The Catoptric Surface research project explores methods of reflecting daylight through a building envelope to form an image-based pattern of light on the interior environment. This research investigates the generation of atmospheric effects from daylighting projected onto architectural surfaces within a built environment in an attempt to amplify or reduce spatial perception. The mapping of variable organizations of light onto existing or new surfaces creates a condition where the perception of space does not rely on form alone. This condition creates a visual effect of a formless atmosphere and affects the way people use the space. Often the desired quantity and quality of daylight varies due to factors such as physiological differences due to age or the types of tasks people perform (Lechner 2009). Yet the dominant mode of thought toward the use of daylighting tends to promote a homogeneous environment, in that the resulting lighting level is the same throughout a space. This research project questions the desire for uniform lighting levels in favor of variegated and heterogeneous conditions. The main objective of this research is the production of a unique facade system that is capable of dynamically redirecting daylight to key locations deep within a building. Mirrors in a vertical array are individually adjusted via stepper motors in order to reflect more or less intense daylight into the interior space according to sun position and an image-based map. The image-based approach provides a way to specifically target lighting conditions, atmospheric effects, and the perception of space.
INTRODUCTION
Harvesting daylight has long been one of the performative characteristics of a facade system as a mediator between internal and external environments (Addington 2009). Overtly functional elements clipped onto a facade, such as light shelves, are effective at reflecting indirect light deeper into a space, yet remain aloof from the architectural facade. A more integrated approach utilizes a more extensive brise-soleil system that reduces undesirable solar heat gain, bounces indirect light deeper into the interior of a building, and defines the identity of the architectural facade (Moe 2008). More recently, heliostats have been employed to kinetically track solar position and redirect light down through glass roofs into atrium spaces. Heliostats are typically mounted on a roof and are motorized to follow the movement of the sun across the sky, reflecting the light with mirrors. The geometric position of the mirror finds the median angle between the sun position and the target location within a building. Most of the associated discussions around daylighting in architecture revolve around a functionalist agenda of reducing energy for illumination and increasing access to daylight when a building massing is too deep (Hausladen, de Saldanha, and Liedl 2008). Beyond the functionalist approach, intensifying the accumulation of light provides the opportunity to modify spatial perception through the generation of atmospheric conditions and optical effects.

This research avoids a purely building science approach in favor of the notion of architecture affecting human senses as well as investigating the effects generated by the architectural entity. Light can stimulate any surface, having an immediate effect on the perception of space by creating an atmosphere from a range of luminous intensity and contrast. These variable atmospheric conditions create a series of microclimates that emanate from the architectural object, yet they are perceived to envelop the people and not the building (Wigley 1998). The generation of optical effects from fragments of images was 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 extravagance of fragmented images of the surrounding environment within their interior. Their intention was to generate spatial and visual effects that dematerialized the limits of space through light, depth, and dynamic reflection (Agrest 1983).

More generally, a person’s perception of their environment is in a dynamic negotiation according to continually changing light level, contrast, continuity, or fragmentation (Larson 1964). Atmosphere acts as a mediator between subject and object that simultaneously mediates between the production of the effect and its reception (Böhme 2014). Therefore, the generation of atmosphere affects the perceptible boundaries of an interior space, defined by the interplay between the light pattern and the surface it is mapped onto. Architecture develops tactility through the effects generated by the interplay between markings and material conditions, or rather between the surface and ornament (Bressani 2013). This intimate co-dependence of atmosphere and mapped lighting pattern can be found in the French term intérieur, which simultaneously describes the artistic effect inside a room and its two-dimensional representation (Rice 2009). The indeterminacy between the effect and the two-dimensional pattern mapped onto the receiving surface creates an adaptable atmospheric condition that affects a person’s interaction with it. Thus an architecture of affect blurs the distinction between the figurative pattern and the architectural surfaces that receive the projections. Yet, it also reveals an anxiety from trying to associate the architectural object with an atmosphere (Sprecher 2012). This condition creates a perception of space that is independent of the surfaces that structure the...
interior environment (Semper 1989). This new atmospheric environment reveals the symbiosis between the surface, light, and atmosphere in order to produce an architecture of affect.

BACKGROUND
An initial investigation was conducted through a seminar taught by the lead author, titled “Surface of Affect/Effect,” which introduced the notion of architecture affecting human senses as well as the effects generated by the architectural entity. Both affect and effect focused on the architectural surface as a plane of contact between people and their architectural environment. The class developed systems and physical prototypes that explored dynamic responses to environmental variables of light reflection to 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 (Figure 2). The reflecting surfaces are held within a series of interconnected frames so that their movement is coordinated. The focal point is adjustable in relation to the light source (Figure 3).

