Caress of the Gaze: A Gaze Actuated 3D Printed Body Architecture

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ABSTRACT

This paper describes the design process behind Caress of the Gaze, a project that represents a new approach to the design of a gaze-actuated, 3D printed body architecture—as a form of proto-architectural study—providing a framework for an interactive dynamic design. The design process engages with three main issues. Firstly, it aims to look at form or geometry as a means of controlling material behavior by exploring the tectonic properties of multi-material 3D printing technologies. Secondly, it addresses novel actuation systems by using Shape Memory Alloy (SMA) in order to achieve life-like behavior. Thirdly, it explores the possibility of engaging with interactive systems by investigating how our clothing could interact with other people as a primary interface, using vision-based eye-gaze tracking technologies.

In so doing, this paper describes a radically alternative approach not only to the production of garments but also to the ways we interact with the world around us. Therefore, the paper addresses the emerging field of shape-changing 3D printed structures and interactive systems that bridge the worlds of robotics, architecture, technology, and design.

1 Careess of the Gaze: 3D printed garment, which moves in response to the onlooker's gaze by Behnaz Farahi. Photographers: Charlie Nordstrom, Elena Kulikov. 2015.

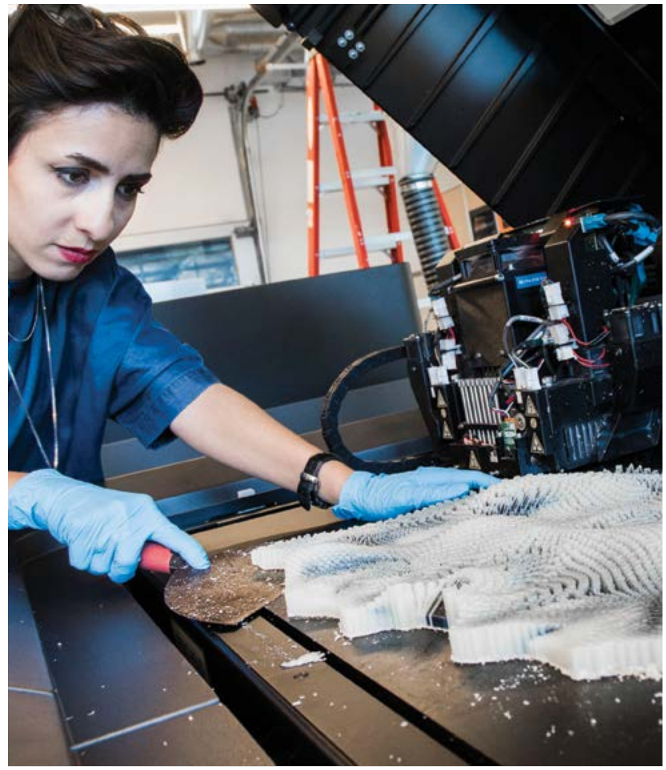
INTRODUCTION

3D printing and interactive design have revolutionized approaches to design in many different industries, including fashion, and wearable and architectural design. The relationship between the body and architecture has a long history. From Vitruvius onwards, there have been attempts to relate buildings to the proportions of the human figure. More recently, the connection between the body and architecture has developed into an interest in the fashion industry among architects, as in the "Skin + Bones: Parallel Practices in Fashion and Architecture" exhibition (Museum of Contemporary Art, Los Angeles, 2007), which drew extensively on architects designing wearables. Since then, there has been a veritable explosion of architects working in the realm of fashion—largely, but not exclusively operating through 3D printing technologies. Architects such as Neri Oxman, Philip Beesley, Julia Korner, and Daniel Widrig have collaborated with leading figures within the fashion industry, such as Iris van Herpen.

The term "Body Architecture" has been used by the avant-garde media artist, Stelarc, who notes that "altering the architecture of the body results in adjusting and extending its awareness of the world." Later, the term was used by artist Lucy McRae to refer to practices which aim to transform conceptions of the human body. In the context of this paper, Body Architecture is a form of proto-architecture where there is an attempt to engage with the human body and its relationship with the space immediately around it.

The intention is to explore the domain of the body as the site of architecturally inspired investigations. The main attempt in such a work, is to engage with geometries and forms in order to understand dynamic material behaviors in relation to the human body. Inevitably, these lines of thought draw our attention to some groundbreaking works in the realm of material intelligence, including 4D printing by Skylar Tibbits of the MIT Self-Assembly Lab. In these attempts, material intelligence is informed not only by geometry but also by real-time changes in the material properties that inform matter.

