Prototyping Interactive Nonlinear Nano-to-Micro Scaled Material Properties and Effects at the Human Scale

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Abstract

The goal of the eSkin project is to explore materiality from nano to macroscales based upon an understanding of the dynamics of human cell behaviors. Immediately at hand, is the necessity to understand, speculate, test and simulate which nonlinear nano-to-micro scaled material properties are possible at the architectural scale. The synergistic, bottom-up approach across diverse disciplines, including cell-matrix biology, materials science & engineering, electrical & systems engineering, and architecture brings about a new paradigm to construct intelligent and sustainable building skins that engage users at an aesthetic level. In this paper, we present two human scale prototypes combining real-time presence detection with specialized display technology and interactive computer simulation. The prototypes probe the possible features and effects of eSkin at the scale of a building façade unit.

1. INTRODUCTION

1.1. Background

How might architecture respond to issues of ecology and sustainability whereby buildings behave more like organisms in their built environments? We are interested in probing the human body for design models that give rise to new ways of thinking about issues of adaptation, change and performance in architecture. The eSkin project starts with these fundamental questions and applies them towards the design and engineering of responsive materials and sensors. The work presented here, titled *eSkin*, is one subset of ongoing trans-disciplinary research spanning across the fields of cell biology, materials science, electrical and systems engineering, and architecture. The goal of the eSkin project is to explore materiality from nano to macro scales based upon an understanding of nonlinear, dynamic human cell behaviors on geometrically defined substrates. To achieve this, human smooth muscle cells are plated on polymer substrates at a micro-scale. Sensors and imagers are then being designed and engineered to capture material and environmental transformations based on manipulations made by the cells, such as changes in color, transparency, polarity and pattern. Through the eSkin project, insights as to how cells can modify their immediate extracellular microenvironment are being investigated and applied to the design and engineering of highly aesthetic passive materials, sensors and imagers that will be integrated into responsive building skins at the architectural scale.

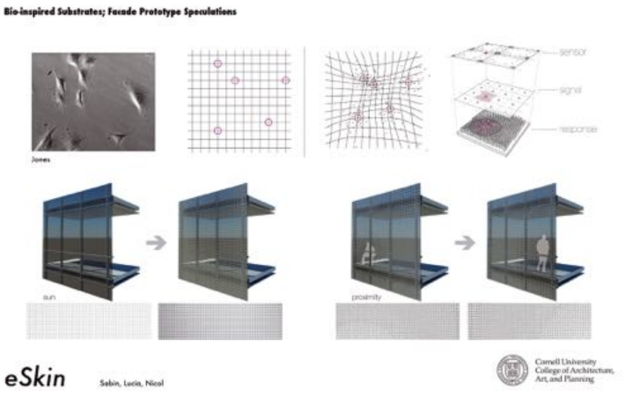


Figure 1. Previous simulations and architectural speculations of eSkin. Cell data originally produced in Dr. Peter Lloyd Jones lab, University of Pennsylvania. Our emphasis continues to rest heavily upon the study of natural and artificial ecology and design, especially in observing how cells interacting with pre-designed geometric patterns alter these patterns to generate new surface effects. These tools and modes of design thinking, are then applied towards the design and engineering of passively responsive materials, sensors and imagers.

A building's envelope must consider a number of important design parameters including degrees of transparency, overall aesthetics and performance against external conditions such as sunlight levels, ventilation and solar heat-gain. In contrast to existing examples of adaptive architecture, we are specifically interested in the role of the human in response to changing conditions within the built environment. Additionally, our group is carrying out fundamental and applied research to develop novel materials synthesis and fabrication methods not yet available on the market. Our applied design offers additions to the paradigm of responsive and adaptive architecture through architectural treatments in the form of an adaptive building skin, eSkin, which modulates passive solar, light and moisture control with embedded sensors that ultimately (re)configure their own performance based upon local criteria.

Our role as architects, involves generating tools to visualize and simulate cell attraction forces and cell behavior such as forces distributed via a virtual extracellular matrix environment, over multiple time-states while also incorporating micro-scale material constraints. Beyond visualization, we also direct the architectural intent of the project by constantly speculating on how results at the nano and micro-level will potentially look, feel, and assemble at a building scale (Figure 1). For example, one of the interactive prototypes featured in this paper integrates actual simulation data from micro-scale material substrates to speculate upon how these complex behaviors and effects may translate to the building scale and initiate human interactivity. Based upon these nonlinear and dynamic responses that human cells generate, we are redesigning and re-engineering interfaces between living and engineered systems with the ultimate goal of implementing some of the key features and functions revealed by cells on a chip for sensing and control at the building scale.

