Senspectra: A Computationally Augmented Physical Modeling Toolkit for Sensing and Visualization of Structural Strain

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ABSTRACT
We present Senspectra, a computationally augmented physical modeling toolkit designed for sensing and visualization of structural strain. Senspectra seeks to explore a new direction in computational materiality, incorporating the material quality of malleable elements of an interface into its digital control structure. The system functions as a decentralized sensor network consisting of nodes, embedded with computational capabilities and a full spectrum LED, and flexible joints. Each joint functions as an omnidirectional bend sensing mechanism to sense and communicate mechanical strain between neighboring nodes.

Using Senspectra, a user incrementally assembles and refines a physical 3D model of discrete elements with a real-time visualization of structural strain. While the Senspectra infrastructure provides a flexible modular sensor network platform, its primary application derives from the need to couple physical modeling techniques utilized in architecture and design disciplines with systems for structural engineering analysis. This offers direct manipulation augmented with visual feedback for an intuitive approach to physical real-time finite element analysis, particularly for organic forms.

Author Keywords:
Tangible User Interface, 3D visualization, materiality, structural analysis

ACM Classification:
H5.2. User Interfaces: Prototyping

INTRODUCTION
The development of Tangible User Interfaces [1] have allowed us to bring physical form to digital information.

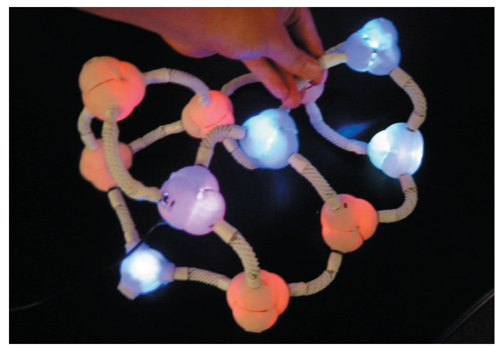

Figure 1. The Senspectra System: Tetrahedral Nodes and Sensor Joints

However, engaging and manipulating the material qualities inherent in the physicality of these systems remains an area largely unexplored. In interface design, we generally rely on the *visual affordances* of an object to determine behavior and functionality. However, *material affordances* can connote a variety of qualities that are the source of rich sensory experiences and occasion for numerous action modalities. From a tactile perspective, the static quality of rigid objects affords unary or binary controls. Hard objects are simply touched or pressed in a singular fashion, while malleable objects have a compliant material quality that invites users to multiple levels of tactile exploration and control. The physical act of deforming a malleable tangible interface can be mapped to a continuum of meanings.

Model-making in both physical materials as well as computational simulation provides a methodology to understand and represent the world and is particularly important as an educational or professional technique in fields such as architecture, design, and engineering. In many of these fields, physical 3D model-making is still preferred over, or applied in conjunction with, on-screen GUI modeling tools, such as CAD, because physical modeling employs the hands and body in the creative process and allows rapid experimentation with a system to understand its structure and limitations.

This paper presents Senspectra, a tangible interface that utilizes the unique material qualities of its elements as part of a control-feedback loop to collocate a physical model and a visual simulation. The system functions as a decentralized sensor network consisting of nodes, embedded with computational capabilities and a full spectrum LED, which communicate to neighbor nodes to determine a network topology through a system of flexible joints. Each joint uses a simple optical occlusion technique as an omnidirectional bend sensing mechanism to sense and communicate mechanical strain between neighboring nodes, while also serving as a data and power bus between nodes.

Senspectra provides a malleable infrastructure which allows users to build organic structures by incrementally assembling and reconfiguring a physical 3D model of discrete elements with a real-time visualization of structural strain. When a user changes the physical connections in a structure, the system reshapes its digital model to reflect the physical structure and strain and feeds it back into the structure so that each node has a general understanding of the overall state of the system.

