Controlling Daylight Reflectance with Cyber-physical Systems

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Abstract. Cyber-physical systems increasingly inform and alter the perception of atmospheric conditions within interior environments. The Catoptric Surface research project uses computation and robotics to precisely control the location of reflected daylight through a building envelope to form an image-based pattern of light on the building interior’s surfaces. In an attempt to amplify or reduce spatial perception, the daylighting reflected onto architectural surfaces within a built environment generates atmospheric effects. The modification of light patterns mapped onto existing or new surfaces enables the perception of space to not rely on form alone. The mapping of a new pattern that is independent of architectural surfaces creates a visual effect of a formless atmosphere and holds the potential to affect the way people interact with the space. People need different amounts and quality of daylight depending on physiological differences due to age or the types of tasks they perform. This research argues for an informed luminous and atmospheric environment that is relative both to the user and more conceptual architectural aspirations of spatial perception controlled by a cyber-physical robotic façade system.

Keywords. Contextual; Computation.

1. Introduction

In the early 1960’s, Cedric Price proposed an adaptable environment empowered by technology for the Fun Palace. Collaborating with Joan Littlewood, the goal of the building was to provide a flexible free space for any number of possible events. The goal was to create a space for creative and education actives that blurred the differences between work and leisure that were not revolving around any particular preconceived program, but rather encouraged people to develop their own activities. In order to achieve such flexibility, the design employed moveable components, but perhaps more importantly the use of equipment to vary or “tune up” the environment. (Price, 1984) Since the program of the space is unpredictable and based on the desires of people using the building, the “Fun Palace would have to self-regulate, and it’s physical configuration and operations would need to
anticipate and respond to probable patterns of use.” (Matthews, 2007) In order for the building to learn and predict patterns of behavior, Price turned to the emerging fields of cybernetics, game theory and computer technology. Cybernetics would enable dynamic modification of the building and its systems to have a degree of intelligence in its ability to adapt and plan for future events and activities. Gordon Pask was a key figure in the development of cybernetics and became interested in how the technology could be employed to organize complex systems that the Fun Palace was enabling. He joined the Fun Palace Subcommittee to discuss how technology could inform behavior of people and how the environment would be informed by technology. The relationship between nascent cybernetics being developed at the time and the desire for dynamic behaviors of buildings seemed to hold endless potential. (Matthews, 2007)

In 1970, a fully technologized, immersive environment was realized with E.A.T’s (Experiments in Art and Technology) Pepsi Pavilion in Osaka, Japan. E.A.T. was an offshoot of 9 Evenings, which were a series of live performances that merged art and engineering starting in 1966. 9 Evening was hosted by Bell Laboratories, which was arguably one of the most prolific companies to produce innovative engineering of its time. The lab invited artists, included Robert Rauschenberg and Merce Cunningham, to collaborate on projects to promote innovation. The live events led to the development of new technologies enabling some of the most influential immersive experiences between human performers and technologically manipulated light, video and sound. (Lindgren, 1972)

Moving beyond the walls of Bell Labs, E.A.T. was invited to design the Pepsi Pavilion for the 1970 Expo in Osaka. The team consisted of many of the same artists and engineers from 9 Evenings, but now they had the opportunity to create a technologically advanced, fully immersive environment for the general public. The pavilion hosted a series of adaptive systems that were responsive to the environment and people. Environmentally responsive systems included a fog system that reacted to meteorological conditions and a proposed heliostat that tracked the sun position. The heliostat, named Suntrak, followed the position of the sun according to the movement of the earth’s rotation. The mirror was located on a 9m tower and rotated during the day to maintain a consistent target location for the reflected sunbeam. The rotation was enabled by two motors- one for the pan and one for the tilt to account for the low altitude sun in the winter and higher altitude in the summer. The reflected sunbeam was aimed at a fixed location on the exterior facade and was made more apparent as it shone through the fog surrounding the pavilion. (Young, 1972) Unfortunately, Suntrak was damaged during installation and never completed.

The interior of the pavilion included a theater where the technology created a more personal experience of the environment through light and sound manipulation. Optical effects were generated from material interaction of a 27m diameter spherical mirror that distorted, inverted and multiplied images of people in the environment. A laser deflection system bathed people in kinetic color changing light patterns. An automated sound control system would spatialize sound by moving and rotating it through the space using a series of speakers located around the pavilion. (Tompkins, 1972) What is most significant about the
interior and exterior environmental conditions is their adaptability using computer automation. The intelligence built into the Pepsi Pavilion resided in the ability to modify its behavior, generating an informed atmosphere using technology.

