muscle

During the investigation of printing on the PAM, an intriguing experiment was conducted. This test involved rotating the muscle during the printing process. Printed in low speed with nylon filament, one end of the muscle was manually shifted counter clockwise. This process resulted in the print of helix geometry on the muscle. When activated, the PAM generates a three-dimensional curve. (Figure 2.16)

This process demonstrates great potential in development of a variety of complex and controlled deformations in PAM. A solution for precise 3D printing all around the muscle requires calcu-
lated coordination between the printing process and rotation of the cylindrical muscle. The movement of this axis can be controlled with the implementation of small motors such as servomotors. Although, the time frame of the thesis restricted further development of this process, future investigations surrounding this topic are envisioned.

Tooling and printing process

Once the appropriate materials and geometry of prints were established, the printing process was optimized through designing a casing tool for the muscles and machine setup calibration. As larger pneumatic artificial muscles were required for application in the final prototypes, the tools and final optimization were developed for the GiGABoT® 3D printer.

Presented in Figure 2.17, this tool is among one of the instruments developed with the aid of Seppo Nummi, Senior Laboratory Technician at the Engineering Production faculty at Aalto

![Image](image.png)

**Fig. 2.17** 3D Printing Process of Bending PAMs. (2015) Serial production of the final kinetic membranes muscles on GiGABoT® 3D printer.
University Engineering Department. The metal structure was placed on the platform of the GIGABOT® printer and was used for secure positioning of the pneumatic muscles. The distance between the PAM slots were precisely calculated and allowed for simultaneous printing on several muscles. Subsequently, the 3D printer parameters were adjusted to conform to this customised printing platform. The distance and placement of the printed geometry within the machine software were as well modified to follow the tool’s specifications. Achievement of a faultless printing process required several tests and revisions.

Fig. 2.18 Final Integrative Kinetic Membrane. (2015)
Study of the membrane’s deformation according to different patterns of muscle activation.
The final production of the artificial muscles included printing 120 muscles that would attach onto the membranes. The combination of these two hybrid constructions (membrane and muscles) resulted in kinetic membranes.

The behaviour of the membranes' two components are complementary. The membrane works as a stable and resilient tri-dimensional surface at the deactivated state. Upon activation, the pneumatic muscles force the membrane to bend in the opposite direction of its stable form. The amplitude of that deformation is directly proportional to the activation of the muscles. The more air pressure is applied into the muscles, the larger the deformation of the membrane. When the pressure is released, the membrane recovers its original shape.

Additionally, the membranes' movement upon different activation patterns was studied for the assemblage in larger kinetic structures. (Figure 2.18) The process of design and assemblage of the final kinetic prototypes are presented in Case Study 03.
KINETIC STRUCTURES

Prototypes & Assembly
Kinetic Control System
The preeminent aim of this case study was to develop an assembly of the kinetic membranes developed in the two previous case studies into larger responsive structures. Two distinct kinetic structures were created as the final prototypes. The first structure constitutes as a self-standing kinetic wall structure; the second is a continuous kinetic suspended surface. This case study focuses on the structural design and construction of the kinetic structures, as well as the kinetic control system developed to activate the latter.

Due to greater knowledge and background in computational design and electronic control systems, Martin Genet and Jim Rhoné were in charge of the majority of the design work in this section of the collaborative thesis. However, most of the decisions and choices made during the design process were collective and resulted from a cohesive and comprehensive teamwork. The final production and assembly of these structures were a joint effort.
The Wall

Antagonistic Behaviour

One of the major design challenges of the self-standing structure was developing a structure able to support its own weight while allowing local elements to reconfigure the global shape. Therefore, this prototype required the design of an articulated three-dimensional skeleton. The structure was designed by associating the membranes and skeleton as complementary elements. Inspired by truss structures, the skeleton bares the compressive loads, while the membranes work as tension elements to stabilise the structure in the deactivated state. An antagonistic configuration was used to allow movement and stability on both sides of the structure. (Figure 3.1) Conceived symmetrically, the activation of one face induces movement in one direction, while the other is relaxed, and vice versa.
Skeleton Structural Design

The two faces of the structure are connected using a carbon fibre rod structure as the skeleton. Carbon fibre was selected as the most suitable material to ensure stability and preserve the structure from excess weight.