RELATED WORK

Senspectra derives conceptual and technical inspiration from a variety of different areas, occupying a unique space among digitally augmented physical building systems. Conceptually, Senspectra builds on Photoelastic Analysis, an optical modeling technique used to give reliable accurate experimental stress analysis based on observation in polarized light of transparent models [2] giving a view of the overall structural behavior of a clear cast epoxy model [fig. 2a]. Senspectra seeks to couples the physicality of photoelastic analysis with the digital simulation techniques of Finite Element Analysis [3], on-screen visualizations of structural strain [fig. 2b], providing an interface with direct material manipulation and real-time visual feedback of strain.

John Frazer popularized the idea of using physical building blocks to create digital models when he proposed the Three-Dimensional Intelligent Modeling System, a reconfigurable network of cubic building blocks [4], Aish's Building Blocks [5] was among the first computational construction kits that allowed a designer to create a 3D CAAD model by constructing its physical counterpart using uniform building blocks. Triangles [6] followed as a physical/digital construction kit which allows users to manipulate the connections of physical triangles to determine the geometry of an on-screen model as well as MERL bricks [7], a system which employs physical bricks which when connected appear as representational elements of an on-screen model of a building.

Technically, the Senspectra system builds on developments in distributed and decentralized hardware and software architectures such as Pushpin Computing [8] a hardware and software platform used for experimenting with algorithms for distributed sensor networks or Tribble [9], an array of multimodal sensors embedded on a networked surface

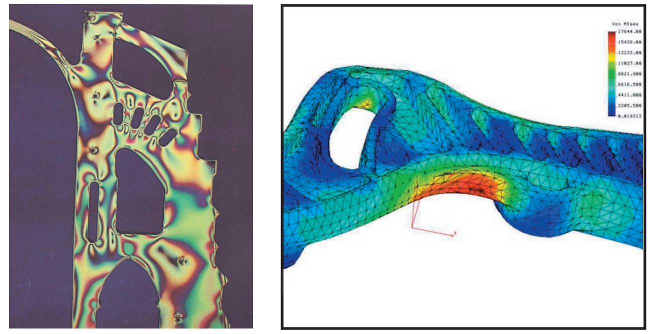

Figure 2. a) Photoelastic Analysis of Chartes Cathedral and b) Finite Element Analysis on the handle of pliers

which generate sounds, colors and vibrations depending on manipulation. However, Senspectra offers a more extensible infrastructure that is more appropriate for 3D modeling applications and uniquely incorporates strain sensing.

DESIGN AND INTERACTION CONTEXT

While we have specifically built Senspectra as a flexible sensor network platform for visualizing mechanical strain, the original inspiration for the system derives from a broader research agenda of incorporating materiality into the interaction loop for TUIs, for which we determined a set of unique design objectives:

> Use texture, plasticity and elasticity to inform the user about functionality of a physical interface.
>
> Map the material affordances of a tangible interface to inform and manipulate its control structure.
>
> Incorporate the malleable property of a material *meaningfully* into a distributed digital manipulative.

Conversations with professionals and students in architecture and building technology, informed the material and computational qualities of Senspectra. We were challenged by the limitations of linking physical models used in architecture to systems of structural engineering analysis, and in educational contexts, to provide an appropriate toolkit for gaining an intuition on form and strain for the design and assessment of structures of non-regular form.

When building with Senspectra, users create a physical model assembling the physical primitives of *nodes* (solid tetrahedrons) [fig. 3a] with interconnecting *joints* (flexible linear connectors) [fig. 3b]. The Senspectra primitives allow for the creation of regular structures, however by making the joints flexible and elastic, the morphology of the regular structure can be altered to reflect non-regular overall geometries. Sensing through the Senspectra joints allows the system to perform *cellular finite element analysis* in real-time as models are constructed. Senspectra computes the stresses locally with each individual node integrating the surrounding stresses to obtain a unique local stress vector. Senspectra provides this real-time FEA functionality and also collocates the output of the visualization directly on the

