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Bio-mimetic Approaches to Kinetic Facades: A Design Proposal for a Light-Responsive Facade Module.

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Abstract. Facades are important for controlling light entering a building and ensuring optimal conditions for occupants. But light can also cause discomfort, such as glare and overheating. Natural light changes with the time of day, the weather, and the season. Creating a responsive structure can enhance the visual quality and energy efficiency. Because of their properties, kinetic facades can react to various stimuli, such as heat and sunlight. In this paper, we discuss bio-mimetic approaches to kinetic facades and how they can be used to develop a design proposal for the light-responsive facade module. Motors drive most kinetic facades, which adds to the maintenance costs, thus,shape memory alloys (SMAs) are investigated as actuators. Facades should be visually appealing and reflect the bio-mimetic concept of the project while allowing natural light to pass through. The results show that the suggested solutions are both feasible and aesthetically pleasing, thus comparable to traditional kinetic facade workflows. In conclusion, if bio-mimicry is to be used in large-scale construction, it is imperative that it is examined for the effects of different environmental conditions on bio-mimetic patterns.

1. Introduction

Through the history of architecture, the role of a facade has evolved from being a defensive shell that protects from threats and instills a sense of safety, into a tool that allows us to stay connected with our surroundings. In spite of the need for sustainability, modern architecture is not always in harmony with natural environment. Even though numerous green zones are being integrated into roofs or atriums, the question is whether modern architecture appeals to us cognitively as a natural thing and what emotions it triggers. Numerous studies have shown how much space can influence our cognitive and affective states [8] [22] [11]. Moreover, light can affect us in various ways from boosting creativity and productivity to raising our mood and making us feel more optimistic by triggering both visual and non-visual pathways in our brain [25].

One of the main functions of a building's facade is to regulate the amount of light entering it and thus, to create optimal lighting conditions for the occupants. Accordingly, a good supply of light and daylight is essential for optimal conditions in offices and residences [2]. Although light is essential for optimal conditions in workplaces and residential buildings, it can also cause discomfort, such as glare and overheating. However, natural light changes depending on the time of day, the weather conditions, and the season [3]. By creating a responsive structure, the visual quality and energy efficiency can be enhanced. kinetic facades are able to respond to external stimuli, such as heat radiation and lighting, and due to their properties, they are becoming more prevalent in contemporary architecture. This paper focuses on a bio-inspired approach to kinetic facades and how it can be used to develop a design workflow for the light-responsive facade module.

The movement of a kinetic facade is usually achieved through motors, which adds to the cost of sustaining materials [19]. We explore the possibility of using SMA (shape memory alloy) and NiTinol (Nickel titanium alloy) wires in particular, as actuators. A "shape" criterion represents the characteristics of the design in terms of the visual appearance of the facade. The facade should be visually appealing and should reflect the bio-inspired concept of the project while passing sufficient natural light [23]. A bio-mimetic approach to solving design or engineering problems involves the imitation of elements and systems found in nature. Computational and generative design tools will be used in this project to achieve the idea of bio-philia. It is important that the design reflects irregularities, imperfections, but at the same time has regularity and harmony, like natural patterns. The adaptability of the responsive facade refers to the geometric properties of the generative design to adapt to constantly changing lighting conditions. The solution is expected to change its shape with a relatively fast speed and minimal energy consumption in order to meet the needs of the occupants [13]. Various bio-inspired facade patterns were tested and compared against regular geometry patterns in order to identify how people perceive and react to each. From the study, it was found that the bio-mimetic patterns elicited a significantly higher preference rating than the regular geometrical patterns. It was also found to be more interesting and appealing to people both in sunny and gloomy pictures. Moreover, participants enjoyed the indoor environment, which evoked good natural associations, such as a honeycomb. But some of the participants found the pattern to be quite disturbing. In conclusion, the study suggests that further investigation should be done to explore the effect of bio-mimetic patterns on different environmental conditions in order to determine the acceptability of bio-mimicry in large-scale construction.