The skeleton was iteratively designed, built, and tested. For these experimentations, the different articulation systems and skeleton configurations were analysed on a single module. The skeleton design was first tested as a quick hand-made model made out of wooden sticks. The most promising models were produced for testing and attached to the kinetic membranes. (Figure 3.2)
The latter were then activated to deform the structure. Its movement and stability were thoroughly analysed. The problems and deficiencies of the designs were solved iteratively until reaching the most appropriate design. The final skeletal parameters were designed and calculated through computational design.

**Dynamic Joints**

According to the successive versions of the skeleton design, numerous customised joints were drawn and printed using Rapid Prototyping to connect the skeleton structure to the membranes and provide the necessary liberty of movement. The complex geometries of these dynamic joints were designed using the 3D

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*Fig. 3.2 Intermediary Kinetic Structure. (2015)*

Illustration of a kinetic structure's movement. Dimensions: 350x470x470mm.
Angular displacement maximum amplitude: 12°
Carbon Fibre Rods, 3DPrinted resin dynamic joints, Integrative Kinetic Membranes.
modelling program Rhinoceros. Then, these connections were printed with Stratasys Objet30 Pro™ machine. This AM printer employs PolyJet™ 3D printing technology. “PolyJet™ 3D printing is similar to inkjet document printing. But instead of jetting drops of ink onto paper, the printers jet layers of liquid photopolymer onto a build tray and cure them with UV light” (Stratasys, 2014). This additive manufacturing process generates high quality and precise models and is suitable for printing complex ge-

![Fig. 3.3 Custom Dynamic Joints. (2015)]

ometries with movable parts. Three kinds of articulations were
designed. The ball joints were used to allow rotation in all direc-
tions. Pivots and sliding mechanisms were attached to each tri-
angle of the structure to allow their transformation. In total, four
different types of connections were designed, with their own
variations according to their function and placement within the
structure. (Figure 3.3)

Pneumatic Fittings

In addition to their structural function, the 3Dprinted joints are
also used as pneumatic connectors. Commercial pneumatic
fittings were utilized during the initial investigations conducted
with pneumatic artificial muscles. Although available in a variety
of configurations, these fittings could not provide the envisioned
air channels for the structure. Therefore, the structural design of
the skeleton was combined with the design of the airflow map-
ping. The dynamic joints were created with a custom design of
pneumatic fittings. A screwing system was designed to hold the braided sleeve and the tubing of the muscles together. (Figure 3.4) The high quality and density of the parts printed with Objet30 Pro™ prevents air leakage and thus operates as a successful application as a pneumatic connector.

To summarize, the connectors hold a triple-folded function within the structure. They assemble the skeleton and the different membranes together; they articulate the skeleton junctions, and they also work as pneumatic fittings for the muscles, creating the necessary air channels. The central pieces offer support for a distance sensor, which will be explained in the following section. The versatility of these joints in terms of functionality reduces material use and assemblage procedures. Printed in one piece, these connections appear aesthetically more pleasant. However, they engender a higher risk in case of breakage and would generate many problems for disassembly.

The final structure (Figures 3.5 to 3.9) is composed of 6 membranes on each side: three in the vertical direction and two in the horizontal direction. Nylon screws were used for the assembly in order to keep a lightweight structure.

Fig. 3.5 The Wall, A Kinetic Self-Standing Structure. (2015) Dimensions: 100x30x150cm.

Fig. 3.6 to 3.9 (Next double-page) The Wall, Details. (2015)
**The Wave**

The purpose of the second prototype is a kinetic interactive surface. This structure represents a much simpler assembly design as the self-standing wall does. Indeed, it mainly consists of joining the kinetic membranes into a continuous surface. This prototype does not need any complementary structure, as it is designed to hang vertically. Nonetheless, the connections needed to simultaneously be strong and flexible. They were designed to carry the weight of the hanging structure while allowing movement without breaking.

Learning from the experience of the Wall, the main difference with the first structure is the division of the connection's functionality into two separate parts. Therefore, the joints are composed of custom pneumatic fittings and junction pieces. The pneumatic fittings distribute the air into the membranes muscles and get attached to the membrane. This joint was 3D printed with Objet30 Pro™. The junction pieces connect the different kinetic membranes together. As acrylic sheets were too brittle, a type of clear Polyethylene Terephthalate (PET), referred to as PETG, was chosen for its strength and flexibility. After numerous tests, PETG sheets of 1.5 mm thickness were laser-cut to produce these attachments. The central joints also integrate support for the distance sensors. (Figure 3.10)

The separation of parts provides a great advantage in the durability of the prototype. The structure can easily be disassembled for transport purposes or repair in case of damage. In total, the Wave is composed of twelve membranes, three in the vertical direction and four in the horizontal direction. (Figures 3.11 & 3.12)
Fig. 3.10 & 3.11 The Wave. Details. (2015)
3.10 - Central attachment with air-in connections and support for distance sensor.
3.11 - Continuous Surface Effect.