As Neri Oxman states, "A bio-inspired fabrication approach calls for a shift from shape-centric virtual and physical prototyping to material-centric fabrication processes" (2011). Advances in 3D printing technologies have enabled us to design shape-shifting objects by distributing a range of different materials in various compositions, so as to open up a variety of mechanical behaviors. This provides us with the opportunity to design objects that are becoming closer to natural systems in terms of their morphologies as well as their behaviors. As researchers from MIT Assembly Lab explain, "3D printing enables us to arrange the stretching



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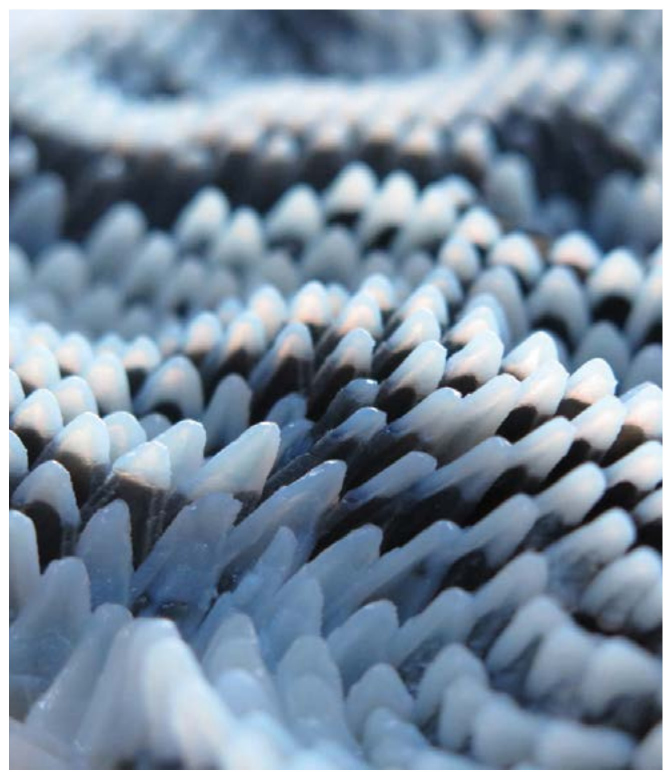

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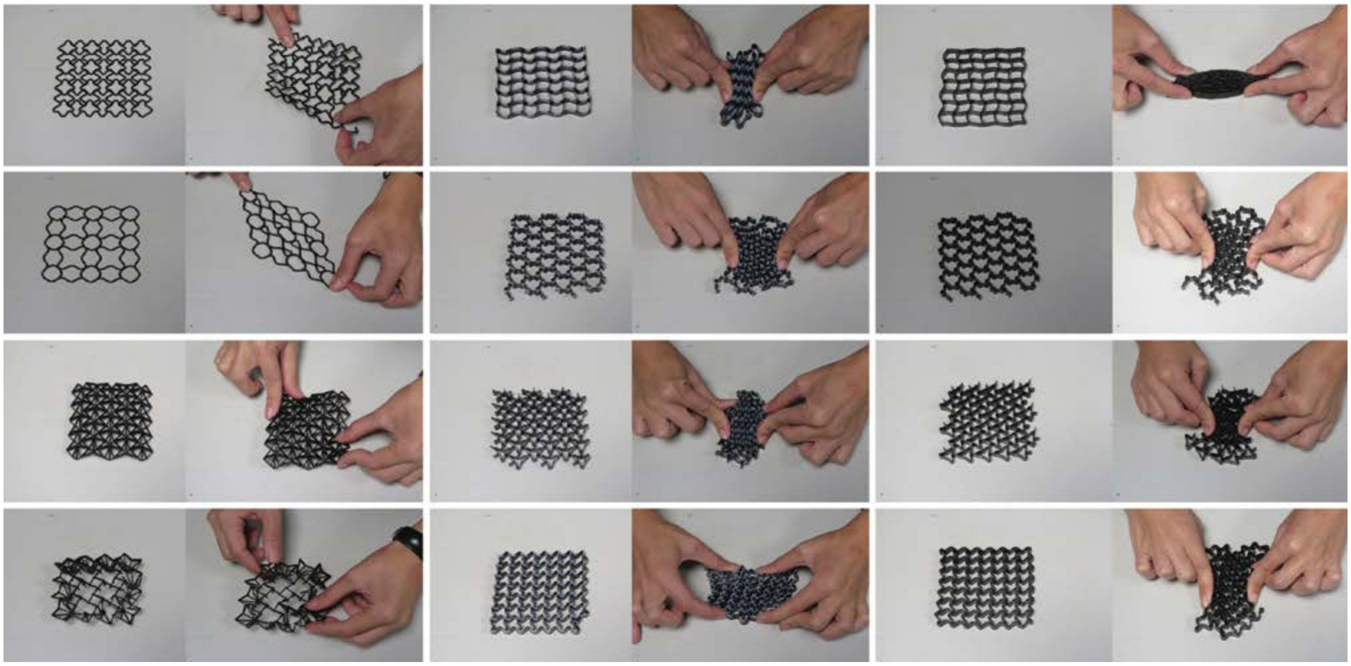
2 Removing the print from the Polyjet Connex 500 3D Printers.