While a variable atmosphere can be generated using audible or tactile conditions, optics plays a significant role in our visually dominated environment. Continually changing light level, contrast, continuity or fragmentation creates dynamic negotiation between a person and their perception of their environment. (Larson, 1964) An awareness of a dynamic environmental conditions creates an atmosphere, which acts as a mediator between subject and object while simultaneously oscillating between the production of the effect and its reception. (Böhme, 2014)

The generation of optical effects from fragments of images were developed in Catoptric Boxes starting in the seventeenth century. These were cabinets or furniture-scale boxes that were typically lined with small mirrors that reflected an extravaganza of fragmented images of the surrounding environment within its interior. Their intention was to generate spatial and visual effects that dematerialize the limits of space through light, depth and dynamic reflection. (Agrest, 1983) The fragmentation of light reflected onto the surfaces of an interior room from László Moholy-Nagy’s Space Time Modulator in 1921 created similar atmospheric conditions, but the effects were dynamic due the kinetic sculpture. The resulting atmosphere affects the perceptible boundaries of an interior space, defined by the interplay between the light pattern and surface it is mapped onto.

2. Background

An initial investigation to manipulate optical effects occurred in a seminar titled Surface of Affect/Effect taught by the lead author in 2014. The class developed systems and physical prototypes to reflect light that were able to be modified to tune the location of the receiving light that continually modify the visual and tactile boundary of the surface as division between a person and their environment. In particular, one of the teams investigated a system of reflecting surfaces that could adjust to redirect light from a source to a target location. The reflecting surfaces are held within a series of interconnected frames so that their movement is coordinated. The focal point is manually adjustable in relation to the light source (Figure 1).
A second investigation was developed in a large, full scale prototype in a design/build studio titled 'the Grid, the Cloud, and the Detail' taught by the lead author, which expanded on investigating methods to alter targeted reflection of daylight as an environmental variable that informs the reading of an existing space. The studio references Rosalind Kraus’ article of the same name to discuss differing scales of viewing. (Krauss, 1994) The site was a small top-lit atrium space in an existing building and the goal amplify atmospheric conditions by reflecting light into targeted locations deep within the building. (Figure 2) This is accomplished through the introduction of 300 customized reflective surfaces that are tuned to reflect light into the darker corners deep in the atrium well. A second and more immediately perceptible method of creating an atmospheric condition was through the repetitive elements that form a continuously varying surface that filters and distorts views across the atrium space. The reflective surfaces interlace fragmented views with views across the atrium space that tends to camouflage any clear reading of the existing space. Thus, the even optical distortion creates an ambient re-reading of the space, through the design of an informed environment.
formation of an image. Their process starts with the desired resulting image, which requires the use of computation to reverse engineer the refractive surface geometry capable of producing the desire result. Thus, the architectural intervention is the surface that produces the desired visual effect.

In conclusion for the background research projects, the static nature of the full-scale student design/build prototype as well as the caustic refraction project by Bompas, et. al. limits the ability to alter the desired atmospheric condition. The adjustability in the student project for ‘Surface of Affect/Effect’ seminar provides adjustability, but with no precision. The image-forming nature of the caustic refraction research holds promise as a method to organize highlights and lowlights through an adjustable surface geometry.

3. Methods: Image-based mapping

The Catoptric Surface research project described in this paper uses an image-based mapping technique to control the adjustment of individual mirrors to reflect light in precise target locations within a room. This method allows the variability of the quality and not just quantity of light, which offers more nuanced methods to define and perceive spatial conditions. The image provides a target for the reflected light pattern, producing a map of points. Each point corresponds to a ray of light reflected from a single mirror. Each of the 618 mirrors has independent rotation and can be individually adjusted to the geometry calculated, which is the median angle between the sun position outside and the target points on the interior. Each mirror can be thought of as producing one pixel of reflected light. (Figure 3) Any raster file can be used for the image, which is located within the digital model and can be positioned on the ceiling, floor or wall as desired. The image is sampled according to black to white value. Since there are 618 mirrors, then the algorithm finds the 618 highest white value points sampled from the image. These points become the target points for each of the 618 mirrors, generating information for the cyber portion of the cyber-physical system.

Figure 3. Five target image iterations; point density based on sampling of the image’s value; worm’s eye view of 618 mirror array.
In order to test the image-based reflection system in a physical environment, a team was established between faculty and student researchers in the Graduate School of Architecture and Computer Science & Engineering department at Washington University in St. Louis. The team established the cyber-physical systems that interface between the image-based computational model with the physical mechanical-electrical systems in order to create an operational prototype.

