ABSTRACT
The Hummingbird is an amazing creature. The male Anna’s Hummingbird changes color from dark green to iridescence pink in his spectacular courtship. Can we exploit this phenomenon to produce color and shape changing material systems for the future of design?

This paper describes the design process behind the interactive installation, *Iridescence*, through the logic of two interconnected themes, ‘morphology’ and ‘behavior’. Inspired by the gorget of the Anna’s hummingbird, this 3D printed collar is equipped with a facial tracking camera and an array of 200 rotating quills. The custom-made actuators flip their colors and start to make patterns, in response to the movement of onlookers and their facial expressions. The paper addresses how wearables can become a vehicle for self-expression, capable of influencing social interaction and enhancing one’s sensory experience of the world. Through the lens of this project, the paper proposes ‘bio-inspired emotive matter’ as an interdisciplinary design approach at the intersection of Affective Computing, Artificial Intelligence and Ethology, which can be applied in many design fields. The paper argues that bio-inspired material systems should be used not just for formal or performative reasons, but also as an interface for human emotions to address psycho-social issues.
INTRODUCTION
Numerous advances in the field of synthetic biology, material science, and imaging technologies, along with new digital fabrication techniques have led to novel approaches in material development. In the past few decades, there have been a series of groundbreaking steps in developing new materials by various research groups. Most of these attempts share a common goal in producing bio-inspired matter. Some work is inspired ‘by’ nature, such as 4D Printing: MIT Self-Folding Strand by the Self Assembly Lab, and other work is produced ‘with’ nature such as the Silkworm Pavilion by the Mediated Matter Group. Some works have also explored changes in color such as Rain Palette by Materiability, and others have explored active living protocol such as in the Hylazoic Ground Installation by LASG.

Many designers, architects, and material scientists, especially those who have a fascination with biological systems, have been influenced by D’Arcy Thompson’s pioneering book Growth and Form (Thompson 1917), in which Thompson explains how physical processes and forces can inform the shape of an organism and its growth patterns through mathematical functions. However, although the form, growth pattern, and hierarchical structures of living systems can provide a good source of inspiration for developing new materials, one might wonder whether a study of ‘morphology’ is a sufficient model on its own. In other words, Thompson’s approach might offer a mathematical explanation for patterns on the skin of the cuttlefish, for example, but he does not provide any ‘sociological’ explanation for shape and color changing behaviors. Whilst Thompson’s work can assist us in developing high-performance materials, it does not offer any insight into the behavior of active matter and its social implications.

However, in terms of the growing interest in the development of active materials, I would suggest that we also need to look at both ‘morphology’ and ‘behavior’, the principle factors in an organism’s survival. The study of animal behavior and how an organism responds to its environment can be a good model for the development of dynamic materials. Sensory receptors in living creatures constantly relay information to the central nervous system about both internal as well as external stimuli. And, as a result, skeletomuscular systems composed of muscles and bones (depending on the morphology of an organism) receive instructions that shape behaviors such as defense tactics, camouflage strategies and sexual selection. These animal behaviors can be manifested as ‘signals’ or ‘cues’ sent from a sender and can be encoded by a recipient of the same or another species.

The male Anna’s hummingbird, for example, has feathers on the gorget around his throat that appear at one moment completely green. With a twist of his head, however, he can turn them into an iridescent pink (Figure 2). This is how the Anna’s hummingbird attracts mates during his spectacular displays of aerial courtship. This is one example from nature in which ‘morphology’ (formal characteristics) and ‘behavior’ (sensing and responding capabilities) are tightly coupled together informing social dynamics through a sexual selection. Hsiung et al. discuss this key component...
of color and behavior, indicating that “[c]olor produced by wavelength-dependent light scattering is a key component of visual communication in nature and acts particularly strongly in visual signaling by structurally-colored animals during courtship” (Hsiung et al. 2017).

Can we exploit this phenomenon to produce color and shape changing material systems for the future of design fields? How can new material development suggest new opportunities for social interactions? Can the material of our clothing be emotive and intelligent in responding to the movement and emotions of those around us? If so, in what ways might these technologies expand our sensory experience of the world? And in what ways could our clothing offer a form of non-verbal communication, expressed through changes in color and texture, similar to hummingbird’s feathers?