3 Using multi-material 3D Printing by Objet Connex500. This prototype is demonstrating varying flexibilities and densities from stiff to soft.



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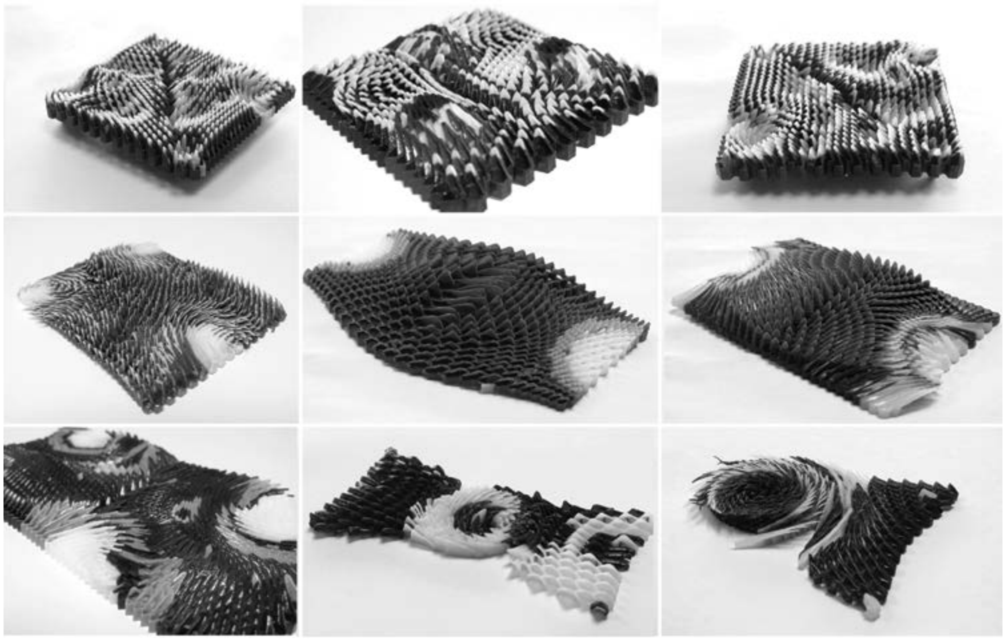
and folding primitives in different orientations, which allows stretching and folding to happen at the desired position in the 3D vector space". (Raviv et al. 2014)

Moreover, advances in interactive design technologies are changing the way that we interact with the world around us by influencing our perception, ways of communication, and awareness. These technologies are also changing the perception of our bodies by allowing them to become augmented, enhanced, and expanded in terms of their functionality. This will fundamentally change what it means to be human and make us closer to being posthuman. As Parks puts it, "ubiquitous and embedded technologies are allowing our devices to become more and more part of us with increasing mobility and pervasiveness" (2008). Hansen explains that the human body does not end at the boundaries of its own skin, but rather constructs intimate relationships with digital information flows and data spaces (2006: 191). Gray believes that when every part of human life, including birth, education, sex, work, and death are transformed by intimate connections with technologies, then "the language of technology will begin to 'invade' the ways we express and perceive these experiences" (1995, 6). But these technologies are equally influential in this coupling. For instance, computer technologies as "non-organic, clear and functioning prostheses" are transformed by their coupling with the human body. Likewise, the human body is perceived as "augmented and enhanced by its attachment to technology" (Clark 2002, 36) This suggests that the notion of the "cyborg" or "posthuman" should not be limited to early speculations from the world of either space exploration or sci-fi about the potential extensions of the human body. Rather, it implies that our understanding of the term has itself evolved to include the use of everyday technological devices. Thanks to embedded computing and bio-sensing, our bodies can now operate as primarily interactive interfaces with the world through the use of interactive systems such as "vision-based eye-gaze tracking" for Human Computer Interface (HCI) that can be attached to the body.

The necessity for such developments is unquestionable. Firstly, they allow us in the process of design to go beyond simply replicating the human body as a static form in order to truly track and understand the dynamic nature of the body as a living and changing entity, which is able to respond to various internal and external stimuli. Secondly, by exploring material intelligence, they allow us to move on from traditional robots to "soft robotics" that have become an increasingly popular area of research as a sub-branch of biomimicry.[1] This is important given that "traditional robots have rigid underlying structures that limit their ability to interact with their environment" [2] (Trivedi et al. 2008). Thirdly, they illustrate how our garments could behave as a second skin capable of changing their shape and operating as an interface with the world, thus influencing social issues such as intimacy, gender, and even personal identities. Lastly, and more importantly, this approach can provide a framework that can contribute to the field of interactive architecture by addressing the emerging field of shape-changing 3D printed structures and interactive systems.