The team located a large, south-facing glass façade in one of the institution’s buildings that measures 9.1m wide by 4.9m tall, which provides ample direct daylight to harvest, though more effectively during winter than summer due to the roof overhang. A vertical array of 618 mirror units are installed on the interior side of the glass. Each unit is arrayed at 150mm on horizontal and vertical centers and mounted on 1.6mm stainless steel cables to minimize any structure that could obstruct the sunlight. (Figure 4) The vertical spacing of the cables was determined to avoid the mirrors from self-shading during the highest altitude of solar geometry for St. Louis. The field of mirrors also provides shading at task surfaces immediately adjacent to the array, which in this case a café seating area. The primary behavior of the mirrors are to reflect daylight to create a low-resolution image of approximately 17 x 51 pixels on the ceiling, wall or floor of the existing building. Though, the array is not even due to three doors in the middle of the façade.

![Figure 4. Array of mirror units inside of a south-facing glass façade (left); Typical mirror unit consisting of 2 stepper motors, custom motor driver board, 3d printed motor mounts and motion stops, and 10cm diameter mirror (right).](image)

Each cyber-physical mirror unit rotates independently according to the computational inputs from the image-based system. The mechanics of the mirror consists of two stepper motors that enable approximately a hemisphere of rotation, which was determined to be the maximum useful amount. One motor is mounted between two laser cut and bent aluminum parts. 3D printed parts connect the motor to the aluminum while also creating the stops for the rotation. Having the motors
rotate until engaging the stops allows the system to find its home position since there are no additional limit switches. The second motor is mounted directly to the motor controller circuit board and connects the aluminum assembly through another set of 3D printed stops. The motor controller board was custom designed and fabricated for this project, integrating the motor mounting along with the electronic components. The board is then mounted directly to the stainless steel cables, which means the board also acts as structure for the mirror unit. (Figure 5)

Figure 5. Parts and assembly sequence of a typical mirror unit.

For the electronics and controls, the pan-tilt of each mirror is driven by a pair of unipolar 12V stepper motors that have 32 steps per revolution (11.25 degrees per step) and in addition a 1/16.032 reduction gear set. This yields a nominal positioning resolution of 11.25/16.032 = 0.702 degrees. Driving each stepper motor is a Toshiba TB6612 MOSFET driver IC, which is stepped through an NXP PCA9685 PWM controller IC that interfaces to an Arduino Uno via the I2C bus. The PWM controller IC supports up to 63 mirrors per Arduino Uno (a 6-bit I2C address for which one address is a global broadcast).

The software comprises a distributed compute system with 32 Arduino Unos (2 per row of mirrors), a pair of Raspberry Pis (providing wireless connectivity) and a Windows-based laptop. Each Raspberry Pi communicates with 16 Arduino Unos via a serial link over USB. Mirror movement commands are delivered to the Arduino Unos via a messaging protocol of our own design. Each message is comprised of the following byte fields: [MAGIC_NUMBER, KEY, <mirror_row>, <mirror_column>, <motor>, <direction>, <count_MSB>, count_LSB]. The purpose for each field is given in Table 1.

Table 1. Byte field for the command protocol.

<table>
<thead>
<tr>
<th>Field</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAGIC_NUMBER</td>
<td>Constant byte to indicate start of message, 0x21</td>
</tr>
<tr>
<td>KEY</td>
<td>Message type – mirror movement command, 0x41</td>
</tr>
<tr>
<td>&lt;mirror_row&gt;</td>
<td>Row ID of mirror</td>
</tr>
<tr>
<td>&lt;mirror_column&gt;</td>
<td>Column ID of mirror</td>
</tr>
<tr>
<td>&lt;motor&gt;</td>
<td>Pan/Tilt</td>
</tr>
<tr>
<td>&lt;direction&gt;</td>
<td>Forward/Backward</td>
</tr>
<tr>
<td>&lt;count_MSB&gt;</td>
<td>Most significant byte of step count</td>
</tr>
<tr>
<td>count_LSB</td>
<td>Least significant byte of step count</td>
</tr>
</tbody>
</table>

The desired mirror positioning is calculated in Rhino3D/Grasshopper, and the desired positions for each mirror are written to a CSV file. A Python program
(also of our own design) reads this CSV file and composes messages for the appropriate Arduino Unos (using the messaging protocol described above). These messages are communicated via TCP/IP over a wireless LAN to the Raspberry Pis, which forward them to the appropriate Arduino Uno (based on the row, column coordinates). On the Arduino Uno, well-formed messages elicit an ACK (acknowledgement) message in response, while ill-formed messages trigger a NAK (negative acknowledgement) message. In this way, the Python control software is aware of any communications issues that might arise and can resend a mirror movement command if needed.