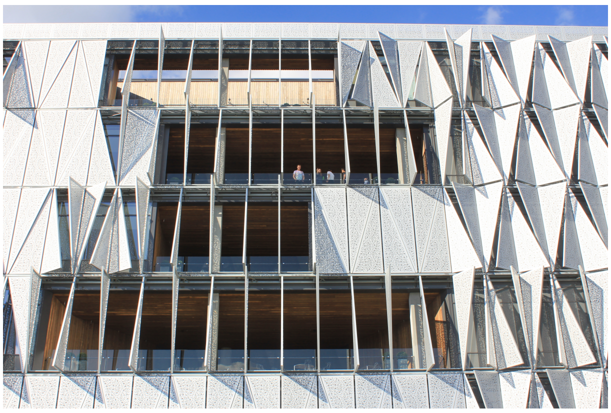

Figure 1. University of South Denmark, responsive facade with moving mechanical parts.

2. Bio-inspired design

The term bio-mimicry, originated from Greek - bios meaning life, and mimesis meaning imitate - and has been widely used in industrial design, medicine, and engineering.The natural selection process is a driving force for the evolution of better suited species and traits based on pre-existing conditions [11]. As a result, more advantageous and best adapted organisms can survive [11]. Nature's most perfect systems can often be found in this iterative process, therefore, people have learned from nature by imitation while solving life's problems for thousands of years. Regardless of its popularity in other fields, bio-mimicry has recently gained popularity in architecture [17]. Based on the ability of nature to adapt to a variety of conditions, bio-mimicry is now widely used as a tool in the design of built spaces in order to meet certain challenges regarding thermal and visual comfort in buildings.

2.1. Bio-mimicry as a design practice

Bio-inspired design is usually divided into five main stages: planning, abstraction, searching a space of solutions, analyzing, and comparing the final solutions [9]. Data analysis is usually the next step after project planning. Since there are no direct links between biological systems and industrial needs, problems and possible natural analogies should be simplified. A popular method is to use bio-cards. Bio-cards describe a biological phenomenon's function and are used to generate design proposals and abstract descriptions based on conceptual ideas [16]. After the abstraction is complete, the next step is to decide which phenomena are relevant and applicable to the specific problem at hand. Finding a solution that could be applied requires to determine whether the phenomenon is transferable to an engineering domain.

Two main approaches are used in bio inspired design: (a) A problem driven or a technology pull approach [16] [10] which is based on identifying the problem in the biological domain that must be solved. (b) A biology push or solution driven approach where designers and engineers have to find a problem where an already known biological solution can be applied [16] [10] [24].

3. Shape Memory Alloys in Adaptive Facade Design

SMAs are often used as a substitute for muscles in robotics, which goes hand in hand with a bio-inspired approach. SMAs refers to alloys that are able to "remember" their initial shape. SMA is a family of materials that changes theirs physical shape when subjected to certain temperatures [6]. The shape of the material can be pre-programmed, or deformed, in low temperatures. When the material is heated again, it recovers its original shape (figure 6.1). Different types of SMA exist, such as Ni-Ti, CuAlNi, CuZnAl, AuCd, FeMn, etc [6]. NiTinol is one of the most popular SMA materials being used today [1]. Nitinol gained great popularity due to its unique properties combining ductility, bio-compatibility, corrosion resistance, and longevity (it can withstand up to 185000 cycles of deformations [20]).

Depending on the alloy composition and the temperature at which it is exposed, Nitinol will react differently. The activation temperature varies between 30C (86F) and 130C (266F). The material could be used in architecture for ventilation or facade structures, where it could change its shape depending on the temperature inside or outside of the building. Nitinol is activated through heating as it reacts to temperature changes. Electrical current is conducted through Nitinol, resulting in an increase in temperature due to the electrical resistance of the material. When the material increases its temperature, it will change its shape. Wires made of Nitinol have significant pulling force [1], which makes them a good choice for an adaptive facade as they can support heavy loads.