4 Study of Auxetic behavior of 3D Printed prototypes with cellular structures using two materials.

5 Various topologies and taxonomy of geometries and material combinations.



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CARESS OF THE GAZE: A GAZE ACTUATED 3D PRINTED BODY ARCHITECTURE

What if our outfits could recognize and respond to the gaze of the other? Caress of the Gaze is an interactive 3D printed garment, which can detect the gaze of other people and respond accordingly with life-like behavior. This project offers a vision of the future by exploring the possibility of designing a second skin, fabricated using multi-material 3D printing and enabling the wearer to experience and "feel" the most subtle aspect of social interaction: people's gaze (Figure 1).

The design process behind this project can be broken down into three different sections: morphology (shape), actuations (shape-changing mechanism) and interaction (control). As such, the task is to understand the relationship between morphology, behavior, and interactive systems of control.

Morphology: Multi-Material 3D Printing

Many natural materials have exceptional mechanical properties through the organization of their cells or fibers. (Ashby et al. 1995) As such, natural materials are often superior to man-made materials. The study of natural systems can therefore show how materials can be distributed to allow for a desired mechanical behavior. In this sense, the design of forms capable of movement based on their material composition can be inspired by the elastic mechanisms in biological systems. In the human body, there are many examples of flexible structures made of springy, soft tissues to be found both in active elastic elements, such as muscles, and in passive tissue elements, such as skin. As Roberts and Azizi put it, "Elastic mechanisms are likely to play a significant role in all vertebrate locomotors systems" (2011). Understanding the morphology and functionality of elastic structures in nature can lead to new concepts in the realm of design. Ultimately, these designs can be fabricated using 3D printing technologies.

3D printing includes a range of techniques, such as selective laser sintering (SLS), selective laser melting (SLM), stereolithography (SLA), fused deposition modeling (FDM), multi met modeling 3D printing (MJM), electron beam melting (EBM), laminated object manufacturing (LOM), and PolyJet Connex500 printing. For the fabrication of Caress of the Gaze, Polyjet Connex 500 printing was used (Figure 2). This technology has made it possible to generate composite materials with varying flexibilities and colors, and to combine materials in several ways, which enables the simultaneous use of two different materials (flexible and stiff) or any combination of them known as "digital material." [3] This has allowed forms to be fabricated with elastic properties by creating digital materials with full Shore scale.[4] Besides its comparatively large bed size, this high-resolution machine has an accuracy of up to 16 microns. After being extruded, each photopolymer layer is cured by UV light. Gel-like support material can be removed with pressurized water.

The design of Caress of the Gaze was inspired by the system of scaling in animal skins, which is composed of both stiff and flexible tissues (Figure 3). However, the material composition of the Caress of the Gaze was simplified to (a) a cellular mesh varying in its properties in various nodes ranging from stiff to

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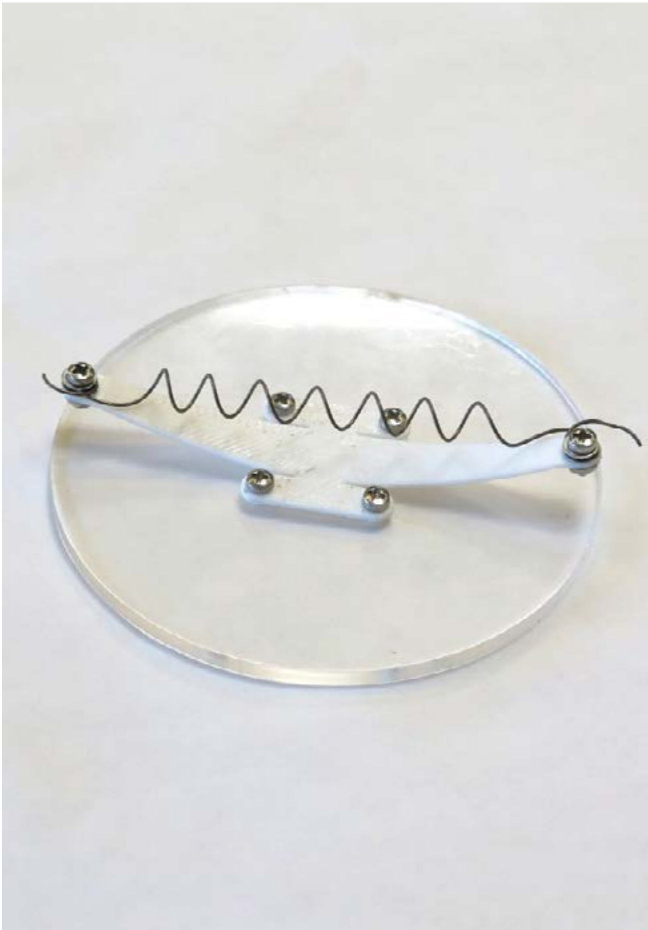
soft, which holds (b) semi-rigid, stiff scales in order to provide maximum curvilinear contraction and expansion. This was a highly iterative and hands-on process whereby printed samples were continuously tested and catalogued (Figure 4). Various geometrical and material combinations were also explored in order to enhance the aesthetic expression of the form as well as to control the types of motion it could afford. It is important to note that the composition of natural biological skin morphologies varies across the body, with varying densities and porosities providing different behaviors. For example, the microstructure of the skin on our face is different to the skin on our feet. It is also worth mentioning that a particular cell composition and distributed density will inform a specific behavior in biological skin. For example, fish scales—although quite hard—are located on a semi-flexible mesh, which provides a certain flexibility for the fish to move and bend its body in various directions. Therefore, the main intention here was to study natural skin systems in order to develop a formal language that exhibits different behaviors ranging from stiff to flexible in various parts of the body.