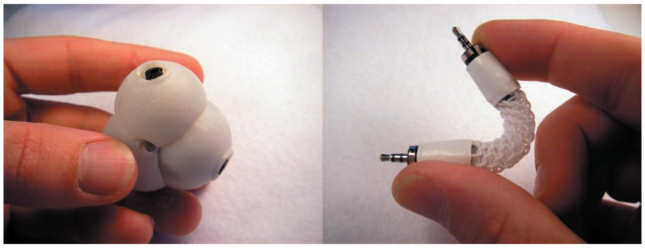

Figure 3. Senspectra elements a) node and b) joint

physical model.Current FEA tools are effective at showing potential failures in indeterminate structure in the form of digital models. However, there are currently no means for users to seamlessly modify a structure (physical or virtual) and visualize the effect of those modifications in real-time.

The material affordances of the flexible Senspectra joints to chosen to entice users to physically manipulate the digital model in two ways. The bending of a joint between two nodes shows the physical strain on the joint as a mapping of the color in the nodes (red - maximum strain, blue - no strain) [fig 4]. The squeezing of a joint can act to slow the flow between nodes in a model visualizing flow, as pinching a straw would slow the flow of liquid through it.

Figure 4. Nodes change color as the joint between them is bent.

In addition to real-time feedback, Senspectra provides the ability to visualize the resonance of a structure in terms of its elastic stability, by allowing users to record the stresses generated by high frequency oscillations and playback the recordings slowed down as visualizations on the structure. The Senspectra distributed network structure also supports the ability to show the flow of parameters through a 3D medium, by the propagation of a message through the system, for example, demonstrating thermal conductivity simulating the transmission of heat through a structure of a particular material.

In terms of specific applications, two areas have naturally emerged from our real interactions with Senspectra. The first, as we mentioned in the inital design context, is using Senspectra as a teaching tool in structural engineering, for developing an intuition via a physical material for the internal stresses of structures organic in form. The second area emerged as part of a discussion with a leading furniture design company, who upon seeing the system, requested to embed Senspectra into the cushion architecture of an office chair as a way to record strain mappings of a person shifting naturally while seated throughout the day, using it as a testing tool to inform the ergonomics of their design. In addition to these applications, we see many more real world uses emerging as we further develop Senspectra.

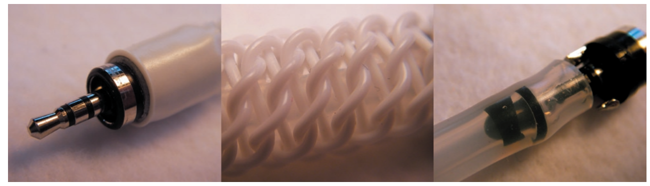

Figure 5. A Senspectra Joint a) radial connector b) eight conductors woven into a diamond braid c) phototransistor embedded in silicon tubing

TECHNICAL IMPLEMENTATION

Joints

The joints are made of silicone tubing and eight conductors wrapped around the tube in a diamond braid [fig. 4b]. This braiding technique allowed the Senspectra joints to maintain a consistent flexibility and elasticity throughout the designed structures. The braided wires serve for power distribution, peer-to-peer networking, and the sensing of the bending angle of the joint. The tips of the joints are made of two radial connectors [fig 5a] which allow for free rotation of the connected nodes, reducing unintended mechanical stress.

The silicone tubing within the joints serves as Senspectra's omnidirectional bend sensing mechanism. It uses a simple optical occlusion technique measuring the intensity of infrared light coming from an LED on one end of the joint with a matching phototransistor placed at the other end [fig. 5c]. When the joint is straight, the intensity of the infrared light is at its maximum. As the joint bends the tubing occludes the light to a point where the phototransistor cannot detect any infrared light emitted from the LED. The advantage of using this method over traditional resistive bend sensing is that the joints can bend in any direction and give consistent readings.