4. Challenges of Using Nitinol as a Facade Actuator

Fatigue is a common effect caused by cyclic loads and therefore deformations placed on the components. Deformation is difficult to estimate, since numerous factors affect that parameter, such as structural fatigue (strength declines under cyclic loads) and chemical fatigue [18].

It is important to consider how SMA can withstand a wide range of temperatures when designing facades. The composition and diameter of an alloy can affect how it deforms at different temperatures. Therefore, for temperate climates could be more suitable, where metals heat up during the day and become cold at night, but in extreme climates, SMA could be activated in an unpredictable way. Another challenge of using SMA as an actuator is the amount of power required to drive their shape change profile. SMAs require a lot of electric power, and this power could be difficult to provide if the facade is not connected to the grid or an alternative power source like Solar panels, and this power demand is likely to vary from season to season.

5. Designing Daylight Envelopes

One of the main functions of the facade is to regulate the amount of light that enters the building, and therefore to create an optimal lighting environment for the occupants. Although natural light, and daylight in particular, is essential for optimal conditions in workplaces and residential buildings, it is also associated with glare and overheating [2]. However, natural light is dynamic, the intensity varies according to the time of day, season, or the weather [7]. Creating a responsive structure would improve energy efficiency and visual appeal [13] [15].

The speed of light adaptation, as well as the frequency of lighting adjustments, must be taken into consideration when creating an autonomous dynamic facade. It is also important to address the question of whether people need to be shielded from direct sunlight, in order to avoid discomfort, or to have some kind of light patterns projected in the interior in order to maintain a connection with the outside and natural world. It is thus, extremely important to understand key factors that affect the perception of any design solution when exploring how people react to certain lighting conditions within an architectural environment.

Diversity, complexity, and intensity are aspects of designing disciplines that affect occupant stimulation [5]. In any interior, daylight is a constantly changing element. As time passes, we adapt to certain qualities of the interior (old stimuli) and stop responding to them. People can easily get bored when there is not enough stimulation or change, or they can get overstimulated if those changes are too drastic and frequent. This may result in either mental fatigue or sensory deprivation. It is therefore extremely important to keep medium levels of sensory stimulation [5]. Thus, in addition to regulating lighting in a space, a kinetic facade can also provide new stimuli, such as the "play of light" and light patterns in the room.

6. Design and Implementation

Three criteria were used to ensure that the design solution meets the project requirements in accordance with its vision.

- *Shape* is primarily a design criteria that represents visual requirements. The facade should reflect the bio-philic idea of the project, while allowing for sufficient light to pass through. Moreover, based the concept of bio-mimicry, the generated patterns should demonstrate irregularities and other imperfections, and yet still be harmonious, thus, computational and generative design methods will be employed to achieve this.
- *Bio-mimicry* can be used to solve engineering problems as a principle that imitates elements and systems in nature.
- *Adaptability* refers to the ability of a design to adapt to constantly changing lighting conditions depending on its geometry. The shape of the solution should be easily changed in a relatively short amount of time.

We aim to create an autonomous facade module that reacts only to external temperature changes by directly activating the actuators with electrical current. The next step was to find a pattern in nature that could be used as a visual reference for the facade design. Two different shapes were conceived and realized. The first shape was inspired by the patterns on the gills of mushrooms 5. Mushroom gills are thin structures, under the cap, which vary widely in pattern from species to species. Every one of them has a slightly different geometry, giving a nice pattern when they're layered together. We translated the pattern of the lines into a window