As discussed by Lin et al., fish scales display a hierarchical architecture, "with a hard, mineralized outer layer and a softer inner layer composed of collagen fibers arranged in a Bouligand, or plywood-like pattern" (2011). What is very interesting about fish scales is their capacity to protect against predator penetration while also allowing for the uniquely flexible mechanical behavior of fish locomotion. However, in this project, the main focus has simply been on the characteristics and flexible behavior of natural skin systems.

For the design of the elastic component of Caress of the Gaze, a cellular mesh, which can hold scale-like members, was deployed. The cellular mesh is able to provide sufficient porosity and therefore desirable contraction/expansion behaviors. Initially, a series of experiments was conducted in order to understand the flexibility of the mesh and its scales by changing parameters such as density, as well as material properties of the mesh (particularly with respect to Shore values and their influence on curvilinear motion). This allowed the mechanical behavior of the mesh to be fine-tuned. The cellular mesh also controlled the scale position and overlap and thus the scale-scale interactions. Meanwhile, control of scale sizes and their softness/stiffness was also essential in terms of the distribution of forces as well as aesthetic expression (Figure 5). As Browning et al. demonstrate, the overlapping of the scales in fish skin is crucial for the distribution of forces across the material, making it possible to tailor the overall stiffness of the material by adjusting structural parameters such as the scale overlap, orientation, aspect ratio, and volumetric filling within the substrate. (2013) Therefore, a series of experiments was also conducted exploring the different



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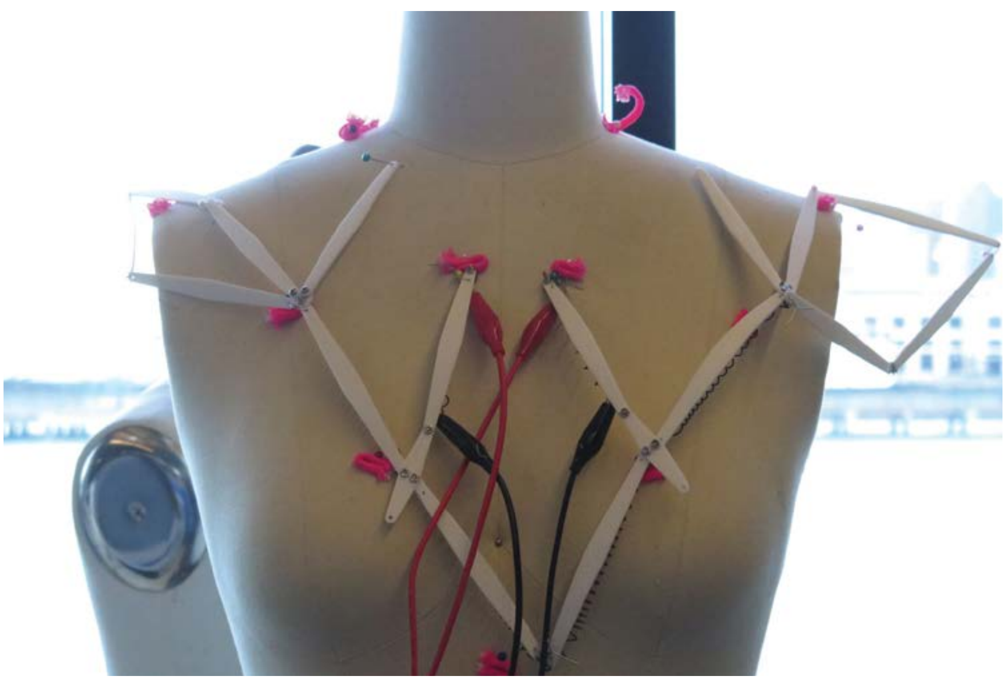
ratios of flexible to stiff materials on the scale-like members. While the flexible material (Shore 60 Black in this case) provides flexibility to the entire structure, the stiff material (Vero White in this case) provides structural rigidity and stability.