A second investigation was conducted through a digital fabrication studio taught by the lead author, titled “The Grid, the Cloud, and the Detail” (Krauss 1994), which investigated methods to alter the targeted reflection of daylight as an environmental variable that informs the reading of an existing space. In order to test the system, the studio designed, fabricated, and installed a full-scale prototype (Figure 4). The intervention on the lighting focuses on amplifying the atmospheric conditions in the existing space in two ways. First, the installation redirects light down from gable ends of the existing building into the darker recesses of the atrium in an attempt to create a more even ambient lighting condition in the space (Figure 5). 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. The 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 (Figure 6). The reflective surfaces interlace fragmented views with views across the atrium space that tend to camouflage any clear reading of the existing space. Thus the even optical distortion creates an ambient rereading of the space through the design of an informed environment (Figure 7).

The installation is located in a historic building, and thus it needed to respond to the existing columns and beams...
within the atrium space. The surface definition is defined by a hyperbolic paraboloid geometry that spans between the existing columns and beams. The field of custom reflective surfaces acts independently from the twisting surface, thus the system is adaptable to operate on any guiding surface topology (Figure 8).

The redirection of light through design of the surface geometry has been explored by Philippe Bompas et al. (2013). Rather than using reflection, their research focuses on caustic refraction by varying the thickness of a transparent material. The aspect relevant to the research in this paper is the resulting 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 that is capable of producing the desired result. Thus the architectural intervention is the surface that produces the desired visual effect.

METHODS

The research outcomes in the seminar and digital fabrication studio mentioned above were based on the designer locating either a target point or an evenly distributed field on which to reflect the light. The current research advances the investigation of reflected light by designing specific intensities in some areas and dissipating lighting conditions in other areas, according to predetermined yet adjustable image-based maps. Varying the intensity of light on a given surface focuses on the quality and not just quantity of lumen’s, which offers more nuanced methods to define and perceive spatial conditions (Figure 9).

The image-based map provides the target locations for the light ray reflections and can consist of any raster image. The image is sampled according to value to determine the density of target points—the higher the value, the denser the resulting field of points (Figure 10). The image is thus translated into the mapping of target points within a space. The position of the image-based map can be moved to the desired location within the digital model of the architectural surface to receive the reflected light. The median angle is calculated between the new cartography of points on the light-receiving surface and the light source at the surface of reflectors (Figure 11). The calculated angle determines the position of each mirror according to the specific image and the location of the light source. There are 650 mirrors, which corresponds to the number of sample points on the image-based map in the Rhino/Grasshopper digital model. The light-source location can be set manually or be automated to track the solar position (Figure 12).

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...
of Architecture and the Department of Computer Science & Engineering at Washington University in St. Louis. The team established the cyber-physical systems that interface between the image-based computational model and the mechanical-electrical systems in order to create an operational prototype.

The team located a large, south-facing glass facade in one of the institution’s buildings, which measures 30’ (9.1 m) wide by 16’ (4.9 m) tall, thus providing ample direct daylight to harvest, though more effectively during winter than summer due to the roof overhang. A vertical array of 650 mirror units is installed on the interior side of the glass. Each unit is arrayed at 6˝ (150 mm) on horizontal and vertical centers and mounted on .0625˝(1.6 mm) stainless steel cables to minimize any structure that could obstruct the sunlight (Figures 13 and 14). 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 is a café seating area. The primary behavior of the mirrors is 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 facade.

Each mirror unit rotates independently according to the computational inputs from the image-based systems. The mechanics of the mirror consist 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 lasercut and bent aluminum parts. 3D-printed parts connect the motor to the aluminum while also creating the stops for the rotation (Figure 15). 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, and integrated the motor

<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>&lt;count_LSB&gt;</td>
<td>Least significant byte of step count</td>
</tr>
</tbody>
</table>

Table A

11 Artwork 02: Light ray tracing from source point to image-based map on target surface.

12 Artwork 02: Positioning of reflector panels relative to moving light-source location.
mounting along with the electronic components (Figure 18). The board is then mounted directly to the stainless steel cables, which means the board also acts as structure for the mirror unit (Figure 17).

For the electronics and controls, the pan-tilt of each mirror is driven by a pair of unipolar 12 V stepper motors that have 32 steps per revolution (11.25 degrees per step) and 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 A.

