RESINANCE: A (SMART) MATERIAL ECOLOGY

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ABSTRACT

What if we had materials that weren’t solid and static like traditional building materials are? What if these materials could dynamically change and adapt to varying environmental situations and stimulations and evolve and learn over time? What if they were autonomous, self-sufficient and independent but could communicate with each other and exchange information? What would this “living matter” mean for architecture and the way we perceive the built environment?

This paper looks briefly at current concepts and investigations in regards to programmable matter that occupy various areas of architectural research. It then goes into detail in describing the most recent smart material installation “Resinance” that was supervised by Manuel Kretzer and Benjamin Dillenburger and realized by the 2012/13 Master of Advanced Studies class as part of the materiability research at the Chair for CAAD, ETH Zürich in March 2013. The highly speculative sculpture links approaches in generative design, digital fabrication, physical/ubiquitous computing, distributed networks, swarm behavior and agent-based communication with bioinspiration and organic simulation in a responsive entity that reacts to user input and adapts its behavior over time.

1 “Resinance”, a touch responsive thermoactive installation
INTRODUCTION

A constantly growing area of scientific research is investigating the concept of encoding digital information into physical materials, a field also commonly referred to as programmable matter. While this topic merges the domains of materials science, chemistry, biology, computer science, mechanical and structural engineering, robotics, interaction design and many others it simultaneously gains more and more prominence in the field of architectural research.

In a very applied approach this happens, for example, in the work of ETH Zürich’s Chair for Architecture and Digital Fabrication, who propose to overcome the focus on form and geometrical representation through the design of material processes (Gramazio and Kohler 2007). Similarly Achim Menges (Institute for Computational Design, Universität Stuttgart) advocates a coherent understanding of form, material and structure, enabled through new possibilities in computational methods and manufacturing processes (Hensel, Menges, Weinstock 2010). Neri Oxman on the other hand, who is based at MIT’s Media Lab, finds her inspiration in nature and looks at organic principles of intrinsic growth and bottom-up assembly where materiality defines structure and in turn formal expression (Oxman 2010). Equally biologically and technologically inspired, Skylar Tibbits (Self-Assembly Lab, MIT) focuses his research on “smartening” the individual components within a larger assembly rather than improving certain fabrication techniques and as such he looks at concepts in self-assembly and self-organization (Tibbits 2012). Loosely this idea conforms to research projects that aren’t necessarily architectural in nature, like Smart Dust, a proposal of the University of California for a microelectromechanical data sensing system (Kahn, Katz, Pister 1999), or Claytronics, (Carnegie Mellon University and Intel Labs, Pittsburgh), which are nanoscale computers that can relate to each other to form tangible objects (Karagozler et al. 2009).

The experimental installation “Resinance”, which was realized in March 2013 as part of the materiality research (www.materiability.com) at the Chair for CAAD, ETH Zürich (www.caad.arch.ethz.ch), explores some aspects of the ideas described above while adding another potentiality, the use of smart materials. Smart materials are generally described as materials that have the ability of sensing an external stimuli and/ or actively responding to it in a controlled way (Fox and Kemp 2009). One of their great advantages in comparison to standard actuators (motors, hydraulics, pneumatics) is, since they’re not mechanically complex, that a separation between structure and actuator can be avoided (Lochmatter 2008). As such they have the potential for the creation of holistic lightweight systems without heavy infrastructure or support.

The design of “Resinance” was strongly influenced by the behavior of simple organic life forms, in particular the formation of cellular colonies. In its assembly it represented an ecology of functional units that could both work autonomously but also in coordination with their neighboring units. It consisted of forty active elements that were gradually changing their surface color in response to human touch (Figure 1). While this slow transformation could not be perceived directly, each device had a second actuator, providing immediate response through shivers and vibrations. Every four elements were connected through a control unit that formally resembled the rest of the objects but without the ability to change color. These units both choreographed the behavior of the particular cluster and transmitted the current state of each element to its neighbors. Therefore the tactile input not only changed the touched element but also was transmitted throughout the whole installation in a networked, swarm-like behavior.

The month-long course was split into three parts. During the first part cell, co-taught by Hironori Yoshida, the students investigated the design and fabrication of three-dimensional hollow modules produced from a polyester resin that had been enhanced with thermochromic pigments. The second part metabolism was supported by Weixin Huang and Lei Yu and focused on the sensual and transformative abilities of the units and the embedded electronic infrastructure, physical computing and control algorithms. The last part ecology was joined by Tomasz Jaskiewicz, Stefan Dulman, Andrei Pruteanu and Mariana Popescu and looked at the communication between the different units, their emergent behavior, networked agency and response to the environment. The finished installation was set up and exhibited for several weeks.

CELL

The crystal-shaped elements of the installation were produced through a rotational molding technique from a custom-made thermochromic resin.