The lessons from the aforementioned experiments were then applied to the form of the garment, so as to allow it to move, open, close, and change its shape based on stimuli from the onlooker's gaze (Figure 6).

Actuation System: Shape Memory Alloy

The actuation system for Caress of the Gaze was inspired by animal/human skin and its complex architecture—the interplay of muscles, hair, feathers, quills, scales, etc.—and endowed with life-like behavior by incorporating Shape Memory Alloy (SMA) actuators as a main shape-changing mechanism (Figure 7). This project therefore explored the potential of a shape-changing actuation system assembled as a form of muscle system using SMA that informed the motion of the 3D printed quills.

Muscle functions have inspired numerous researchers and scientists to explore the potential of developing smart materials embedded with soft and compliant actuators such as EAPs (Electro-Active Polymers), SMAs, and so on. We refer to materials that can be significantly changed in a controlled fashion by external stimuli—such as stress, temperature, moisture, electric, or magnetic fields—as "smart materials." As Coelho notes, "Smart



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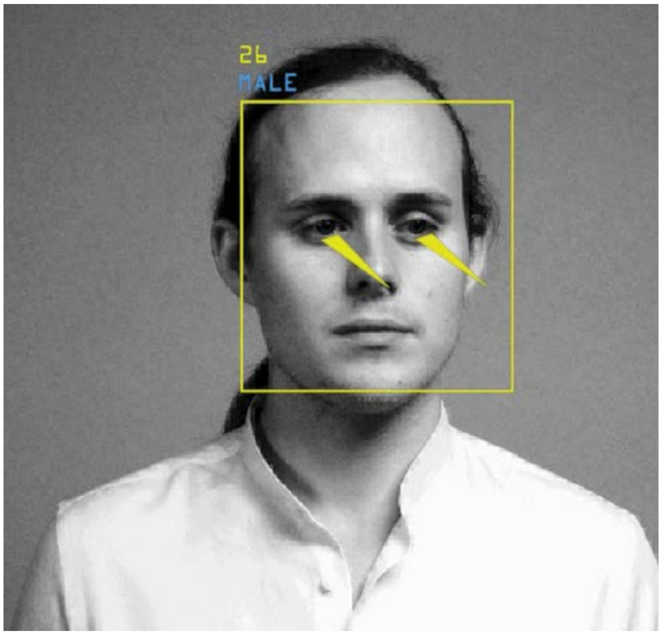
6 Morphologies applied to the form of the garment.

7 Inspiration from natural skin systems such as fish scales and geco skin.

8 SMA assembled to the PLA 3D Printed prototype to develop a compliant actuator. Exploring material properties as a mean to compensate for the nonequal cooling and heating curvature.

9 Study of the motion using SMAs and cataloguing behaviors.



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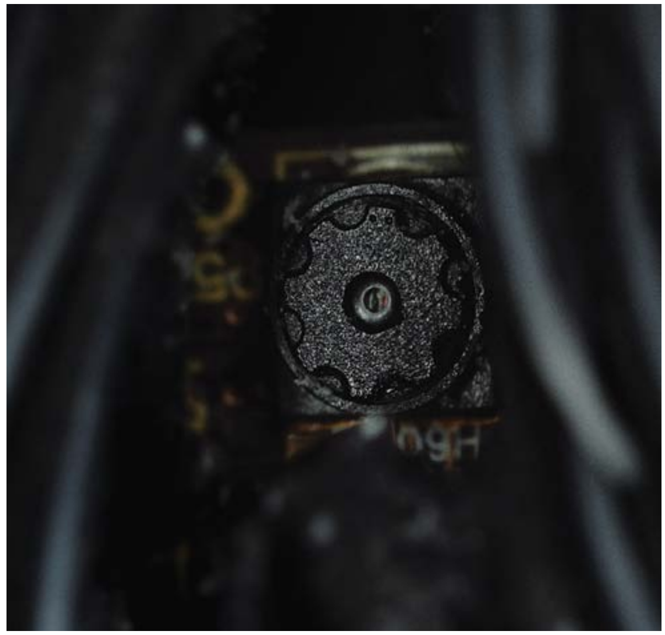

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materials and their composites are strategically positioned to fulfill this desire by transforming input stimuli into controlled material responses, while presenting a wide range of material properties and behaviors" (2008, 23).