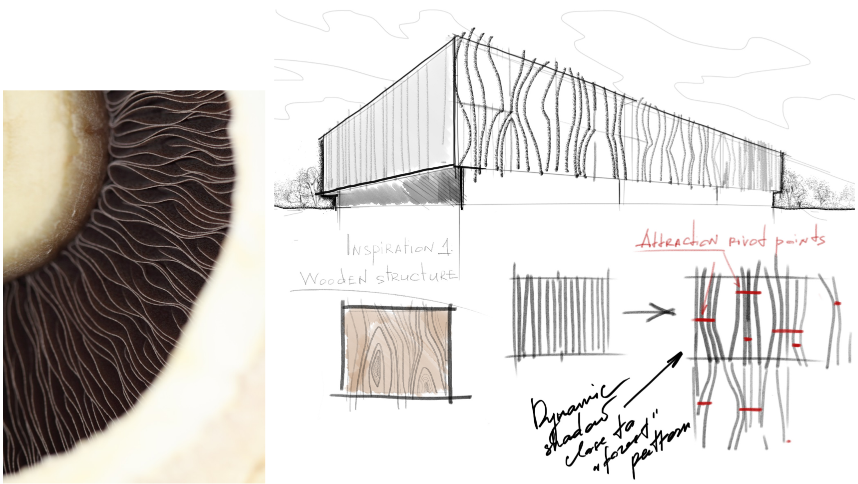

Figure 2. (Left) Mushroom gills as an inspiration for the facade pattern. (Right) Sketch of the actual facade, flexible strips and attached Nitinol wires in red.

shading module pattern with thin flexible sheets aligned vertically. Each of these modules will be reproduced throughout the facade. In selecting this pattern, we took into account the ease of fabrication, especially with digital fabrication technologies such as 3D printing and robotics assembly. The second shape was inspired by the lotus fruit and seeds. This pattern was recreated in 3D using Voronoi tessellation. Rather than a rigid material, the facade would be made of flexible tissue or material that would be fitted with a flexible SMA. As the wire contracts under certain temperatures, the opening gets smaller and less sunlight gets through the facade. It can also decrease in size, which causes the holes to widen (figure 6). In generative design methodologies, architects are only in control of variables, as the systems used are usually very complex, and cannot fully predict the outcome of the algorithm. Furthermore, when combined with software such as DIVA for illumination analysis, multiple iterations can be performed automatically to determine an appropriate opening ratio.

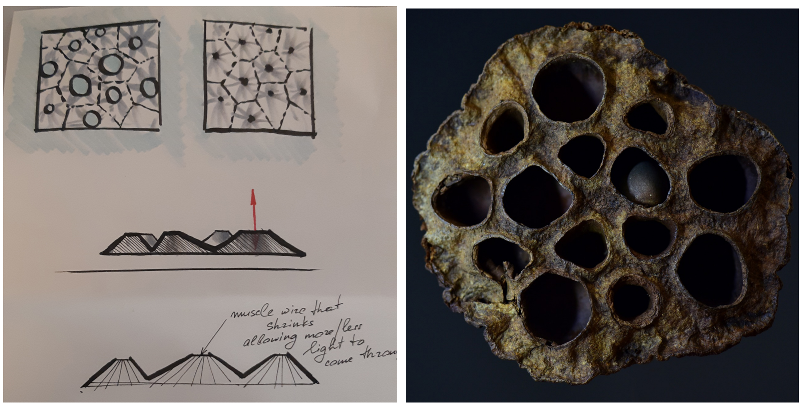

Figure 3. (Left) Sketch of the second concept (Right) Lotus seeds as an inspiration for the openings of the facade.