The desired mirror positioning is designed in Rhino 3D/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.

RESULTS AND REFLECTION

Individual control of each mirror through an image-based approach gives the designer the ability to adjust both the qualitative and quantitative light conditions in any given space. The Catoptric Surface prototype allows the research team to design the atmosphere within the built environment by providing a kinetic system to tune the lighting conditions with a far higher resolution than a static system. The increased control allows anyone to design with light as an architectural material in the same way as they would with any surface patterns. Such a qualitative
approach reconsiders light as a fungible material that can be deployed over any architectural surface to redefine boundaries independently of walls or ceilings. The visible energy intensity of light defines a gradient boundary of space. The independent rotation of the mirrors allows designers to adjust the nuances of the energy intensity to subtly affect the perception of space. The regular field of mirrors also produces a pattern of shading immediately adjacent to the facade; there, the decreased lumen’s work in concert with the intensification on the wall or ceiling since the perception of brightness is relative to the milieu.

The resulting image-based light patterns generated by the prototype subtly generates new zones based on light intensity in the existing building’s café. One challenge is that the ceiling above the café next to the prototype is not flat, but is rather a field of three-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, it is to create an abstract image for the mapping to generate gradient light intensities and patterns to go across the folded geometry. These new patterns reorganize and unify a highly active surface, drawing a temporal image on the ceiling or wall surface. The light reflected off of the wall and ceiling surface defines spaces based on greater and lesser light intensity (Figure 18).

Another challenge is that the cables that hold the mirror units flex, even under high tension, which allows them to rotate slightly. This affects the accuracy of the reflected angle and thus the exact location of the light pixel is not as precise as desired. A third challenge is the roof overhang
on the south facing glass facade, which means there is very little direct light within two months of the summer solstice. At the time this paper was written, there was not enough solar exposure for in-depth testing of the system. Therefore, more extensive testing will occur during late fall, winter, and early spring.

The results of the prototype can also be examined pragmatically, in addition to perceptually. Considering the effect of the system from a more practical view, the increased control due to the independent rotation of the mirrors can provide functional benefits for people that need more or less light due to age of the occupant or the task they are performing. For example, users of computers need less light than readers of physical media, since computers are themselves artificial light sources. The light level required for vision also varies with the age of the occupants. As people get older, they need higher light levels and increased luminous contrast. Furthermore, regardless of age, people have different qualities of vision. Therefore, having a system that can accommodate these varying conditions using daylight rather than artificial light is beneficial.

Future Development
The research project is a nascent investigation into the potential to use an image-based map to redirect daylight to targeted locations within a building. The current prototype only allows one person to create or adjust the image for the target map that the mirrors attempt to recreate with reflected light, which is problematic for deploying this system into a multiuser environment. Future plans for this project will be to develop a graphic-interface app that allows multiple users to adjust the amount of desired light in their zone. The desire for light level is highly subjective, thus creating a collaborative app that gives multiple users the ability to influence the amount of light in their space will be critical to the advancement of the project. Further aspects that could be integrated into the software of the user interface include light sensors to give real-time feedback from ambient light conditions. Another future development to the hardware could enable all the mirrors to move simultaneously, since in the current prototype, there is only enough electricity to move one column at a time. The mirror units will also be designed for exterior use, rather than being limited to inside of a glazed facade. An exterior location will act as a brise soleil to provide shading on task surfaces and the floor inside the building.

CONCLUSION
Technologies that are responsive to fluctuating environmental conditions such as heliostats are typically associated with a modernist, functional agenda that attempts to control nature with an architectural machine. Yet the conditions induced through the manipulation of environmental variables such as light can produce visual effects, shifting the discourse from a solely quantitative basis to one that includes the way people perceive space. The Catoptric Surface research project investigates the nature of variable light patterns projected on any receiving surface, activating them by creating areas of intensity and diffusion that alter the perception of space. The subtle variegation in light patterns reveals an ethereal environment that is also adaptable to changing desires for creating moods with 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 and Menges 2009). The interaction between the reflected light pattern and the receiving surface generates formless spatial effects, which reveals the synergy between the surface, light, and atmosphere in order to produce an architecture of affect. 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, 25). The juxtaposition of reflected daylight, receiving surfaces, mathematics, and mood generates an architecture of formless atmosphere.

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REFERENCES


**IMAGE CREDITS**

Figures 1 and 2: Youngjae Lee, Janghwa Park, Jinkyu Lee, 2014

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