Thermochromism is the property of a substance to reversibly change its color and/ or optical characteristics in response to a change in temperature. There are several types of thermochromic materials, including liquid crystal dye systems, and leuco dye systems. Liquid crystal thermochromic materials are generally more expensive but can be engineered to respond very precisely to particular temperatures (Hallcrest 2008). Each phase changes the way the material structure interacts with light, allowing us to see a different color as the temperature of the material varies. While liquid crystal systems don’t have a limited color range and respectively move through the full color spectrum structurally from colorless (black) to red to yellow to green to blue and back to colorless, leuco dye systems can change from one specific color to colorless. While liquid crystal dye systems are usually screen-printed, sprayed or coated onto surfaces, leuco dye systems can be very easily dispersed into polymers to be completely integrated into the material. While the main focus in “Resinance” was initially to focus on representing a dynamic and constantly shifting spectrum, which would more readily be achieved using liquid crystal dyes, the working properties and reduced cost of leuco
Different component designs and prototypes gave more freedom for experimentation and consequently proved to be more suited to the realization of the project at this stage. Still, it was important to not only change from one color to transparent, which is what leuco dyes usually do, but to create a gradual transition between a range of colors. In order to achieve this effect pigments with different reaction temperatures were combined. The first color change happened from 30-33°C, the second between 43-45°C and the last at 62-65°C. However, it was quickly realized that going beyond 50°C would require too much energy and time and, therefore, the transition was reduced to two reactions. Also the idea of adding a base color, which would remain solid but would increase the color range, was discarded after several experiments in order to reveal the “true” nature of the polyester resin objects.

Polyester resin is a thermosetting resin produced by a reaction between several organic acids and polyhydric alcohols. Industrially used for molding reinforced fiber and composite products, polyester resin was chosen primarily for its perfect binding of the thermochromic pigments. In addition, its property to take on almost any form and surface texture, its aesthetic qualities of translucency, surface quality and relative ease of post-cast processing made it an ideal choice of material for the project. Rotational molding was used to cast the resin, as this technique allowed for hollow components to be cast using an economic amount of material, in addition creating a visually interesting effect of layer variation within each component.

After a series of design experiments where a range of forms from expressively curvilinear to rigidly orthogonal were prototyped (Figures 2-5), it was established that a simpler form would be most effective in demonstrating the complex properties
of the thermochromic resin. The crystalline geometry of each component was derived by dividing a cube into thirds, with variation created by altering the height of each shape. The faceted geometry of the components provided a strong contrast to the organic fluidity of the material behavior. Each component was produced by rotationally molding the resin in laser cut polypropylene molds, with two of the crystal’s six sides created by casting clear acrylic plates into each polypropylene. These acrylic plates were designed as support plates for the component’s electronic hardware, to ensure its accurate positioning inside the resin container.

During the prototyping stage, various fabrication techniques were tested, including automating the rotational molding process with a KUKA robot. However, the inability to effectively control the temperature of the curing resin while being rotated by the robot meant that rotating the molds by hand was—at least for the small amount of elements that were needed—a far more effective process in producing casts of a consistent quality.

Mixing ratios for the thermochromic pigment, cobalt, catalyst hardener and resin were also experimented with and eventually established at approximately 2g/1ml/2.5ml/50ml respectively. After measuring out each part, the thermochromic pigments were first mixed with the polyester, before adding hardener and finally cobalt. The mixed resin was then poured into each polypropylene mold and rotated individually by hand until the chemical curing process began. Just as the resin started to change from liquid to a gel-like state, the required openings (as templated by the cast acrylic plate) were cut, before allowing the piece to finish the curing process. The process of creating an opening in the otherwise hollow form allowed for the hot air created by the curing process to escape from the cast, which minimized shrinking that could otherwise occur.

METABOLISM

Every four components in the system were grouped together with a fifth transparent control unit. These in total ten control units contained an Arduino Fio (a version of the open source Arduino project intended for wireless communication), a connection to a 12V power supply, an XBee Series 1 Wi-Fi component, and a custom-built Arduino shield that routed signals between the arrays of sensors and actuators. Each active component had a piezo vibration sensor acting as a touch sensor, a thermistor as internal temperature sensor, a heating element, a modified CPU fan for cooling, and a vibrating motor (Figure 6).

Because of the very distinct tactile qualities of the plastic material, along with the variation in temperature throughout the installation, it was important that the primary interaction with “Resinance” would be touch, rather than proximity, which was the initial idea. This was accomplished with a small piezo vibration sensor, which is a cantilevered flexible PVD/V piezo polymer film, loaded with a small mass to detect vibration. The sensor was connected to one of the Analog inputs on the Arduino. In combination with a 1mΩ pull-down resistor, it read out reliable on-off signals, as well as analog values of the severity of the touch.