1.2. Background on materials research & importance of scaled prototypes

The particular material research presented in this paper focuses on one subset of study within the eSkin project, the optical simulation and application of geometrically defined nano-to-micro scale substrates that display the effects of nonlinear structural color change (Figure 2) when deployed at the building scale. Specifically, nano/micro scale pillar substrates, designed in the Yang lab, form the basis of this investigation. These substrates are fabricated via microlithography and softlithography, first requiring a negative nano/micro pattern to be etched into a substrate in which PDMS is subsequently cast, cured, and removed, thus producing a positive relief of nano/micro pillars. For a full description of the materials used in the context of this investigation, please see Wang, et al. 2013.

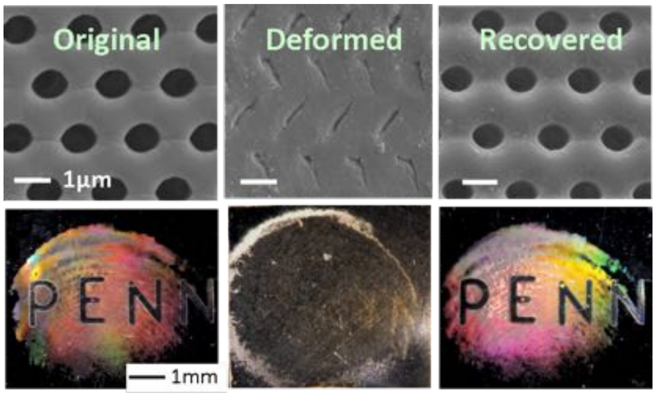


Figure 2. Example of a predefined geometric pattern embedded within a shape memory polymer material displaying structural color change under deformation and recovery. Here we exhibit SEM images of membranes consisting of a hexagonal array of micron-sized circular holes (top row) and demonstrated dramatic color switching as a result of pattern transformation (bottom row). Image originally published in Li, J., et al, 2012.

Though these specific types of optical qualities can be seen by the naked eye (Figure 2), extracting their optical performance quantitatively for speculation at larger architectural scale applications is necessary given a.) the current limitations in which these substrates can be fabricated (currently 4 inches maximum), and b.) the necessity to speculate on large scale deployments of potential materials without the need to actually fabricate. Thus, simulating the effects of larger swathes of these materials has been a goal and focus of this research; to speculate as to the larger scale application and effect of these substrates in an architectural context.

Thus, as actual fabrication of the desired nano material is still unattainable, we demonstrate in principle, 2 distinct types of speculation for the architectural scale. The first is a simulated, digital, real-time and interactive prototype that harnesses the optical properties and attributes of the particular desired nano materials being designed and tested within the Yang Lab for the eSkin project. Here, through the use of video input, a viewer's proximity and movement trigger a simulated response in the virtual substrate's appearance (Figure 8).

The second output aimed at advancing speculative design trajectories within the eSkin project is a physical, interactive, and scaled component prototype whose properties behave in a comparable manner to those sought, but which can be fabricated at a larger scale. Importantly, this second scaled prototype provides a test bed for another fundamental element in the conception of eSkin, that of local adaptation to environmental stimuli. Here, we consider the role of the individual sensing node and its affects upon a local region of change within a global surface substrate. To this end, our scaled prototype makes use of sensing and control technologies developed in the labs of Van der Speigel and Engheta, which then influence local regions of change within the eSkin prototype (Figure 6 & 9). While the adaptive materials, colloidal particles, used in this prototype are not the intended final material output for eSkin, they allow for a rapidly responsive testing ground for the local sensors' adaptive technologies. The thrust of this paper demonstrates these 2 distinct trajectories, both of which offer insights and allow for development of further architectural speculations as we traverse scalar dependent properties generated at the nano and micro levels, yet that are applied at the macro human scale.

2. METHODS

2.1. Prototyping Optical properties at the Nano-Micro Scale

Previously (Wang et al, 2013), we have demonstrated the extraction of simulated optical properties and their deployment through a suite of off-the-shelf and custom written software, enabling the speculation of nano/micro scaled material properties at an architectural scale.