Nodes

The nodes are made of a 3D printed ABS plastic shell [fig. 6a] embedded with a surface mount PCB [fig. 6b]. The rigid shell acts as a light diffuser for the embedded full-spectrum LEDs [fig. 6c] with holes for connectors separated by 109° angles to form a perfect tetrahedron. The heart of the circuitry is an 8-bit RISC AVR® microcontroller running at 8MHz. It controls the color of the LEDs, calibrates the signal coming from the bend sensors and communicates with neighboring nodes through a UART that is multiplexed on four channels and runs at 500kBps.

Senspectra's networking algorithms were designed to accomplish three specific tasks:peer-to-peer communication, topology discovery and centralized control of individual nodes.

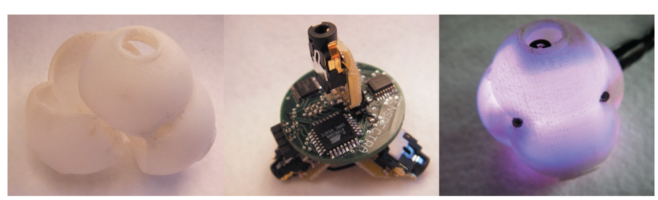

Figure 6. Senspectra Node a) casing b) PCB and c) glowing assembled node

Peer to Peer

This networking scheme is used for communication between neighboring nodes. It is used by individual nodes to agree on sensor readings but can be extended to propagate control messages or requests in a viral manner.

Topology Discovery

This functionality uses the peer-to-peer layer to map the topology of the network from any point in the structure. A ping request propagates virally throughout the structure and a pong replies a return to the sender using the shortest path possible recorded by the virally propagated ping. This functionally is currently implemented in our *host node* that connects the constructed structures to a PC, but could be called by any node in a completely decentralized fashion.

Centralized Control

The topology discovery allows the creation of a routing table by the computer. The computer uses this table to quickly address individual nodes, requesting specific sensor data or commanding a transition to a particular color value.

On-screen Representation and Issues of Resolution

While we have observed the physical immediacy and direct manipulation characteristics of Senspectra to be engaging and intuitive as an interface, one basic limitation of the current Senspectra system is resolution and scale. In order to address this issue, we have developed an initial system to interface Senspectra with an on-screen representation, allowing for interpolation to provide a greater resolution of a model. The system is connected to a PC and once the network topology is determined, every nodal connection is fed into a simulated annealing model [10] that generates a virtual 3D representation of the physical structure on-screen.

FUTURE WORK

In addition to continuing our current work of a GUI interface for Senspectra, we are also interested in further exploring issues of materiality for the flexible connectors. We plan to experiment with more rigid or more flexible tubing and also to insert aluminum rods into the weave to change the characteristics of the flexing. By changing the material properties of the connectors, models could be constructed with physical characteristics their reflect the appropriate structural and material properties of the model being simulated. We have also begun studies with students in structural engineering and architecture to further test the usability of the system and intend to conduct a more involved task oriented study soon.

CONCLUSION

We have presented Senspectra, a computationally augmented physical modeling toolkit designed for sensing and visualization of structural strain. Senspectra provides a malleable infrastructure which allows users to build organic structures by incrementally assembling and reconfiguring a physical 3D model of discrete elements, allowing simulation to occur with direct manipulation and physical immediacy and materiality.

As computational systems become more integrated in our everyday physical environment and tied to our tangible materiality, we believe the invention of new physical/digital systems which mimic the material affordances of the natural world and incorporate that materiality into the control-feedback loop becomes critical. We hope the system presented in this paper contributes to an emerging discussion to promote the creation of new digitally augmented but less-rigidly defined material systems which seek to match different realms of human expression and natural materiality, seeking to bridge the organic structures in the natural world which we seek to emulate with the exactness of the digital systems which provide the tools for manipulation.

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