to the design process. In fact, these qualitative changes in the time required to design and analyze make it critical to involve engineers, environmental designers, and architects in using these tools together in a collaborative fashion.

5.1 Future Research

We are actively engaged in research to improve the responsiveness of the design tools mentioned here, as well as others under development. We are increasingly looking into parallel processing on multiple cores, heterogeneous processing environments, and networked cluster computing to achieve not only quantitative improvements in responsiveness, but also the sort of qualitative shift mentioned above regarding what sorts of activities can be considered an integral part of the design process. At the same time, we are also looking at new ways to exploit the potentials of tangible interfaces and other user experiences in order to maximize the efficiency and immediacy with which designers can understand the impact of their choices across a range of time scales.

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REACTIVE LIGHT DESIGN IN THE "LABORATORY OF THE STREET"

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ABSTRACT

This paper presents and discusses results related to a full-scale responsive urban lighting experiment and introduces a light design methodology inspired by reactive control strategies in robot systems. The experiment investigates how human motion intensities can be used as input to light design in a reactive system. Using video from three thermal cameras and computer vision analysis, people's flow patterns were monitored and sent as input into a reactive light system. Using physical as well as digital models, four different light scenarios are designed and tested in full scale. Results show that people in the city square did not engage in the changing illumination and often did not realize that the light changed according to their presence. However, from the edge of the city square people observed the light patterns "painted" on the square, as some people became actors on the urban stage, often without knowing. Furthermore, the experiment showcased power savings of up to 90 percent, depending on the response strategy.

1 INTRODUCTION

Illuminating streets, paths, squares, and parks has been practiced from the very dawn of civilization. In the ancient Roman empire, lighting primarily served the purpose of security, both to protect the wanderer from tripping over something on the path as well as to keep potential robbers at bay (Scott 1904). This historical notion presents two fundamental purposes of illumination: to illuminate the pavement and to illuminate the people in the space in such a way that potential observers could take action, if needed—a social mechanism described by Jane Jacobs as passive surveillance (Jacobs 1961), which serves as a central mechanism in the organization of everyday life. Today street lighting is often controlled with binary control logic: on/off. The system is preprogrammed to turn on according to the time of day and year. This notion of global control assumes that people always need evenly distributed light, even when nobody has the need for light. With new light sources, sensors, and embedded dimming technologies, it is possible to detect changes in occupancy patterns and make simple response patterns in the lighting, thus enabling feedback between light pole and occupants for a more flexible and site-specific response. The study of feedback between sensors and acting environment can be tracked back to Norbert Wiener's notion of cybernetics: a marriage of control theory, information science, and biology that seeks to explain the common principles of control and communication in both animals and machines (Wiener 1948). Since then much work has been done in the field of computer/human interaction, and new research fields such as robotics (Arkin 1998), responsive environments(Negroponte 1975), situated technologies (Shepard, Scholz, and Khan 2010), etc., all contribute to a particular focus within the field of sensing and responding to change related to the environment.

Inspired by the cybernetic notions of Gordon Pask (Pask 1962; 1961), Usman Haque presents experiments that utilize sensor technologies and lighting as part of a larger collective constructed environment where people and objects collaboratively create social domains, as in the case of Sky Ear and Open Burble (Haque 2007). In the two cases, environmental feedback between weather systems and social actors is essential in the temporary composition of the color and intensity of the light. Another example is the Dune project (de Rijk, Chong, and Roosegaarde 2011) by artist Daan Roosegaarde: a 60-meter-long reactive light and sound installation unfolding in the landscape along the Maas River in Rotterdam. The installation consists of thousands of illuminating light straws that react to the presence of people. The behavior of the lighting is inspired by natural mechanisms, hence it can be scared, excited, or curious. Within the last decade, these (and many other) initiatives present cases in the emergence of a new creative discipline that proves to have aesthetic and social potentials in the field of lighting design. Within the industry of lighting, firms such as Echelon (Echelon 2007) and IBM (IBM 2012) have entered the development of technologies for large-scale control systems of smart cities (Batty 2012). They contribute to the development of an infrastructure for a new type of responsive and more effective environment. The study in this paper aims to develop prototypes for simple and robust reactive lighting scenarios and test how the changing light might reveal new social behaviors in a full-scale experiment in everyday life situations. As an early hypothesis, we argue that responsive lighting in public space will affect people's behavior in the square, and furthermore that by dimming the light when nobody is there we are able to save energy. We test this argument through design of small-scale models and full-scale experiments, realized at Kennedy Square in Aalborg, Denmark, during January 2012. The paper describes and discusses the design methodologies, tools, and technologies utilized in the experiment.