First, the unique physical and angle dependent optical properties of a small portion of these periodic geometric substrates are simulated in the labs of Van der Spiegel and Engheta through the use of Lumerical FDTD Solution, material simulation software. Due to the periodic nature of the substrates in question, only a portion of these substrates need be simulated, after which the characteristics of the material would "repeat" itself. These simulations, which derive the angle dependent optical properties of the material substrates, ultimately form the basis for larger scale simulations of potential material applications within the eSkin system. The angle dependent property can be formatted into a function of reflection coefficient and transmission coefficient versus wavelength of light.

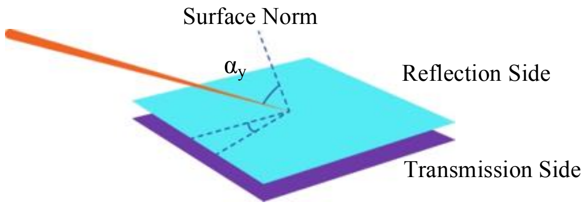


Figure 3. Incident light angle on two sides of a surface

Initially, at the architectural scale, speculations as to the extracted performative and aesthetic qualities of these nano/micro materials were deployed using custom written algorithms in conjunction with the Rhinoceros (NURBS modeling) software environment. We would later rewrite these algorithms in alternate software to facilitate a smoother real-time simulation. To maximize the color changing effect and efficiency calculation, the simulated geometry was approached as a tessellation of panels that respond to peoples' movement in front of a video camera serving as a sensor. Each panel can be treated as an individual surface with a single light source of uniform distribution, with each point on the surface having the same optical properties. Therefore, evaluation of the center point upon each discrete tessaltaed surface represents properties of the whole. With one single light, the two sides of the surface can be named as the reflection side (C_r) and transmission side (C_t) (Figure 3). After calculating the incident angle, a matrix of C_r and C_t at different wavelength (λ) can be obtained by interpreting the measured data. For a given light source with a specific spectral power distribution ($I(\lambda)$), reflected/transmitted spectral power distribution can be obtained by $C_r(\lambda)$ $I(\lambda)$ and $C_t(\lambda)$ $I(\lambda)$, so that the a XYZ color can be generated for the surface. (Figure 4).

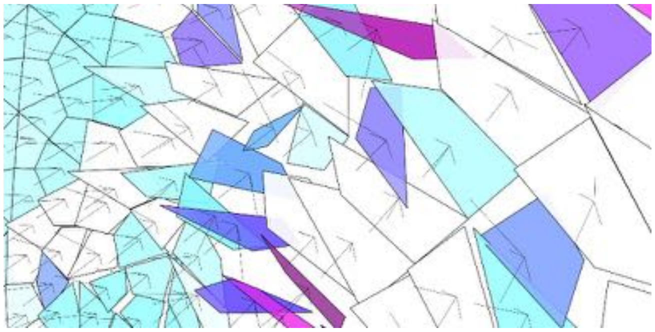


Figure 4. Incident light and normal of tessellated surfaces

2.2. Interface Design for Simulation: Prototype 1

As mentioned, in the context of the prototypes and simulations, the previously constructed suite of digital tools proved too computationally heavy and burdened with a significant temporal delay to perform adequately in a real-time situation, operating at speeds of 1 second plus between refresh. As a result, it became necessary to rebuild the same properties, qualities, and interactions within a single software environment rather than across platforms. Having resolved networking issues across platforms, the remaining performance criteria largely surrounded issues of spatial and temporal fidelity. Issues of efficiently computing movement and coloration of mesh faces were important design constraints. Similarly, spatial fidelity of the environmental triggering stimuli (here taken from differences across a real-time temporal pixel array) was minimized to avoid unnecessary lag in computation. Temporally, frame rates were a limiting factor based upon the amount of computation required per frame. A sufficiently smooth frame rate was set empirically and weighed against all other spatial parameters.

While using the prior studies as a framework (Wang et al, 2013), the open-source scripting environment Processing was chosen to work within, firstly for its computational efficiency. In addition, Processing allows an ability to easily import geometry and optical data from the prior simulations, as well as having the capability to easily interface with real-time interactive inputs via a camera installed in the prototype, thus integrating a viewer's experience as part of the simulation (Figure 7). For the purposes of this simulation, the new application retains much of the original functionality of the initial studies (i.e. rotation and color change), querying simulated angle dependent optical data arrays as a user moves about the environment, ultimately affecting the viewers' virtual angular difference with respect to the simulated substrate.

This interactive simulation features a built in camera that detects your motion through a custom script. When one waves their hand or moves in front of the screen--to the left, right or center—the input adjusts the virtually simulated eSkin in real time (Figure 8). The simulation incorporates real optical data in the form of color and geometric transformation from micro scale material substrates to speculate upon how these nano to micro scale material effects and related geometries may be applied at the architectural scale. Here, visitors are able to interact with the actual material effects of eSkin in real time and in a scaled way.