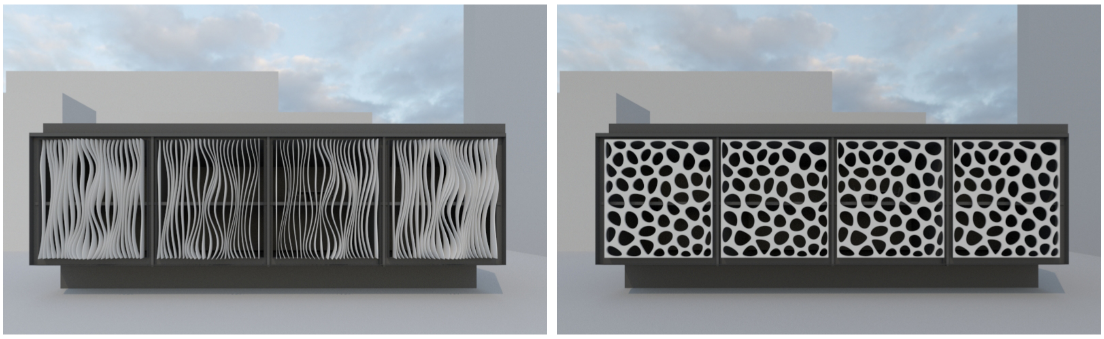

Figure 4. Generative Facades based on the concept of SMA controllable modules. (Left) A facade resembling mushroom gils, (Right) a Voronoi tessellation resembling lotus seeds sockets.

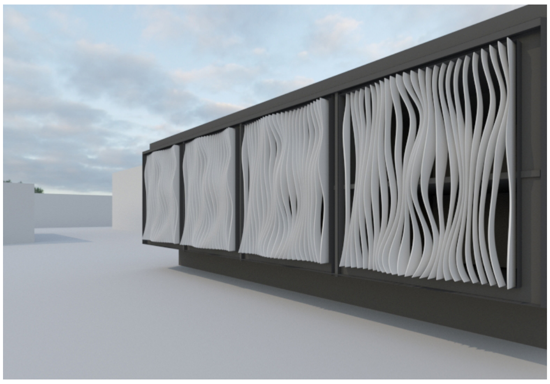

Figure 5. Perspective view of Voronoi tessellation facade

6.1. Prototype

A simulation was used to explore a range of possible solutions and to predict the behavior of the facade. Diva for Rhino was used for lighting simulations. The yearly daylight autonomy was simulated, including the mean daylight factor (figure 8). For the deformed vertical blinds, we used Kangaroo and the Weaverbird plugin to create a Voronoi network. It is possible to model nitinol actuators using Kangaroo, but we found it difficult to simulate the linear expansion of the SMA wire under different loads. Therefore, optimizing the form using a global optimizer such as an evolutionary algorithm might be a potential solution. In this case, the optimization process could take into account how much light passes through as well as the number of SMA wires attached to the modules and their hinge positions.

To test the behavior of Nitinol under a variety of scenarios and loads, a prototype was implemented. The module consists of a rectangular frame made of plywood with a series of equally spaced soft wooden stripes and 4 Nitinol wires attached to the stripes 6.1. The size of the unit was 45x45cm and was equipped with a single light sensor. By deforming the shape of the stripes more or less light was able to penetrate the unit, thereby providing a regulating effect. An Arduino microcontroller measures the amount of light in the environment through a light sensor, and based on the sensor readings, the Arduino activates the Nitinol wires 6.1. The prototype showed that Nitinol can responded to light stimuli, but it was challenging to control the light response. Further development of this method requires optimization of Nitinol wires, their arrangement, and control. Controlling the light entering the facade would be more precise with a closed loop controller such as a PID controller, but that was beyond the scope of this project. A PID controller is a common type of controller used in many industrial applications such as robotics, automotive, aerospace, and manufacturing [4]. It is used to calculate an ”error” value as the difference between a measured process variable and a desired set-point. The controller attempts to minimize the error by adjusting the process control inputs.