The paper is organized as follows: the experimental site and setup are presented, followed by an introduction to the applied computer vision analysis, interactive illumination design, and observation methodology. The observations of the four different light scenarios are then presented and discussed, and finally the findings are concluded.

figure 2

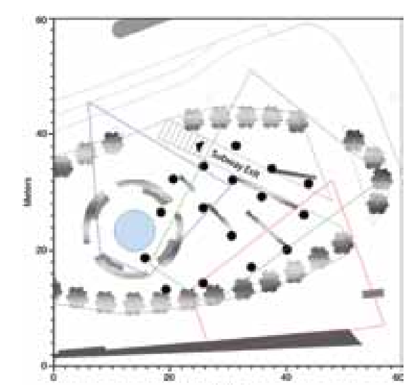

figure 3a

figure 3b

figure 1

(a) Overview of Kennedy Square with 16 lamps. (b) Nighttime overview of the square seen from the position of the thermal cameras.

figure 2

(a) Lamp housing. (b) LED module.

figure 3

(a) Overview map of Kennedy Square with the areas covered by the three cameras. (b) Snapshot of the iPhone application by which it was possible, in real time, to see the result of the computer vision tracking and control the light settings of the lamps.

2 EXPERIMENTAL SITE AND SETUP

During January 2012 the authors of this paper presented a 1:1 experiment at Kennedy Square in the city of Aalborg in Denmark. The square is located between the main train and bus station and the city center, and serves primarily as a transit space between these two locations; see Figure 1a for an overview. To monitor the square, three thermal cameras (type Axis Q-1921-E, with a 19 mm lens) were mounted at the height of 15 meters at one of the buildings facing the square. The cameras covered the area from the exit of a subway to where people leave the square on their way to the city center, as illustrated in Figure 1b. Along this pathway the 16 RGB LED lamps were placed

figure 4a

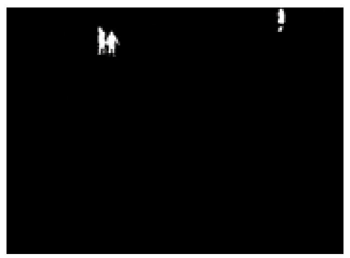

figure 4b

(Figure 1b). The streetlamp is composed of a Riegens Ray light fixture (Figure 2a), a 3.5 m tall light post, and a 60 × 60 cm sidewalk tile as foundation. As light source, an LED module containing 18 1W LEDs is mounted at the bottom of the light fixture. The LED module is connected to a DMX module that enables a 0–255 step brightness control of each LED color as well as a unique address for each lamp.

2.1 Computer Vision Analysis

Detecting and tracking people is a large research area in computer vision, with most approaches using normal visual cameras. But due to falling prices on thermal cameras, new approaches using these sensors have been developed lately. Thermal cameras measure the amount of thermal radiation that lies in the long-wavelength infrared spectrum (8–15 μm). Since thermal cameras only measure radiation and not visible light, they have a clear advantage over visual cameras especially in night conditions. Figure 4a shows an example of the input image from one of the camera views. Real-time information about the position and velocity of people in the square is being transmitted to the light control interface (Figure 3b).