The intention here behind deploying smart materials was to embed them within a 3D printed structure whose inherent properties could be changed to meet dynamic external conditions. One possible solution for creating a living system is to develop prototypes using "smart materials" and define their behavior and form based on different stimuli. For this research, SMAs were chosen. SMAs change their shape when heated to the required activation temperature and subsequently return to their initial state. In other words, SMAs can be deformed and then "remember" their original shape when triggered by a specific activation temperature. SMAs are often manufactured as wires. Since these are small, strong, durable, and easy to trigger, they can be used in many products. And since they move silently and organically, they could be a good medium for developing life-like movements. These small diameter wires contract typically 2% to 10% of their length. The diameter of the wire is one of the really important factors in terms of their actuation. Higher-diameter wires have lower resistance and need more power. Thus, they are more likely to overheat and lose their original contraction abilities. Wires that are 0.006" or smaller can be charged constantly without fear of overheating. High-temperature (90°C) wires take longer to cool than low-temperature (70°C) wires.

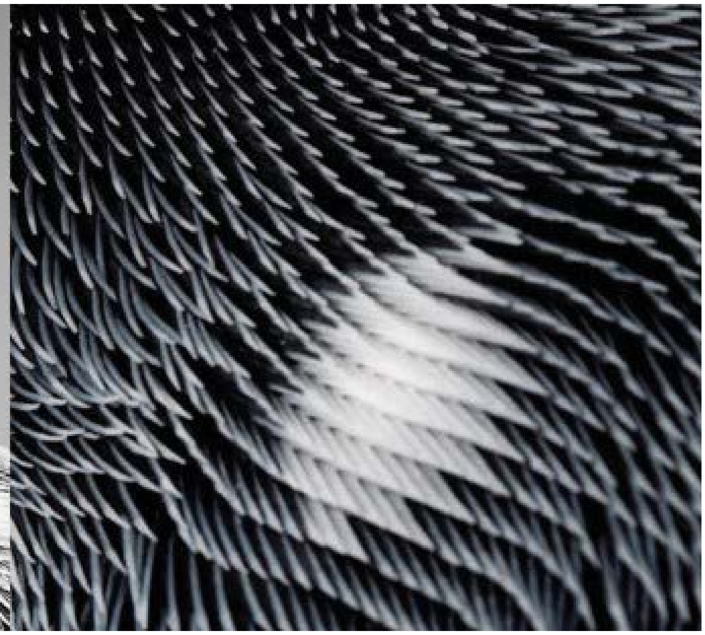
One of the main challenges in working with SMA wires is that their cooling and heating curvatures are not equal. As Paik, Hawkes, and Wood explain, when working with SMA actuators, there is no standard model that prescribes temperature, load, and material geometry for a desired performance; the convention therefore is to "derive an actuator model's thermo-mechanical properties experimentally, either partially or fully" (2010). A considerable amount of time in this process was dedicated to fine-tuning the desired motions, including bristling, swirling, and changing shapes (Figure 8) in various sections of the garment and cataloging their behaviors (Figure 9). Please note that although in this project the actuation system was embedded in a post assembly process, the possibility of 4D Printing and printing with smart materials could be explored in the future.[5]

Interaction: Vision-Based Eye Gaze Tracking

Thirdly, Caress of the Gaze explored how our clothing could interact with other people as a primary interface using computer vision technologies.

While HCI researchers have focused on complex mechanisms for acquiring precise data from the eye tracking technologies as a mean of developing human computer interaction, designers can now take advantage of these technologies to design systems that go beyond simple 2D digital interfaces. Therefore, this section is less concerned with adding new scientific findings per se to the field of computer science, and more with introducing a new design application into the field of interactive dynamic design. This might also provide a great opportunity to link recent research in HCI to developments in interactive wearable design.

Caress of the Gaze aimed to create an interactive system which



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10 Caress of the Gaze equipped with facial tracking camera, detecting age, gender and gaze orientation of the onlookers.

11 Small tracking camera -with lens smaller than 3mm embedded underneath the quills.

12 Caress of the Gaze: A gaze actuated 3D printed garment.

would make the garment become an extension of the wearer's skin and respond to external stimuli in a manner not so dissimilar to some of our involuntary skin responses such as pupil dilation or goose bumps. Our skin is dynamic and constantly in motion. It expands, contracts, and changes its shape based on various internal/external stimuli. In animals, we can see more or less similar responses, particularly for mating or defense mechanisms. For instance, a porcupine feeling threatened might bristle its quills, or a bird trying to find the right mate might puff up its feathers, or fish trying to camouflage themselves from predators might change their skin colors.