This paper attempts to answer these questions, by explaining the design logic behind Iridescence (Figure 3). Here I propose the theme of ‘bio-inspired emotive matter’ as a framework to develop material systems, which can learn from complex ‘physical’ and ‘physiological’ architecture of living creatures and are capable of responding to human emotion (1). Other factors that need to be taken into account include the function and logic behind a particular behavior and the message it is trying to convey. Emotive matter builds on the work has been done in this field, particularly on the programmable and active matter. However, it specifically addresses design strategies for interfacing with human emotions through tangible material interfaces. This research therefore grounds itself in the context of Affective Computing, in which computational systems are able to detect, interpret, and simulate human emotion (2). In order to develop an empathic relationship with the user, these material systems need to be able to sense the emotional state of the user by employing biosensors or computer vision technologies in order to detect physiological responses such as facial expressions. Ultimately, these material systems should be capable of using their dynamic behavior to ‘elicit’ certain emotional responses in the user.

**IRIDESCENCE**

Iridescence is an interactive 3D printed collar, inspired by the gorget of the Anna’s hummingbird. It is equipped with a facial tracking camera and an array of 200 flipping quills. The custom-made quills flip their colors and start to make patterns, in response to the movement of onlookers and their facial expressions.

**MORPHOLOGY**

Among the many colorful birds, hummingbirds stand out because of their spectacular iridescent feathers. Hummingbirds produce iridescent colors using highly ordered arrays of microscopic structural colors on the surface of their feathers. These structural colors can refract light like a prism, leading to an iridescent effect so that the feathers take on different shimmering hues when viewed from different angles. In other words, structural coloration is often caused by interference effects rather
than by color pigmentation. Another example is a peacock tail feather. The pigments are brown but the microscopic structures make the peacock feathers reflect iridescent colors.

Not dissimilar to how light is refracted by the feathers of a hummingbird, *Iridescence* uses lenticular lenses laminated onto an array of flat colored surfaces to provide color changing effects. This technology is nothing new. Lenticular technology was invented in the 1920s and can produce images with the ability to change as the image is viewed from different angles. Inspired by the color changes of the Anna’s Hummingbird, we have revisited this old technology and implemented it in order to produce material surfaces, which can change color from gold to magenta to dark blue. This technique is called 3D lenticular flip effect, and it occurs when an object contains multiple images interlaced together and laminated with a lenticular lens (Figure 4). As a result, different images can be seen from different angles. It is possible to achieve the color changing lenticular effect using a sliced color palate printed on a vinyl overlaid by a clear lens (60 DPI: Dot Per Inch) (Figure 5).

Taking the form of a large collar—shaped as a Toroidal surface—around the wearer’s neck, *Iridescence* is covered with color changing lenticular materials (Figure 6). The formal distribution of these elements follows the Phyllotaxis pattern of a sunflower, allowing a comparatively equal subdivision of the collar surface. The design of each lenticular feather is based on the underlying geometrical features resulting in location-specific ellipse-like geometries.

The collar itself is composed of eleven discreet polygonal segments printed using SLS 3D printing technology (3). Each segment is connected to its neighbor with finger-like joints, essential for load bearing. PCB boards with a set of screws, join the segments together, allowing the assembling and disassembling of the entire collar. As La Mangna et al. argue, “[f]inger joints are good in handling shear load forces,” and were therefore used in the design of this collar (La Mangna et al. 2012). Moreover, concave undulations with variations in their peak heights are designed to provide not only additional strength to the structure but also clearance for the movements of each moving lenticular element (Figure 7).

The piece was commissioned by the Museum of Science and Industry in Chicago, and one of the pragmatic challenges in this project was to provide an interactive kinetic piece which would be both capable of surviving an exhibition that would last for 15 months, and of being serviced and maintained based on a comparatively easy set of instructions. Therefore, a modular system was selected that would allow each lenticular element to flex and flip individually in order to change its color. The challenge was to build a mechanism that could flip each lenticular element in one degree of freedom, in order to mimic a hummingbird’s flapping motion and color change.
Most mechanical systems are prone to failure. Transmission problems, interconnected mechanisms, and so on, are among the common problems with conventional mechanical systems. For this project, we, therefore, looked at the production of custom-made actuators with simple electromagnetic mechanisms. The principle behind these actuators has been known for some time now and has been used for many items, such as tiny indoor airplanes designed by Didel, Inc (4), or the earlier flip dot display technology invented in 1961 and used in public transportation stations (5). However, nowadays they are seldom used by the design community.