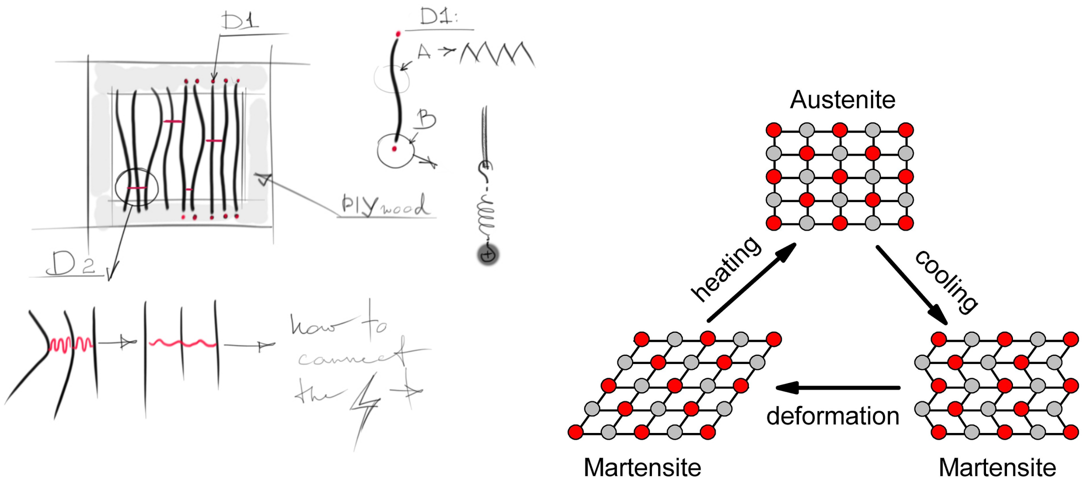

Figure 6. Sketch of the facade module prototype, and Illustration of the shape memory effect of Nitinol alloys. SMA alloys expand when heated and contract when cooled, (right)

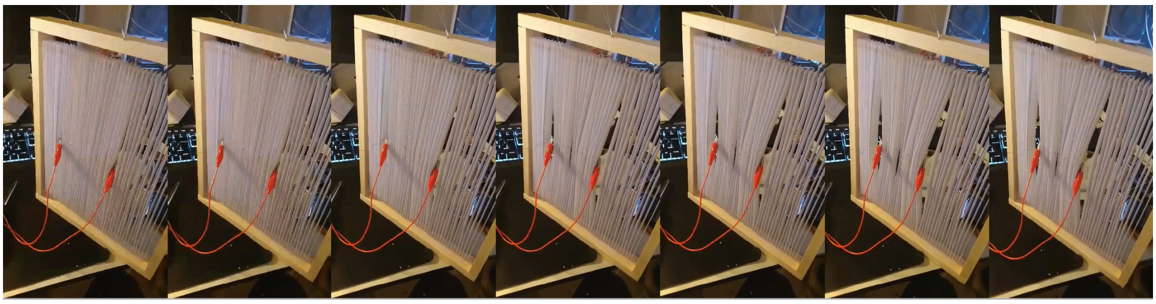

Figure 7. This time series shows the prototype module’s horizontal strips being deformed as a result of Nitinol wire activation through electric current.

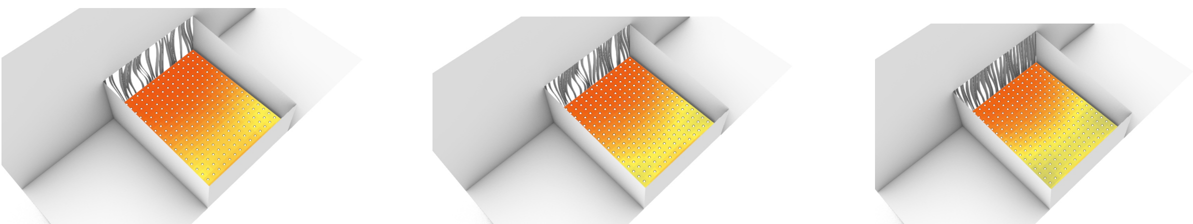

Figure 8. Daylight autonomy simulation. (Left) High open ration of the facade with Mean daylight factor - 2.1% (Center) Medium open ratio with Mean daylight factor - 1.9% (Right) Low open ration with Mean daylight factor - 1.6%