4. Results

The reflected circles of light onto the walls and ceilings appear to have high contrast compared to the light level on the surround surfaces even though the room receives ample diffuse daylight through the south-facing glass façade. This contrast is beneficial to draw people’s attention to the pattern created by the reflected light pixels onto the existing architectural surfaces. The resulting effect alters a person’s perception of the geometry and materiality of the architectural surface. For example, the ceiling above the café next to the prototype is not flat, but rather a field of 3-dimensionally triangulated folded planes. The planes distort the image and makes it less recognizable compared to the target image used in the digital model, but the goal is not to make a representational image. Rather, the goal is to create an abstract image for the mapping to generate gradient light intensities and patterns that traverse the folded geometry. These new patterns reorganize and unify the complex geometry through the projection of a temporal image, generating an atmosphere that envelops the architectural surfaces. (Figure 6)

Figure 6. Mapped light pattern flattens the folded ceiling geometry.

The system allows for individual control of the mirrors, thus generating an informed atmosphere according to its adjustability. The intelligence is built into the design of the system by the ability for modification rather than the systems
acting autonomously. The Catoptric Surface allows the designer to manipulate daylight to generate new patterns across any surface, resulting in the ability to use light as an architectural material to affect the perception of space. The regular field of mirrors also produces a pattern of shading immediately adjacent to the façade where the decreased lumens works in concert with the intensification on the wall or ceiling since the perception of brightness is relative to the milieu. A second challenge is the roof overhang on the south facing glass façade, which means there is very little direct light within two months of the summer solstice.

In addition to the qualitative ability to generate atmospheric conditions, the prototype produces quantitative benefits. The intelligence built into the system is designed to create differing daylight levels in targeted locations within an interior room. The main benefits is that people need different light levels based on their task, age and vision abilities. (Lechner, 2009) For example, someone who is reading text on physical paper needs more light than someone reading from a screen; older people tend to need higher contrast than younger people; and there is a wide range of vision ability for people of all ages. This research argues against the desire for a homogenous lighting level in favor of the ability to vary the quantity and quality of lighting. (Larson, 1964) The image-based system allows for the control of daylight to be more or less intense without the need for artificial lighting, reducing the amount of energy needed to customize the light levels within a space.

5. Conclusion

In the Fun Palace, Cedric Price and Joan Littlewood envisioned the advantage of modifying the environment according to a wide range of uses by the occupants. Realizing this, they invited Gordon Pask to collaborate on the project to advance a system for adaptation through the potential of cybernetics. Though very early in the development of cybernetic theory, Pask provided the framework to develop an informed and intelligent design that could adapt to the needs and desires of the occupants in the Fun Palace. It is unfortunate that this experiment did not get tested since the Fun Palace was not built. Though, the members of E.A.T. (Experiments in Art and Technology) were able to advance ideas of an adjustable technologized environment in the Pepsi Pavilion as part of Expo ’70 in Osaka. The pavilion was truly a transdisciplinary collaboration between artists and engineers where they were generating spatial, visual and atmospheric effects through the implementation of newly invented technological systems. The result of the collaboration is the development of the most advanced immersive technologized environment of its time, which has had an immense influence on future generations of artists, architects and engineers.

In the spirit of E.A.T., the Catoptric Surface is a collaboration between computer scientists and architects, focused on the goal of creating an informed and adaptable environment. The particular environmental condition is atmospheric light effects created by variable light patterns projected on any receiving surface, activating the surface by creating areas of intensity and diffusion that alter the perception of space. Using cyber-physical system enables the researchers to control the subtle variegation in light patterns, revealing an ethereal environment that is adaptable to desirable moods perceived from the atmosphere. The
synergy between formulation and modulation generates a Morpho-Ecological heterogeneous space by creating a virtual space nested within a physical space. (Hensel, 2009) The interaction between the designer modifying the reflected light pattern through cyber-physical systems and the receiving surface generates formless spatial effects, resulting in an architecture of affect. (Bressani, 2013) The formless nature of atmosphere is a result of a clearly defined set of rules to manipulate environmental conditions, creating a meteorological cartography of atmospheric effects. (Wigley, 1998) The juxtaposition of reflected daylight, receiving surfaces, mathematics, and mood generates an architecture of informed and intelligent formless atmosphere.

References