In outdoor environments the temperature naturally changes, which gives a slowly changing background image. Therefore, a running average background subtraction is performed as the first step in detecting people (Piccardi 2004). The background will be updated with selectivity, meaning that only if the pixel is segmented as background will it contribute to the new background. As the experiments take place in an urban space with limited car access, it is assumed that all activity detected is human activity of interest. The different images produced by background subtraction show the area of interest. The detected objects must be mapped to real-world coordinates at the square in order to correspond to the positions of the lamps. The mapping is calculated using a homography matrix (Criminisi 1997) (Figure 3a).

This matrix can be calculated using at least four corresponding points in image and world coordinates. Since the camera views are not aligned, a mapping must be calculated for each individual view. Figure 5a illustrates the mapping from image to world plane. For the purpose of illumination control from tracking data, groups of people should be considered as one object.

The individual objects detected are grouped using single-linkage clustering (Hartigan 1975) with a distance threshold of three meters. In order to determine stable positions and velocity of the groups, a Kalman filter is applied to track the groups (Welch and Bishop 2001). Splits and merging of groups are handled based on the distance between predictions of group tracks.

From the analysis it is now possible to estimate trajectories of persons in the square. Figure 6 shows the results of such trajectories for (a) one minute, (b) two minutes, and in (c) the velocities vectors for persons walking in the square for a period of one hour. This information may also be illustrated by how the square is occupied, which means not taking the motion of the persons into account. Such an occupancy map with a resolution of 1 × 1 meter for 24 hours is illustrated in Figure 5b, sampled for every 10th second. In this way it is possible to get information about both the instant motion of people in the square and accumulated motion over time. The former information may be used for instant control of the illumination, whereas the latter representation can be used for placement of lamps—that is, the physical design of the illumination setup for a given urban environment—and to design basic illumination according to how the area is being used.

2.2 Observation Methodology

During the experiment, observations of body language, gestures, and behavior of the occupants in the square were made. The observation methodology was based on ethnographic studies and fieldwork techniques, as they are articulated by sociologists such as Erving Goffman and Edward T. Hall (Goffman 1980; Hall 1973) and utilized by architects such as Jan Gehl and William Whyte (Gehl 2004). By observing the interactions from the edge of the street, we were able to describe "space routines" in the transit space (Jensen 2010; Gehl 2004; Whyte 1988) and evaluate if people were immersed in or affected by the different light scenarios. Observing people's gestures, behavior, and nonverbal signals according to the different illuminations provides us material to compare the involvement and interaction between people, supporting the findings from the flow maps.

3 LAYERED RESPONSE MODEL

To approach a reactive light design of an urban square calls for a creative process similar to that needed in the development of architecture. We are interested in novel design tools and methodologies that allow designers to intuitively sketch interactive scenarios and to evaluate response patterns through digital and physical models. As a fundamental question, we would ask: what is the internal performance goal of one light pole? First, to shower the pavement with light, protecting the wanderer from tripping; and second, to illuminate people's bodies/faces to reveal nonverbal body language. However, this notion assumes that the space is occupied and does not describe the need for light

figure 4

(a) Thermal image. (b) Binary image. Example of the thermal input image and resulting binary image from one camera view.

figure 5

(a) Example of the thermal camera input from one camera. (b) Occupancy map of the square, counting the number of observed persons in 1 × 1 meter cells sampled every 10 seconds.