7. Evaluation

This study used Nitinol as a smart actuator to add flexibility to a facade design by copying natural processes. Therefore, we need to determine how people react to various facade designs in terms of aesthetics and other perceptive factors. Four rooms of the same geometry and position were created using Rhinoceros 3D, Grasshopper and Corona Render. Two lighting scenarios with direct sunlight and overcast sky were rendered for each room. Twenty-four participants were interviewed (15 males and 9 female). The age ranged from 22 to 54 years old, with an average age of 29 years. None of them had any design background. Participants were shown 8 different images of facades: two geometrical and two bio-inspired facades with two types of daylight 9. The testing process was divided into three phases. During the first phase participants asked to rate each image based on how attractive or pleasing they found it using a discrete analog scale of 1-10, with 1 being very unattractive, 5 being slightly unattractive, 6 being slightly attractive, and 10 being very attractive. The second phase of the experiment had participants rate the same pictures on how interesting/exciting they found the room using the same discrete analog scale of 10 points. In the third phase, participants had to evaluate 4 images with different facades but with only direct daylight. Participants were asked to select one or more words from the list of antonyms below to describe visual qualities of the room (table 1). More open-ended questions were posed at the end of testing to gather qualitative feedback.

Table 1. Visual qualities.

Organic	Geometrical
Beautiful	Ugly
Simple	Complex
Stimulated	Subdued
Pleasant	Annoying

8. Results

We use a modified version of the circumplex model of affect [21] to describe the different emotional states of our participants. This is a continuous two-dimensional model of affective states that describes the structure of emotions and their relationships in terms of two independent underlying dimensions: pleasure and arousal. Emotions are placed along the circumference of a circle and are defined by their level of pleasure and arousal. The circumplex model has been proven to be a very useful tool for representing and understanding emotions. It has also been used to investigate the emotional reactions of people to different stimuli, such as music [14] or to characterise four different emotion states (liveliness, relaxation, tense and gloom) for a workspace lit environment [12]. For facade C 9 most participants found the bee-shaped pattern and strong sunny pattern to be very appealing. The lines and sunny patterns on image B received the most mixed and evenly distributed grades in the first image. Image D received the least favorable ratings of all other images while "Very attractive" ratings were not given. The results show that people tend to rate rooms as less attractive when there is no direct sunlight present, and that rooms also appear less positive when there is no daylight. Most participants rated the facade on image A (~50%) and image C (~75%) as organic. The facade on image B was mostly described as Simple (95%) and Pleasant (40%). In contrast, the facade on image D was described as very annoying (25%) by a majority of respondents. The pattern

Figure 9. From top to bottom. A: Deformed Vertical Strips, B: Vertical Strips, C: Voronoi Tessellation, D: Regular Openings. All rooms were simulated under two different lighting conditions, direct sunlight and overcast.

in this image was difficult for the eye to discern, which resulted in it being rated annoying. Interestingly, the facade pattern in image C was rated at the same time as ugly and beautiful (25/0%).