In order to achieve this, a faceted mesh "wall" model composed of 1,728 individual faces was generated in the Rhinoceros modeling environment. The number and geometry of mesh subdivisions was based on empirical design decisions goverened by spatial fidelity (impacting computational speed) and aesthetics. This mesh was then imported into a Processing sketch (workspace in Processing) as an .obj via the external OBJLoader library by Saito and Ditton. Next, each mesh facet within the sketch is embedded with identical angle dependent optical color data array extracted from simulated nano/micro materials fabricated in the Yang Lab. At its inception, this color data appears generic, but is given specificity per simulated viewing angle. Within the simulation this color data is then queried through time as a list array of RGB values corresponding to virtual incident dependent viewing angles initially established according to actual material testing in the Yang Lab (for a full discussion of color simulation prodedures, please see Wang et al, 2013).

In order to engage with viewers in an environment external to the simulation, a video camera captures a real-time image feed and a resultant low fidelity image difference is taken (Figure 5a). This image difference is achieved by simply comparing corresponding pixel brightnesses at each pixel (x_i, y_i) of a possible 256 values through time and at each frame of image capture (designated *i*). If the difference in brightness between 2 spatially coincident pixels (x_i, y_i) and (x_{i+1}, y_{i+1}) is sufficiently changed through time, the resultant pixel is said to have changed and is added to a counter for further inquiry. In order to increase computational speed for real-time interaction, not every pixel in the initial image array is considered for calculation. Thus, every n^{th} pixel in the array is queried; in the prototype simulation presented here the fidelity was chosen to be every 300th pixel in both the x and y dimensions. For the purposes of this study and simulation, the optimal fidelity of the differenced pixel array was set imperically satisfying outcomes based upon speed and the amount of sensitivity to environmental stimuli deamed sufficient. To this end, the image capture and differencing occurs at a rate of 7 frames per second. Ultimately, this crude image difference is mapped to an underlying grid of circular bins whose regions correspond to mesh facet centroids (Figure 5c). Depending on the amount of difference at a given moment within the underlying grid of circular bins, varying degrees of rotation about each mesh centroid are triggered within the corresponding meshes (Figure 5d). Finally, based upon the amount of rotation and each corresponding mesh normal to the viewing plane of the simulation screen, the array of simulated angle dependent color data from the Yang Lab is accessed assigning appropriate color data to the mesh at each instant in the simulation. Thus within the overall field of change, as a single mesh facet is allowed to rotate within the model a resultant color variation is expressed within each facet, corresponding to the optical color data array (Figure 5e-5f).

The implementation of incident light source and transmission properties in the real-time simulation is still being further developed through ongoing iterations of the software. While the work presented here relies on the assignment of one color value per mesh, ongoing investigations are the subject of more advanced and accurate shading techniques such as vertex interpolation.

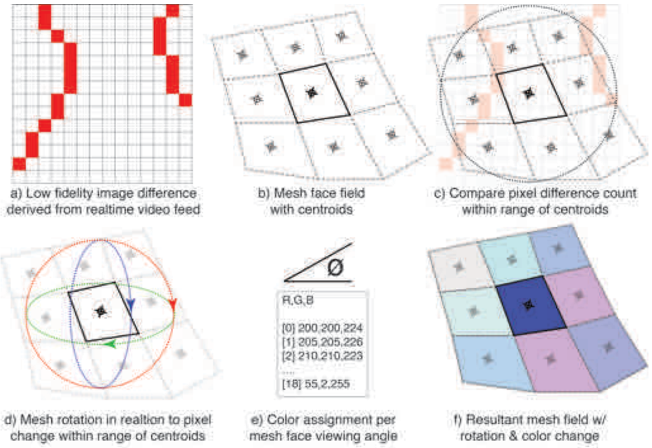

a) Low fidelity image difference derived from realtime video feed
b) Mesh face field with centroids
c) Compare pixel difference count within range of centroids
d) Mesh rotation in realtion to pixel change within range of centroids
e) Color assignment per mesh face viewing angle
f) Resultant mesh field w/ rotation & color change

Figure 5. Schematic Diagram of Real-time Simulation. A real-time image feed is subject to low-fidelity image differencing. The virtual resultant difference map (a) is compared to the actual mesh face field visible in the simulation (b). Within a given range of every unique mesh centroid, the number of changed pixels is quantified (c). Each mesh is then rotated about its centroid corresponding to the given pixel count (d), while a corresponding viewing angle is calculated and coupled with a change in color (e).