The aim of Caress of the Gaze was to establish an interactive autonomous system enabling the wearer to "feel" the invisible and the most subtle aspects of our social interaction: the gaze of other people. This process is not dissimilar to way that we develop goose bumps on our skin as a natural involuntary response to the cold or even to emotions such as fear, nostalgia, sexual arousal, and admiration.

For this purpose, an image sensing camera with a lens of less than 3 mm, capable of detecting gender, age, and orientation of the onlooker's gaze, was positioned underneath the garment quills. The garment then responds autonomously to a front-mounted camera as it detects the orientation of an onlooker's gaze. Basically, the data related to the orientation of the onlookers' gaze is relayed to a Teensy microcontroller on the back of garment, which is capable of actuating and controlling up to eight various nodes of SMAs in the garment (Figures 10 and 11). Technically speaking, this was achieved by mapping the yaw and pitch values of the onlooker's eyes to the garment actuators and allowing the garment to move in response to the onlooker's gaze.[6]

In a sense, by using facial tracking algorithms, this outfit, with its responsive skin of 3D printed spikes, opens up numerous possibilities for the interaction of the wearer to the environment and people around. First of all, it increases the awareness of wearers to their social context by being able to literally "feel" the garment on their bodies as they move according to the onlookers' gaze. Although, at the moment, this garment is equipped with one front-mounted camera, further developments could also incorporate back-mounted cameras in order to increase security and awareness for the wearer. Secondly, it allows the wearer to communicate to onlookers that their actions have been perceived, thereby allowing them to ward off any further disturbing actions. However, the full potential of such a system is not solely to prevent onlookers from staring, but also in some cases to attract desired onlookers. As mentioned above, information on age and gender can also be gathered. As a result, if one is willing to use this interactive garment as a mechanism of attraction, one can possibly define the desired age and gender and the garment would just respond by attracting the attention of that desired group.

CONCLUSION

Caress of the Gaze addresses the challenge of developing an interactive shape-changing body architecture through the design of a 3D printed dynamic garment operated by a vision-based eye-gaze tracking system that bridges the worlds of fashion, architecture, technology, and design.

Traditional static, single-state 3D printing has now given way to printing flexible, multi-state technologies employing a range of different materials, which can provide opportunities for physical shape changing through the distribution of those materials. The project has also demonstrated the novel ways of interacting with our environment through the use of eye-gaze tracking technologies. Just as our skin can respond to various internal and external stimuli, so too our outfits can now do the same and also respond to various social issues such as intimacy, privacy, gender, and identity (Figure 12).

Therefore, by implementing 3D Printing, SMA, and gaze-tracking technologies, this project has served as a provocation, encouraging us to rethink both the production of the garment and also the way that we interact with the world around us. It has also been an attempt to demonstrate a new coupling of our biological body with a nonorganic garment as an extension of our skin. It has done so in the belief that by implementing design/ motion principles inspired by natural systems, both in terms of morphology and behavior, we might be able to rethink the relationship between our bodies and the surrounding environment. Even though this research is still speculative, it opens up the possibility of a radical new approach to interactive dynamic design, particularly in the field of interactive clothing, interactive architecture, and soft robotics.

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NOTES

1. “Soft robotics” is a new field of research in robotics. As Verl, Albu-Schäffer, Brock and Raatz explain, thanks to bio-inspired technology design, instead of implementing the rigid mechanical structures of the past, a new robotics paradigm is now starting to focus on soft, pliable sensitive, organic representations on soft robotic.
2. The use of smart material and compliant actuators in this research was an attempt to move away from a mechanical system of actuators such as servos and motors toward soft robotics.
3. For further information on digital materials see: http://www.stratasys.com/materials/polyjet/digitalmaterials
4. The Shore Scale was invented by Albert Ferdinand Shore, who developed a device to measure Shore hardness in the 1920s. The term ‘shore durometer’ is often used as a measure of hardness in polymers, elastomers, and rubbers. http://www.matweb.com/reference/shore-hardness.asp
5. For 4D Printing and Self-Assembly see the research of the Self-Assembly Lab at MIT. http://www.selfassemblylab.net/
6. Yaw value refers to horizontal angel between onlookers gaze to the center of camera lanes. This value can be measured in degrees. Meanwhile, pitch value refers to the vertical angle between the onlookers’ gaze and the center of the camera lens.

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IMAGE CREDITS

Figure 1,10,11,12: Charlie Nordstrom and Elena Kulikov, 2015.
Figures 2–10: Behnaz Farahi, 2015.

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