When the resin component was touched, it responded with strong and immediate “shivers” as a form of direct haptic feedback, an animal acknowledgment of being touched, and a reciprocal “touching back” signaling the friendliness—or otherwise—of the animal. This feedback was provided by a 12V vibration motor connected to one of the PWM (Pulse Width Modulation) pins on the Arduino. The length and intensity of the vibration was a result of a function of the number of times the component had been touched, the severity of the touch as well as the current behavior of its neighbors.

Beyond the shivering, the tactile input triggered a second, much subtler and softer reaction: the thermochromic color transformation. This was achieved by heating up a small amount (~200ml) of
The temperature of the liquid was kept at a baseline of 26°C and would increase to as much as 46°C. This was because of the two types of thermochromic pigment, that would be triggered at 30°C and 43°C respectively. The adjustment of the container’s internal microclimate lead to a gentle change in color of the thermochromic plastic material, until full translucency was reached. The component always displayed some combination of available colors, varying or gradating in places between darker and lighter colors, as well as, at its highest temperature, white (translucent). Like the immediate feedback of the vibrators, this temperature response could be modulated by the popularity (touch count) of the component, as well as the behavior of its neighbors.

The heating element and thermistor were suspended inside the water, which acted both as a conductor for thermal energy on the lower portion of the unit, and as a source of steam which heated the higher portion of the component. The element would show some color change within the first minute after activation, and would reach its peak within ten minutes, depending on the desired temperature. The CPU fan then cooled down the air space, the majority of the space inside the component, so that the color of the container would shift back within two to four minutes (Figures 7-10).

ECOLOGY
To bring all parts together into a coherent installation, several methods of configuring and installing the components were tested during the design phase. Hanging, floor and wall mounted designs were considered, however in the end a table-level design with a plinth was decided upon as it readily allowed for hands-on interactivity with the installation (Figure 11). This design also ensured that the electronics could be configured in a consistent way.
and eliminated the need to attach structural fixings to the resin components. It further provided space for cables and power supplies underneath the installation. The geometry of the plinth was based on a set of triangles arranged on a Penrose tessellation matrix. The facets of the plinth related to the geometry of the components, it complemented but didn’t detract from demonstrating the material behavior. The plinth was fabricated on a three-axis milling machine from polystyrene foam boards and finished with epoxy resin paint (Figure 12).

The size of “Resinance” and corresponding number of elements was based on the amount of available time and materials. However, future applications of this material technique have the potential to involve significantly more components and complex constellations. Therefore, the applied control system solution was developed to allow for other scenarios, rather than to only facilitate the limited scope of the prototype.

Conventionally, a behavior of active devices in a building is either a very simple action-reaction mechanism, or is performed by a centralized control unit for the entire building sub-system. Such control unit is connected directly to all devices, or in more recent applications—via the Internet. However, this approach shows many limitations. Firstly, it requires extensive network infrastructure and its costs for setup and maintenance grow exponentially with the number of interactive components included in the system. Secondly, with large numbers of sensors and actuators the central control unit becomes a significant bottleneck, always having a limit on the number of devices that it can control and requiring costly solutions for significantly raising that limit. Lastly, any error or malfunctioning of the control unit may disable the entire network.

Conversely, architectural applications that deal with dynamic materials, interactivity and adaptation over time, may significantly benefit from an approach, that would allow creation of interactive building systems without any form of centralized control, removing existing bottlenecks, increasing flexibility in adding and removing components, and dramatically improving resilience to possible errors and malfunctions.

The control system embedded in “Resinance” involved programming and networking the installations as a distributed network. For this, a pre-release version of the “HiveKit” system architecture and software (www.hive-systems.net) was employed (Figure 13).

To realize this approach, each small cluster of devices had its own locally operating control unit, which was configured so that messages were sent only to and from its closest neighboring clusters. In larger installations, this happens naturally by filtering messages by radio signal strength. Due to the small scale of “Resinance”, the links between the individual components were predefined. The global and emergent behavior of the entire installation was decomposed by the software into individual, simple actions for...
each node, such that all computation required in the interactive behavior was ultimately performed “in the network”. Each node continuously communicated its state to its neighbors and through a variety of well studied distributed algorithms emergent properties of the installation as a whole could consistently be predicted. In this way, the network of devices became a true ecosystem of artificial organisms, locally informing and influencing one another.

As a result, the created network was highly robust. Potential failures of individual nodes did not impede on the global behavior of the entire installation. Furthermore the re-programming of the installation could be done virally, which means that modifications, adjustments and extensions of the installation were trivial to perform. A new group of elements could simply be connected to the installation and it would obtain the behavior-defining code from the adjacent nodes.