2.3. Interface Design for scaled eSkin components: Prototype 2

The second prototype aims to advance speculative design trajectories within the eSkin project as a physical, interactive, and scaled component prototype whose properties behave in a comparable manner to those observed at a nano-to-micro scale, but which can be fabricated at a human scale. Silica colloidal nano particles dispersed in an organic medium (solvent) are sandwiched between two transparent conductively treated Indium Tin Oxide (ITO) pieces of glass, housed within an assembly of 3 laser-cut plexiglass frames. The light reflected from the ordered structure (depending on the particle size, distance and reflective index contrast between the silica nanoparticles and the organic medium) provides a specific wavelength of light. When a voltage is applied to the particulate solution, the surface charge of the particles is altered, thus, changing the distance between the particles, leading to the change of color appearance. At each intersection between the color cells, a sensor based on shifts in light intensity levels actuates voltage change between the adjacent color cells. Thus, when a finger, hand, or figure passes by a sensor, a detected shift in light intensity level triggers a voltage shift across the ITO component, reorganizing the distribution of particles in the solution, ultimately affecting the reflected appearance of color from the nano-particle solution (Figure 6).

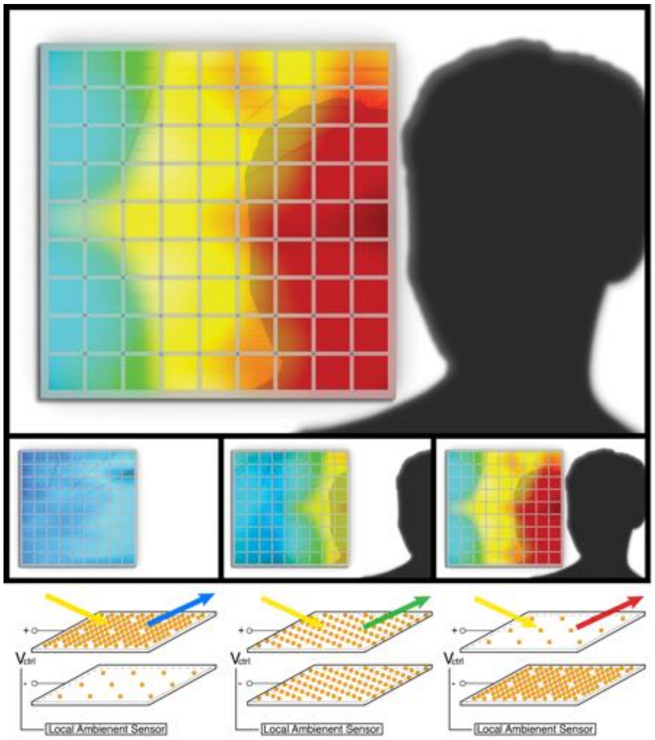


Figure 6. Rendering of eSkin material prototype demonstrating user interaction as an active input with resultant speculative transformation of the material substrate (top). Schematic diagram of circuit design interfacing with nano-colloidal particle solutions through voltage control. Individual sensing nodes interact with the material substrates locally through voltage control via the sensing of changes in ambient light, ultimately affecting the appearance of the prototype components (bottom).

3. RESULTS

3.1. Interface for Simulation: Prototype 1

While the primary aim of the first prototype is to simulate macro scale possibilities of nanoscale technologies and effects of eSkin, it was also important to create a provocative representation of the technology at hand through an interesting and dynamic simulation that exemplifies the capabilities of the technology and suggests further real world applications. Therefore, we approached this installation as an interface that alludes to the possible spatial characteristics of a thin film laminate in relation to the tangible built environment. In order to distance the installation from a typical screen displaying an interactive simulation, we disassembled a contemporary Liquid Crystal Display monitor, removed everything nonessential to the display, and applied the LCD panel to a box of our own creation. The liquid crystal screen serves as a façade for the box, constructed of frosted plexiglass, mirrored plexiglass, and an array of high-voltage cold-cathode fluorescent bulbs, 2mm in diameter. The pattern of the bulb array within the box, in conjunction with the mirrored surface provides a seemingly infinitely deep space that expands within the box and behind the screen, lit at a standard interval by bulbs that resemble typical office fluorescent lights. Along with the screen, at the face of the box is an embedded camera. This camera is the input for the simulation run on the machine hidden in the underside of the box that is in turn displayed upon the front of the box as a mock interactive building façade/curtain wall (Figures 7 & 8).