The design of these actuators is based on a magnetic field acting upon a permanently installed set of magnets. Each actuator is composed of an assembly of many components. This assembly includes a set of permanent magnets housed on each side of a rotor that is able to flip and change position according to the controlled changes in the magnetic field of a closely coupled magnetic coil. The magnetic field of the coil is switched by reversing the control signal, and thus the rotor flips to the opposite direction. In other words, the permanent magnets located inside the rotor are either attracted or repelled by the field of magnetic coil.

The design of these actuators evolved over many iterations (Figure 8). Factors that informed the design of the actuators included:

- Hinge design
- The design of magnetic coil mount
- Resistance of magnetic coils
- Shape and strength of installed magnets
- Shape and weight of lenticular elements attached to each actuator

In this project, we established a workflow for the manual fabrication of parts, post-processing, and assembly of components, in order to achieve a satisfactory result. Each custom-made actuator is made of a 3D printed bobbin-like element (6) threaded with a 42 AWG magnetic wire (900 turns, 260 Ohm). The rotor itself is 3D printed, and installed inside the magnetic coil, so that it is capable of flipping on its axis with minimum friction. Two permanent magnets (¼" diameter, 1/16" thickness) are installed on either side of the rotor. The centering magnet is located underneath the magnetic coil, allowing the rotor to be centered so that it has a smooth movement, and can be controlled using Pulse Width Modulation signals (1/10" diameter, 0.5" length) (Figures 9 & 10).

Custom-made USB connectors are designed, so that each actuator could be replaced easily in case of failure (Figure 14). The male MicroUSB connector is attached to the bottom of the magnetic coil, and can provide the control signal for activation. The receiving female MicroUSB connectors are attached to the back of 3D printed surface with two small screws (M1.59, 4mm) and receive signals from the embedded microprocessors.
BEHAVIOR
Not dissimilar to the way in which the brain, nervous system, muscle, and vision in a hummingbird are synchronized together, this piece is equipped with 200 actuators acting as 'muscles,' 40 PCB (printed circuit board) driver boards acting as a 'nervous system,' 4 micro-computers acting as a 'brain,' and a facial recognition camera acting as an 'eye,' all mounted inside the piece (7) (Figure 11).

Four microcontrollers (Teensy 3.2) work together to orchestrate the collar’s behavior. One of these is the master ‘brain’ in charge of figuring out what the wearable should be doing at any given point in time. The brain communicates with the other three microcontrollers via conductive wires, using messages transmitted as precisely timed electrical pulses. One of the microcontrollers is attached to a camera and two of them are attached to 40 PCB driver boards. These electrical boards act as a ‘nervous system,’ in which they receive the signals from the brain and transmit them to the ‘muscles’ actuators.

These PCB driver boards were designed to leverage the mature ecosystem built around light emitting diodes (LEDs). By using existing, open source code libraries, we were able to take advantage of code that had been optimized to run on small microcontrollers that then drive thousands of LEDs. LED driver integrated circuits (ICs), without the LEDs are inexpensive components. They have a high-speed communication protocol that delivers three bytes of data, to each IC, 60 times a second, 60 Hertz (60Hz) (8). Microcontrollers were selected instead of LED drivers to communicate with the actuators. However, programming and maintaining the code for 100s of microcontrollers appeared to be a daunting task and would not allow us to easily use existing libraries (9). Therefore, one of the major engineering challenges in this project was to design and develop electrical boards to control the actuator’s behavior using LED driver ICs.