The behavior of “Resinance” drew inspiration from displays of interactive or adaptive behavior that can be found in a variety of forms in natural organisms. Color change in the animal and plant kingdoms is often used to either attract attention or to divert it, either a signal or used to camouflage. It can have the effect of mimicking other species, to confuse predators, or to lure a mate or symbiote. The installation followed this communicatory quality of color, using color to “reward” interaction, and as a recorded display of prior interactions.

Since the only form of providing input was touch, and the actuation was achieved by color, opacity change as well as vibration of the components, two main kinds of responses were considered when designing the interaction. The first was an immediate response: a small “shiver” when touched, which was passed along to its neighbors, and varied according to the number of touches (the “popularity” of each piece), the severity of these touches, as well as to the state of its neighbor, and to its place in a chain of reactions that rippled in waves across the installation. The second was a long term, more ambient, but continuous response, the color transformation, which can be seen as an echo of the first reaction, played out in communication across a larger distance, and for a longer length of time. Thus the reactions of the installation were dependent on the number and severity of interactions, where, for example, more popular elements became brighter, while less popular ones remained the darker color.

In addition, the effects of the interaction were cumulative in that the installation “remembered” its prior interactions, and varied its behavior according to its record of these interactions. In this way, each
element was a kind of agent, but not wholly autonomous, as it also passed its own information to its neighbors and also responded to its immediate surroundings. The result of the networked condition of the installation was that there was not a one-to-one correlation between an interaction and the response it elicited. Additionally, an element could check its state against its preferences, which could change over time. An element could, for example, grow tired of interaction, and attempt to discourage it by not responding. Because each response accumulated the various local and “neighborhood” conditions, the behavior of the installation was constantly changing, evolving over time as it tried to attract certain attention, forming different areas of intensity and color and adapting to its particular environment.

Realization of this behavior in a distributed network of devices was achieved by combining two distributed algorithms: “gradient” and “firefly synchronization” (Pruteanu 2013), which were used to generate concentric waves propagating at various speeds and originating from triggered elements. These waves were used as basis for determining the state of each node. Their frequency and speed over time was recorded and became part of each node’s memory, altering its future responses. Fast propagating waves were actuated using vibration, while slow waves were reflected in color changes. The parameters of waves and their mapping to triggers and actuators had been empirically tested and adjusted to maximize the aesthetic experience, and are expected to be further “fine-tuned” in the future, based on user feedback. It has been mathematically proven (Pruteanu 2013), that this distributed behavior would function consistently across any number of nodes connected in a distributed way. In this way extending the network to a very large number of devices (10k+) not only becomes feasible, but also improves the algorithm convergence speed.
CONCLUSION

With the rise of dynamic materials in architectural applications not only comes a need for new spatial strategies, new constructions and different designs but possibly a fundamental rethinking of architecture in general. While architects and designers have been very good in adapting computing technology for modeling purposes or the development of new formal languages, they have only faintly addressed questions like temporality, ephemerality or contingency. Our current, western society is strongly influenced by technological advancements at an ever-increasing pace. These technologies are not only mesmerizing us virtually but are also slowly becoming parts that enhance our mind and physicality. In this context architecture still represents itself as an inherently conservative discipline valuing formal representation or functionality over time-based performance and responsiveness.

“Resinance” is first and foremost an educational experiment and a speculative vision, and cannot be seen as a real architectural application. The implemented technologies so far only work in a lab environment and are prone to failure. The durability of the used smart materials (thermochromics) is limited since leuco dyes have a short life expectancy and are vulnerable to chemicals and sunlight (UV radiation). While they are interesting for novelty products and experimental usage they cannot comply with the demands of the building industry in terms of longevity and stability.

Nevertheless, the project and its proposal for an ecology of autonomous, material entities that communicate, evolve and adapt over time opens up a number of possibilities and tries to mediate a vision of how these technologies can be combined to create novel ideas. In its essence it should not be seen as an attempt to propose ways or scenarios on how these systems could be applied in a classical architectural context but rather as a hypothesis for a profoundly different attitude towards materiality and spatial design.

While finding inspiration in natural phenomena it demystifies the applied technologies in a hands-on, do-it-yourself approach and tries to encourage experimentation, radical openness and interdisciplinary exchange beyond academia. The project should be read rather in the context of spatial experiments of the 1960’s and 1970’s, which aimed to fundamentally question postwar architecture and were open-mindedly engaging with new technologies, disciplines and materials. This generation of architects wanted to demonstrate concepts that went beyond static formalities and spatial effects towards the inclusion of programmatic and environmental conditions, playful interaction and the suitable integration of emerging scientific and technological advancements. In that sense “Resinance” hopes to inspire, but leaves the interpretation and/or translation up to the personality and creativity of the reader.
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Further information on the materiability research can be found here: http://www.materiability.com
Further information on the Chair for Computer Aided Architectural Design can be found here: http://www.caad.arch.ethz.ch
Developed by Hive Systems: http://www.hive-systems.net

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