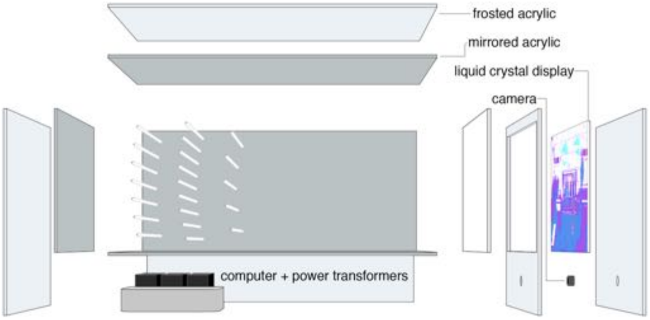


Figure 7. Diagram of simplified installation assembly. An array of cold cathode fluorescent bulbs is housed within a mirrored box. The face of this box is a sandwich of a liquid crystal display and clear acrylic. The mirrored box provides a reflective depth that is much more vast than the actual volume of the box.

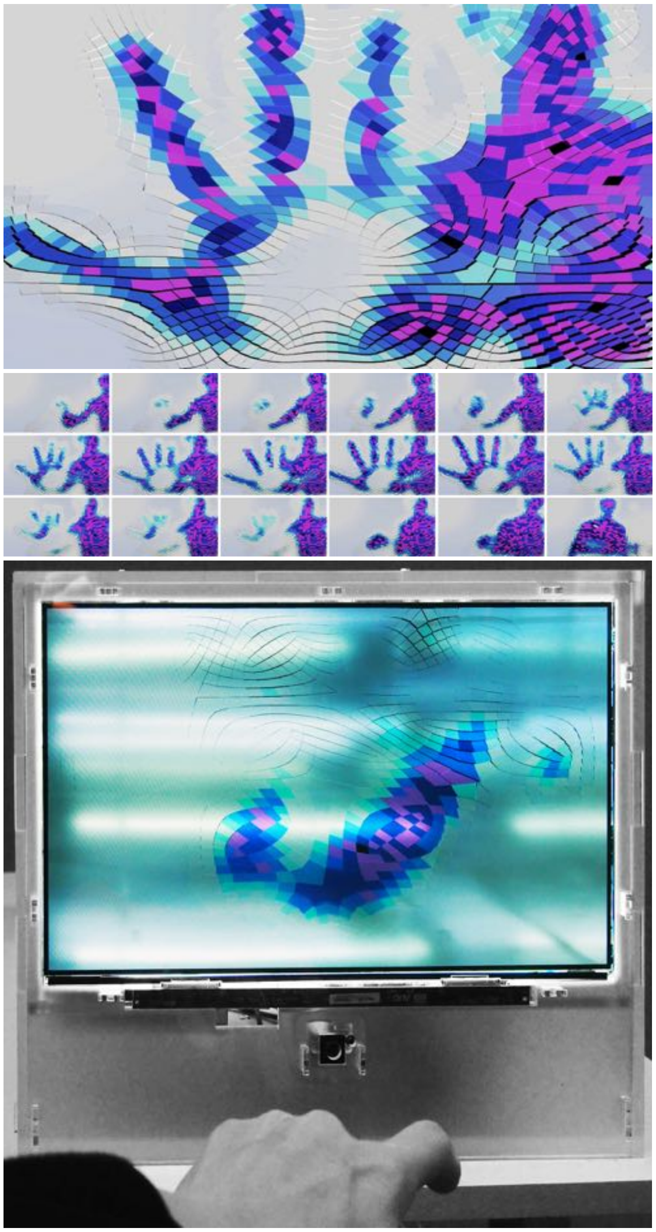
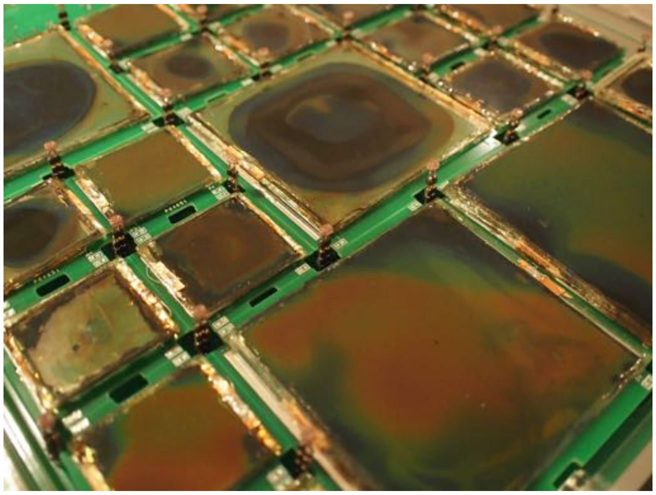


Figure 8. Still image (top) and sequential still images (middle) taken from real-time simulation built with Processing, harnessing geometric variation, optical data arrays, and user input as parameters. Simulation presented on custom LCD monitor, backlit with cold-cathode fluorescent bulbs, and embedded in custom built plexiglass housing.