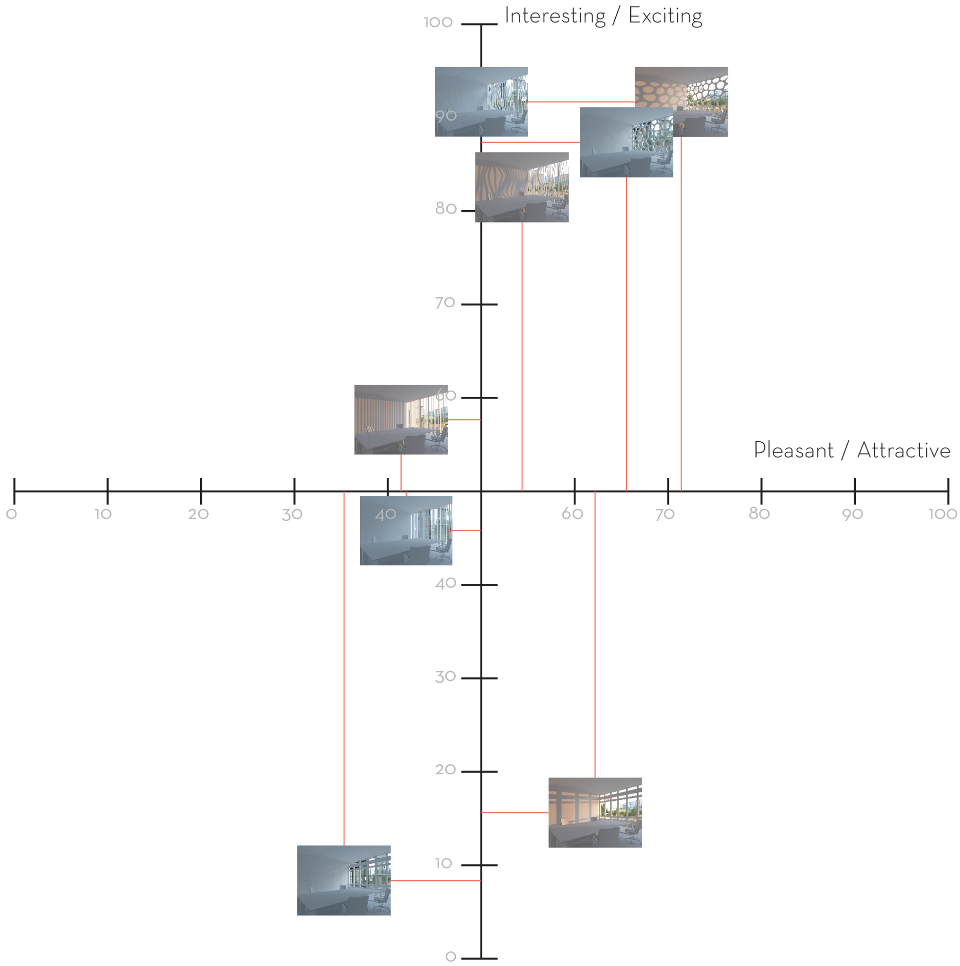

Figure 10. A circumplex model of affect was used to evaluate participants' responses to different facade designs under two different daylight scenarios.

Overall, organic patterns received more positive feedback than geometric patterns. Participants found them to be more interesting and pleasant looking in both sunny and gloomy daylight setups. People have given organic pictures generally positive feedback in an open-ended discussion after the test. An important concern is, however, the cognitive associations that people have with organic facades. In the eyes of some, they were very appealing and evoked positive associations, such as for example a "honeybee comb". However, the hole pattern turned some people off, and they found them frightening. A person referred to the facade with the twisted vertical blinds as "tentacles of a squid". Thus, it is extremely important to address the problem of triggering certain nature-based phobias of potential users while looking for natural inspired patterns.

9. Conclusions

A major concern when using electro-mechanical panels for adaptive facade design is its durability and power consumption. Nitinol has proven to be relatively durable in tests, and using a sheet instead of wire could be a more secure method. Additionally, the proposed design solutions meets all three success criteria, as it can adjust to the light, has a visual representation similar to the natural shape, and is based on bio-mimicry principles. As a result, Nitinol is a viable material for bio-mimetic facade design. Furthermore, it is easier to maintain and replace faulty parts, which may be useful for larger scale construction. It is however important to conduct additional testing in the future to verify Ninitol's durability, its financial benefits, and how it compares to other methods that use moving mechanical parts. Due to the uncertainty of the shape of the deformations or how they will behave under varying conditions, lots of experiments must be performed in order to optimize their use. Moreover, a controller is needed such as PID to make the adaptive facade more efficient and to reduce the amount of energy it consumes. Thus, it becomes clear why we have chosen to simulate the geometry and deformations of the facades. In addition, the human comfort in this space must also be considered. We will conduct more testing via VR to gain a better understanding of how people react to nature-inspired patterns. The majority of participants found the facade visually appealing, but some found it irritating, triggering unpleasant associations. The application of smart materials to the built environment can create unique structures that are constantly changing based on the environment. Thus, the aesthetic experience of the inhabitants should be taken into account in future work, as smart materials are a relatively new field of study and SMAs have tremendous potential for adaptive facades that can shape their appearance according to the time of day or season.

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