Another challenge in using LED drivers was their pulse width modulation (PWM) frequency. LEDs are resistive components, so the PWM only needs to be fast enough to appear lit without flickering. Our actuator design is similar to a voice coil, by changing the magnetic field we rotate a set of magnets. The PWM frequency can be heard in the actuator because the coil-magnet pairing also creates an inefficient speaker. The possibility of using the actuators as a speaker array and adding rhythmic sound to the experience was investigated, but the sound proved to be rather disturbing to the human ear and was determined to be beyond the scope of this project. The challenge was therefore to maintain the PWM duty cycle, and push the PWM frequency out of the range of human hearing. Finally, we were satisfied with flapping noise which was the result of movement of each actuator as the rotor moves on its axes and contacts the inner side of magnetic coil.

Iridescence is equipped with an ‘eye’—a camera embedded in front of the collar—similar to how animals perceive the world around them with their rich sensory inputs such as
visuals and touch. This provides visual input to the brain. Four times a second, the eye microcontroller asks the camera to give it visual information about each face it can see. It summarizes the face positions and facial expressions and sends that summary back to the brain, which decides what to do next (Figure 13).

The visual behavior of the garment results from the messages that the ‘brain’ sends to the two microcontrollers that are wired to 40 driver boards. Thirty times per second, the ‘brain’ first decides the angle each of the lenticular feathers should face, and then sends one message containing the angles to each actuator, divided evenly such that each microcontroller gets 100 angles per message.

When the microcontrollers, connected to actuators, receive a message from the ‘brain,’ they translate it into electrical pulses that can be recognized by the driver boards connected to the actuators. In turn, each chip sends an electrical signal (PWM) through many coils of copper wire to create a magnetic field that precisely orients its lenticular feathers.

The ‘brain’ has to decide and broadcast the angle of each actuator. To do so, it runs a kind of computer program known as a ‘finite state machine,’ which is a technique to model the behavior of a system in various conditions. Iridescence has seven states: ‘dreaming,’ ‘breathing,’ ‘waking up,’ ‘following,’ ‘happiness,’ ‘surprise’ and ‘anger.’ The brain can only have one state at one time. From any given state, there are a limited, or finite set of states it can switch to, based on the information it has about the world. For example, when the garment is in its ‘dreaming’ state, it can switch either to the ‘breathing’ state (if enough time has passed since it last took a breath), or to the ‘waking up’ state (if the eye sees a face).

While in one of these states, the brain evaluates a mathematical formula for each petal in order to choose its angle. The specific formula is different for each state, but often involves wave functions like sine, cosine and organic splines such as the Hermite spline; in which the parameters of their movement such as speed and amplitude are mapped to variables like the intensity of the facial expressions that the ‘eye’ detects (10). For instance, if an angry face is detected, all the actuators start to flip very fast using a sine wave function. The more people express anger, the faster the actuators move.

If no face is detected, Iridescence goes into ‘dreaming’ mode, breathing very gently with a subtle flipping movement. When a neutral face is detected, the location of that face is mapped to the closest sets of actuators on the collar with a heartbeat movement. If a happy face is detected, it shares happiness with a wave of ripples from inside outwards. When an angry face is detected, it starts to tremble, and when a surprised face is detected, it gasps with an asymmetrical flipping movement (inward/outward). Iridescence, with its AI facial tracking technology, is able to compute information up to 35 faces at once. It will get an average of all faces and responds to the average dominant facial expression and their location. Although the overall system is quite complex, each part of it has a small, well-defined responsibility.

What could such an innovative setup tell us?
Sensory substitution refers to the transformation of the characteristics of one sensory modality into stimuli for another sensory modality. In an experiment in 1969, Bachi-y-Rita demonstrates how blind subjects could learn to ‘see’ when visual information is fed to them through haptic stimulations. This example demonstrates the incredible power of the brain. Basically, the brain has the ability to read new sensory information from any source and translate it into meaningful inputs and consequently develop new modes of control once it has become accustomed to the inputs. As Eagleman puts, ‘[t]he brain doesn’t really care about the details of the input; it simply cares about figuring out how to most efficiently move around in the world and get what it needs’ (Eagleman 2015, 83).