3.2. Interface for scaled eSkin components: Prototype 2

Rather than purely display a simulation based upon actual data as recorded from the original nano-pillar material simulation, we were able to create a panel that displayed the dynamism and control achieved with an actual nanoparticle suspension. In collaboration with the labs of Yang, Van der Speigel and Engheta we present a modular component design that exhibits the structural color adaptation of the nanoparticles in relation to variable voltage. Using Indium Tin Oxide (ITO) treated glass acting both as the frame and the conduit for the nanoparticles within, we were able to create a mosaic of a variety of individual units, of multiple sizes. Each of these contained components is then mounted to a PCB, with its own control circuit that adjusts the charge across the glass according to the dynamic impedance of an arrangement of photo-resistors. These photo-resistors, acting as sensing nodes, are placed at each corner of the cells, and react to the presence of the participant/spectator.



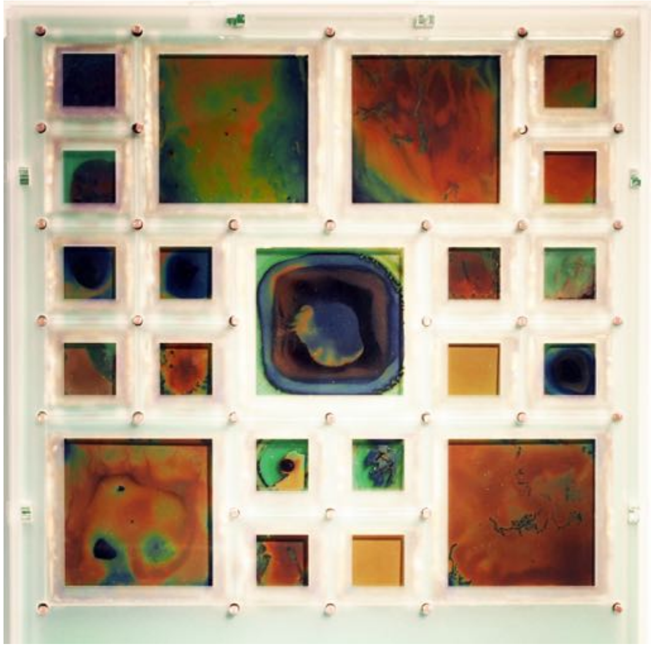


Figure 9. ITO treated glass cells with voltage controlled nanoparticle solution within, housed on a custom-built PCB substrate, and controlled locally via ambient sensing nodes. Note, front face of prototype housing removed to reveal component arrays (top). Component material prototype with local sensing nodes affecting component cells, harnessing user interaction as an active input and resultant transformation of the material substrate (bottom).

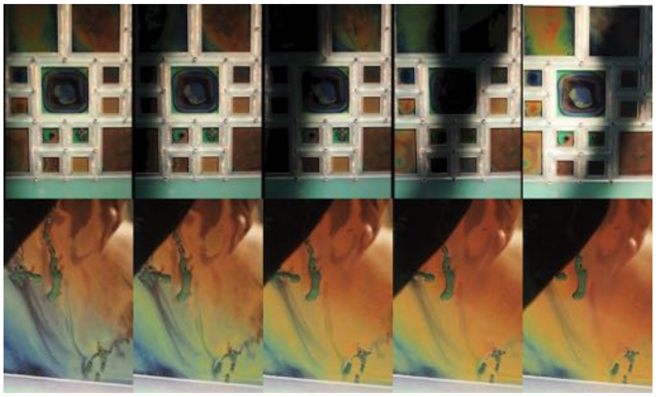


Figure 10. Image stills from a movie demonstrating structural color adaptation of the nanoparticles in relation to variable voltage due to the presence or absence of a hand and arm (as seen in silhouette) passing in front of the sensing nodes.