Fig. 3.12 (Next double-page) The Wave. A Kinetic Surface. (2015)
Dimensions: 200x150cm.
Pneumatic Networks

The pneumatic fittings of the prototypes were designed providing separate air channels. Air pressure can be transferred differently through each part of this network, resulting in the activation of specific PAMs and forcing particular sections of the structures to deform. This allows for a localised control of the prototype’s deformation and offers a multitude of configurations. Because of their specific construction, the structure and the hanging surface present two different channel maps (Figure 3.12a & 3.12b).

The Wall is equipped with seven channels per face, three in the vertical direction and four in the horizontal one. Hence, the structure is able to bend in two directions along three different lines on the vertical axis, and four different lines along the horizontal axis. Double-curvature is then possible by activating, for example, the front left vertical channel and the back right vertical channel at the same time. Here, the local deformation of each membrane is hardly visible but participates to the global movement of the structure.

The Wave’s membranes can all be independently activated, which involves a total of 12 channels. As this prototype bares less structural constraints, it holds a much more important potential for movement. Due to the autonomous structural arrangement of the hanging surface, local deformations of individual membranes are more visible and also impact the overall shape. Each membrane’s morphology depends on its own activation but also on its neighbour’s.
Fig. 3.12a & 3.12b Airflow Mapping of the Kinetic Structures. (2015)
3.12a - Airflow map of a face of the Wall. (2x7 channels)
3.12b - Airflow map of the Wave. (12 channels)
KINETIC CONTROL SYSTEM

For the structures to be digitally controlled and adapt to their surrounding, a numerical control system was needed. As a parallel study, the development of the kinetic control system involved a research into pneumatic electronic control and digital sensing. This research was led alongside the rest of the project.
Pneumatic Control And Circuitry

The movement of a membrane is directly proportional to the air pressure present in its muscles. Therefore the kinetic control of the structure required the regulation of pressure within the system.

Pneumatic control systems are employed within a variety of fields such as robotics, automotive, and industrial manufacturing. Support from the faculty of Engineering Department at Aalto, presented the pneumatic systems provided by SMC Corporation as a viable option for the project. Founded in 1959 in Japan, SMC Corporation is a global company specialised in production of pneumatic control systems for automation industries (SMC world, n.d.). Meetings and support from Ari Salminen, Sales Engineer at SMC Pneumatics Finland Oy, aided in finding the most suitable products for the purposes of the project. Acquisition of these products was financially supported by ADD Lab.

The first product tested was the Electro-Pneumatic Regulator ITV0030-2BL. The latter offers the simplest and most convenient way to control air pressure within a pneumatic circuit. Proportionally controlled by an electric signal from 0 to 5 volts, this product allows for the regulation of air pressure from 0 to 6 bars with high precision. However, this equipment is a very expensive high-tech product. Additionally, due to the construction of this component, the speed of activation of the membranes was difficult to control and presented undesired jolts.

Another solution was then designed and developed to enhance the control for a smoother and cheaper activation. This pneu-
Fig. 3.13 Pneumatic Control Circuit Diagram. (2015)

The pneumatic control circuit (Figure 3.13) uses two Proportional Solenoid Valves and a pressure sensor. One is used to let air in from the compressor while the other lets air out of the air channel (exhaust). The valves function as airflow controllers. They regulate the airflow from 0 to 100L/min in response to an electric signal ranging from 0 to 165mA with 24 volts ('SMC world', n.d.). This electric signal is controlled digitally on a computer connected to an Arduino board, a microcontroller with open source software. The hardware uses Pulse Width Modulation (PWM) output pins.
that operate by sending a series of pulses controlled through a voltage supply and a transistor to modulate the electric signal and control the valves ('Arduino', n.d.). (Figure 3.14)

These valves do not allow the control of air pressure directly. Instead they control the speed at which the air fills the muscles or exits the muscles. In other terms, it means that the valves control the speed of activation or deactivation but not the amplitude. To do so, a pressure sensor is used to monitor the actual pressure within the channel. The data is read by the Arduino and transmitted to the computer. This data can then be compared with the desired pressure value, which informs the control system if more air is needed or the air needs to exit the channel. The air in the valve or the exhaust valve is then activated accordingly.