Iridescence provides a new sensory experience, which takes in information such as the motion and emotion of those around and translates it into a pattern of movements and spatial sounds around the human head. The advantage of using such an innovation can be to gather visual information such as people’s facial expressions for those who have difficulties receiving or decoding this information. It can help visually impaired individuals to perceive the information related to the location and emotions of people around; or it can benefit people with autism who have difficulties recognizing facial expressions. Iridescence can also express non-verbal information through its dynamic behavior. To make this work, we drew from the latest advances in AI facial expression tracking technology and embedded it in bio-inspired material systems. We believe that this approach could be implemented across many scales fostering a new kind of relationship between human body and the environment.

CONCLUSION
Over the past 3.8 billion years of evolution, nature has come up with some highly inspirational models of adaptation. The Mimosa tree gently closes its leaves when touched. The male peacock displays its feathers to impress potential mates, and the cuttlefish changes its color to camouflage itself from a predator. These are just a few examples from nature where living systems are equipped with complex forms of sensing and actuating that serve as tools for survival. Inspired by the ‘morphology’ and ‘behavior’ of natural systems, we can not only develop new performative materials but also open up new social and sensory possibilities.

This paper has presented the design process behind Iridescence, an emotive bio-inspired collar. Inspired by Anna’s hummingbird, Iridescence with its array of custom-made actuators, demonstrates how wearables can become not only a vehicle for self-expression, but also an extension of one’s sensory experience of the world. Even with eyes closed the wearer can sense where people are standing relatively, and even sense the emotions they are expressing through the movement of the wearable. Iridescence can also communicate to the onlookers with color and shape-changing patterns of behavior. It does this by exploring the possibilities afforded by AI facial tracking technology and the dynamic behavior of a smart fashion item.

This bio-inspired emotive approach offers an example of how material systems can sense and respond to human emotions. The goal of developing these dynamic systems is to address psycho-social issues involving emotions.
and sensations, and to see how these might also inform our social interaction. This could be understood as a form of proto-architecture at the intersection of affective computing, artificial intelligence, ethology, and design offering a design approach that could be implemented across many scales from fashion to furniture to industrial and urban design.

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NOTES
1. Note morphology is typically physical characteristic and behavior included physiology of an organism. While morphology studies size, shape and structure of an organism, physiology mainly is dealing with function of an organism.
2. As neuroscientist Joseph E. LeDoux notes, “I treated emotions in terms of essentially non-conscious brain states that connect significant stimuli with response mechanisms, and feelings as conscious experiences arising from these non-conscious brain states." Within this framework we might study, for instance, the way an animal’s brain detects and responds to danger for the purposes of survival. When faced with danger; most animals protect themselves with a series of responses such as climbing, flying, swimming, freezing and running. Interestingly, as Ledoux notes, “If you follow the logical conclusion of all of this, you will see that even bacteria do these things. They’re in their little petri dish in a lab. If you put some acid on one side, they all move to the other side." Could we therefore say that bacteria in a petri dish have emotions? As LeDoux notes, “Every living organism, from the oldest to the most recent, has to do these things to stay alive and pass its genes on to its offspring. Organisms must detect danger; identify and consume nutrients and energy sources, balance fluids by taking in and expelling liquids, thermoregulate, and reproduce. You do these things, but so do the bacterial cells living in your lower intestine.” (LeDoux 2015)
3. Nylon Glass-filled material has been used in this process, which can provide one of the highest tensile strength among various 3D printed materials available.
5. The flip-disc display was developed by Kenyon Taylor at Ferranti-Packard at the request of Trans-Canada Airlines (today’s Air Canada) in 1961. Access from https://en.wikipedia.org/wiki/Flip-disc_display
6. High resolution SLA printing technology of Formlabs used for the production of the actuators.
7. Note this is just an analogy helping the reader to understand the complex relationship between various parts of the system.
8. The LED driver ICs are daisy chained using only 3 wires: positive, ground, and signal.
9. In this case FastLED Library (http://fastled.io/)
10. Our system detects facial expressions with the degree of confidence. As the detected emotion rises, the score changes between 0 (no expression) to 100 (expression fully presented).

REFERENCES


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Behnaz Farahi is a designer working in the intersection of architecture, fashion, and interaction design and exploring the potential of interactive environments and their relationship to the human body. She also is an Annenberg Fellow and PhD candidate in Interdisciplinary Media Arts and Practice at USC School of Cinematic Arts. She has an Undergraduate and two Master degrees in Architecture.