4. DISCUSSION

Within the context of the 2 prototypes presented here, the practical inability to fabricate nano/micro patterned materials at a human scale in turn inspired a speculation as to the behavior of these materials' effects as scale increases were taken into consideration. We found that the scalability of effects and material fabrication to be the largest challenge to the group at hand. Specifically, the micro & nano lithography arrays we intend to utilize cannot currently be fabricated above roughly a 2cm x 2cm feasible sample size with an absolute maximum of 4in x 4in. The 2 prototypes presented in this paper can thus be seen as a designed response and speculation to this limitation as well as a test for more advanced human interaction, including local and regional environmental stimuli.

Through simulation, modeling, and prototyping unique non-linear aspects of the desired eSkin materials, and projected use of these materials in situ, were extracted and redeployed through a series of prototypes. Through each of the prototypes (the simulation and the scaled components) presented here, we were limited to the exploration of aspects of the nano-to-micro material behavior and its application in part, but never as a whole. Thus, for each investigation we took this limitation as an opportunity to interrogate and expand upon particular behavioral aspects of the eSkin materials, while not trying to merely mimic the total functionality within a single prototype.

By their very nature, the eSkin materials in question demonstrate optical variability based upon the relative location between a viewer and the surface. In an ideal large scale application of an eSkin prototype, material effects, specifically color change, transparency, and transmission, would be the result of geometric variation within a surface, a viewers relative position with respect to that surface, and the source of illumination upon or from behind the surface. Naturally, it is impossible to take all of these parameters into consideration in a single virtual modeled environment, especially one in which a viewer's interaction with the simulation space is transmitted to an entire audience via a flat screen display (Figure 8). In the case of the simulation, multiple angle dependent observation points cannot be accounted for given the singular nature of the flat screen display technology deployed here. However, this optical simulation space is essential given the inadequate scalability of the material at hand. While a single virtual simulation allows for a robust overall speculation of material behavior and effect, it does not truly allow for the simulation of a curved geometry in actual space from multiple observational vantages. In order to overcome this limitation of a virtually variegated geometric interactive surface, the use of a gently rotating faceted surface geometry, was deployed, one that could approximate multiple viewers' interaction and involvement with the virtual environment.

In the case of the second prototype, we were able to test changes in color and to some degree, transparency, through nuanced environmental stimuli including multiple participants and changes in light intensity (day to night light shifts in a gallery room) that in turn affected features of the prototype in local, regional and global ways. The ability to 'tune' the second prototype to specific environments was made possible through the incorporation of individual potentiometers located in the back of the control board of the prototype. This enabled adjustments of local thresholds of illumination relative to each component for the control of the materials across the entire prototype. While the selected material for the second prototype, silica colloidal nano particles, is not the actual material being tested currently at the nano-to-micro scale, these interim material assemblies behave in a comparable manner to those observed at a nano-to-micro scale, but which can be fabricated at a human scale, thus providing a useful testing ground for eSkin.

Lastly, though not a criticism but a reality of the interdisciplinary nature of the team, we found the ability to fabricate in an applied fashion to be more or less beyond the scope of scientists and engineers whose areas of expertise reside in fundamental research. Simply put, prototyping through scaled applications is not necessarily the purview or area of expertise of scientists and engineers whose specialty is fundamental research. As a reality of the interdisciplinary work, next steps might include pairing with industry partners who would aid in the development of applied applications.

5. CONCLUSION

Having learned from the 2 prototypes discussed in this paper, we are currently developing a hybrid large-scale prototype whereby the material effects sought are simulated in a manner in which multiple viewers' unique experiences are the consequence of variegated geometry and relative viewing relationship to the surface of interest. Though again this prototype will not be constructed of the specific nano-to-micro materials fabricated in the Yang Lab, our aim is to architecturally prototype the behaviors of the intended materials. From the virtual simulation presented here we are maintaining the modeled material properties of angle dependent color change, coupled with a regioned notion of triggered event space within the surface. This regioned event surface is further controlled and evolved by the motion of bodies in space relative to their unique viewing of the prototyped surface. Aspects of this behavior that were explored in the 2nd prototype presented here will continue to be refined and incorporated in this forthcoming prototype. To this end we are integrating the material substrate's transparency and reflectivity with respect to unique viewing angle via geometry and projection. Taking cues from the 2nd physical prototype discussed here, the large-scale work in progress will maintain an aggregate of faceted surfaces whose variation will be the result of nodal characteristics, or regions of change. These prototypes serve as an interactive testing ground for selecting and refining nonlinear nano-to-micro scaled material effects at the human and architectural scale.

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