Although complex, this pneumatic control system offers a smoother and more detailed control over the membrane’s kinetics. It controls the speed of activation as well as the amplitude of movement. The same circuit was repeated for each channel.
**Fig. 3.14** Pneumatic Control Circuit Components. (2015)

Middle: Circuit board for electronic signal regulation between Arduino PWM and the valves.
Bottom: Circuit board for pressure sensors. (MPXA6400A)
AUTONOMY & BEHAVIOUR

For the kinetic structures to become truly autonomous and show behavioural quality, they need to be aware of their environment but also aware of themselves among that environment. This requires the control system to integrate and combine two new features into the algorithmic logic. First, sensors need to be added to detect the structure’s relative surrounding. Secondly, the structure needs to incorporate a sensing method to read its own movement, which works as a feedback system. Finally, information from both sensor and sensor method are combined within the control system and respectively used to program and adapt to the structure’s own behaviour in real-time.

Sensing and Interactivity

On both structures, distance sensors are used to detect objects and persons in front of them. These sensors were incorporated in different parts of the structures to approximate the location of the detected obstacle. Therefore the presence of someone around a prototype can trigger its activation. According to a certain pattern of obstruction, the prototypes can adopt a specific shape by following the control program. The logic of this program was designed on Grasshopper, a plug-in to the Rhinoceros software.

The Wall uses close-range infrared distance sensors (IR distance sensors) – from 10 to 80 cm, while the Wave uses longer-range IR distance sensors – from 20 to 150 cm. The difference occurs in the scale of interactivity with the user. The hands of the user would model the Wall without touching it. On the other hand,
the Wave would interact with the user’s body by mimicking its movements and positions. By sensing an environment, the structures can interact with it.

**Feedback System**

As far as kinetics are concerned in automation and robotics, the notion of self-awareness describes a feedback system. It allows a machine, like a CNC machine, to ensure the full completion of the task it is presently doing. To do so, the control system requires a closed logical loop between sensing and actuating to adjust itself continuously.

A feedback system involves a cyclical organization of its causal-ity logics to provide a constant re-balancing and re-calibration of an object’s functioning state. Defined by Karl Johan Aström and Richard M. Murray, “A dynamic system is a system whose behaviour changes over time, often in response to external stimulation or forcing. The term feedback refers to a situation in which two (or more) dynamic systems are connected together such that each system influences the other and their dynamics are thus strongly coupled. Simple causal reasoning about a feedback system is difficult because the first system influences the second and the second system influences the first, leading to a circular argument. This makes reasoning based on cause and effect tricky, and it is necessary to analyse the system as a whole. A consequence of this is that the behaviour of feedback systems is often counterintuitive, and it is therefore necessary to resort to formal methods to understand them” (Aström and Murray, 2012: 1).
KINETIC STRUCTURES
In order to monitor the structure’s shape in real-time, an integrated sensor was developed within the 3Dprinted part of the muscles. The objective was to track each membrane’s morphology in order to rebuild a digital model of the whole structure in real-time. To do so, a layer of conductive PLA was printed on the muscles. When a muscle bends, the resistance of that conductive layer changes from about 10kOhms up to 800kOhms and can be read through the Arduino board (Figure 3.15). Due to this electric resistance variation, the four sides of a membrane thence become bending sensors and allow for its geometry to be digitally rebuilt on Rhinoceros with Grasshopper. By extension, this procedure allows the control system to know if the intended shape was attained or not. It can also be used to detect external forces applied on the structure, like wind for example, could compensate that stress by trying to move in the opposite direction or help the movement by accompanying in the same direction. This feedback system is illustrated on Figure 3.16.

**Fig. 3.15** (Left Page) Integrated Bending Sensor PAM, (2015) PAM with electrical resistance variation in response to bending. Conductive PLA + Soft PLA.

**Fig. 3.16** Feedback Control System, (2015) Combination of environmental interactivity and autonomous behaviour regulation and control.
By sensing their environment and by being aware of their movements within it, the structures can now fully interact and show a responsive and controlled behaviour. Further development could expand the control algorithm to a much more complex behavioural logic. However, the control system and structures developed through this project already demonstrate a rich interactive performance.
CONCLUSION

The goal of 'Performative Compositions' was to map the importance of incorporating and grasping materials information, in particular textiles, within design processes, while presenting the significant potentials of digital design tools in material fabrication. This collaborative thesis examines and illustrates the understanding of material behaviours, as well as integrating these behaviours as active components within kinetic structures.

To achieve the objectives outlined, a literature review concerning material behaviour and digital and computational design was conducted. Materials and their implications play a significant role within a practice-based realm of textile design. As a result, the functionality of textile materials are commonly realised through practice and experimentation. Although there is sufficient technical information surrounding textile materials and their construction techniques, literature surrounding the material's behaviour and its application in digital design was mostly found in the realm of architecture. Drawing relevancies and analogies through literature reviews, facilitated the advancement of the project’s goals in integration of textiles within digital fabrication processes. These methodologies introduce material behaviours as active parameters and "material systems [...] as generative drives in design process" (Menges: 2011: 202).
To establish the relationship between the physical and digital design, explorative prototyping and iterative methods were employed throughout the practical phases of the thesis. Throughout the research processes, the characteristics and capacities of materials were explored and subsequently generated information through design practice. Christopher Frayling describes this method as, "research through design" (Frayling, 1993: 1-5). Additionally, documentation, analysis, and assessment of the different stages of the practical research were essential. The systematic development, cyclic iteration and techniques led to the optimization of the structural and functional performances of the prototypes. In this bottom-up approach, computational design methods proved as beneficial tools for maintaining the consistency of the processes and their parameters, while authenticating the materials behaviour.

The 3D printing digital fabrication methods employed in the development of 'Self-forming Membranes' facilitated the process of iteration. Additionally, geometric complexity and variation could easily be reached through this technique. However, it was only through the integration of the tensile textiles within the 3D printing processes that the achieved resilient and malleable surfaces were developed. The control of the overall fabrication procedures and the different parameters involved within the printing processes were key in investigating issues such as the geometries, plastic stiffness, tensile force and textile properties. Computational design presented the potential in expanding on this control over a complex material system. The equilibrium between the tensile force of the textile and the applied constraint by the printed geometry resulted in an articulate material formation. Produced exclusively through 3D printing, and even with access
to the highest quality 3D printing technology, the printed geometries would not have gained the intrinsic characteristics of these hybrid textiles. The production process would have been exceedingly expensive, time consuming and materially wasteful.

Reaching the project’s kinetic objectives in designing an active and adaptive material system, entailed understanding of the membrane’s behaviour in order to utilise its elastic properties. The kinetic surfaces were achieved through integration of pneumatic actuating muscles with the membranes. Presented in Case study 02, the investigation of the behaviour and capacities of the braided textiles in combination with silicon tubing and air pressure, led to the development of pneumatic actuators. Application of air pressure through the silicon tubing resulted in the contracting behaviour of the braided mesh skin. Further control over this behaviour of the actuators was reached through 3D printing on their surfaces.

After integration and upon application of air pressure, the contracting force of the pneumatic muscles in conjunction with the constraint and tensile strength of the self-forming membranes resulted in an antagonistic deformation behaviour. Drawing comparisons with the kinetic project ‘Aegis Hyposurface’, which is dependant on a supporting structure for its kinetic activation, the final kinetic prototypes of this thesis are autonomous. Some of the advantages of their autonomy include their greater freedom of movement and lightweight.

This project achieved the goal of creating an endogenous kinetic system through hybrid material compositions. Their local deformations led to the global movement of the kinetic struc-
tures. The dynamical aspect of these hybrid formations results from the combination of heterogeneous material behaviours.

The activation of the two prototypes is reflective of potential applications. As a self-supporting structure, ‘The Wall’ can be considered as a sample prototype of a larger and stronger structure, which could lead to earthquake resistant structures or transformable canopy architecture. ‘The Wave’ can already be seen as a full-scale working prototype. Further studies could lead to its application as an acoustic modulation surface. Achim Menges reflects upon the integration of material behaviour and digital design by stating that “In the not too distant future, designers will not only be able to employ design computation to integrate and modulate the behaviour and performative capacities of existing materials, but also to design materiality itself” (Menges, 2012: 21). The synthesis of material behaviour, digital fabrication and computational design, opens new opportunities for design of heterogeneous and ‘Performative Compositions’. This thesis provides an example of an investigation into the extensive potential of textile materials and structures through development and integration within the realm of digital and kinetic fabrication. As compounded materials, textiles can embrace multiple characteristics and exhibit dynamic capabilities.

Moreover, it is important to state the significance of collaboration throughout this project. The information, experiences and knowledge shared throughout this thesis are amongst the most valuable accomplishments. After all, it was only through collaboration that I could convince an architect that textiles are structures.


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Additional Readings