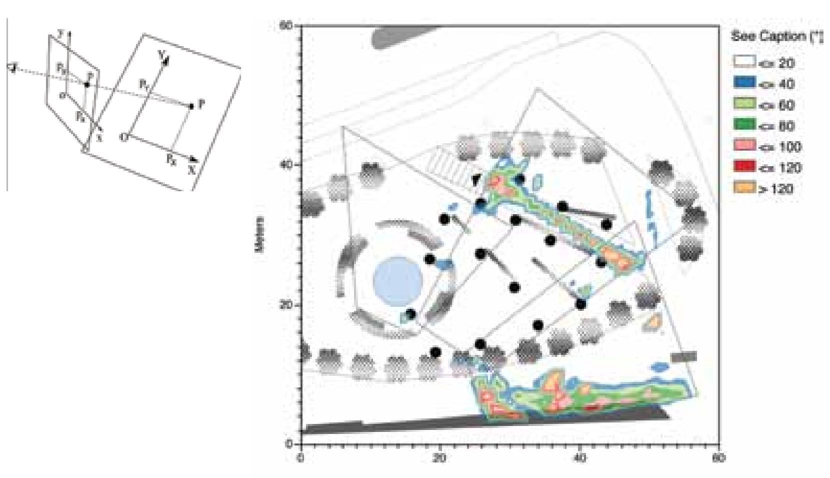

figure 5

figure 6

(a) One-minute trajectory. (b) Two-minute trajectory. (c) One-hour velocity map. Estimated velocities vectors for people in the square.

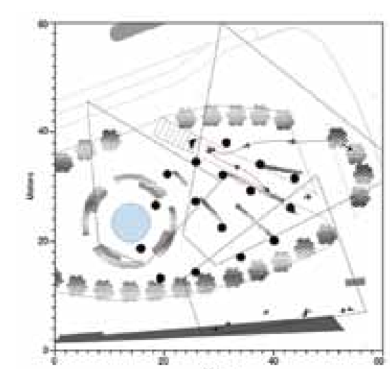

figure 6a

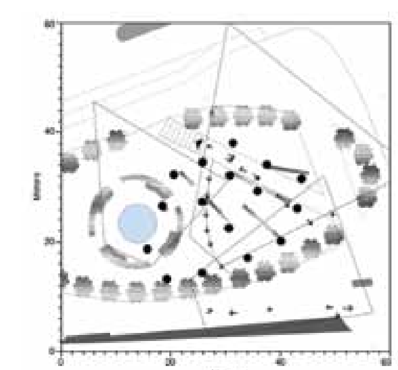

figure 6b

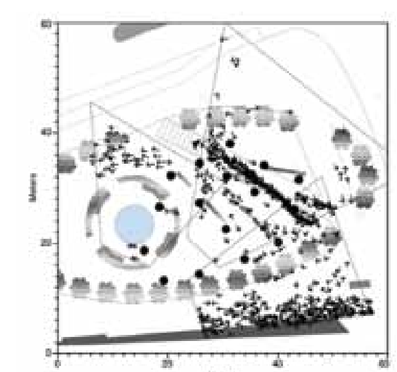

figure 6c

figure 7a

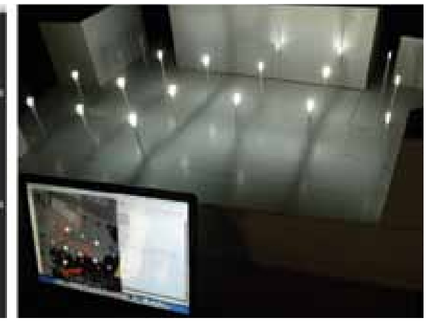

figure 7b

figure 8

when nobody is occupying the space. Because of distributed motion sensors, we are now able to address individual lamps, hence presenting the potential to introduce conditional statements, for example: "if movement, then dim up; else set light intensity to fade slowly between 5 and 10 percent." Under the assumption that lamps can perform dimming and sensors can provide information about occupancy, this paper suggests a two-layered reactive light model, which firstly addresses a minimum lighting that treats situations without occupancy (*ambient light*) and secondly a layer that addresses situations with occupancy (*effect light*). The two layers together produce lighting that is the one experienced on the street.

3.1 Ambient Lighting

Basis lighting is the illumination enabled when no occupants are immersed in the lighting. The concept focuses design attention on the empty square. However, this notion does not exclude the possibility that observers from a distance would appreciate an illuminated square. Typically the square would be observed from a distance—a balcony, a living room, a café, etc. Dark places could lead to an avoidance of the square. In the experiment, we worked with two ambient light scenarios:

- A global minimum: all lamps are dimmed down equally to 10 percent of the full intensity.
- Ember: the light slowly fades up and down between 0 to 20 percent in a random pattern.

3.2 Effect Lighting

Effect lighting is the action triggered by an event (the presence of a person, a vehicle, or an animal) perceived by the perceptual organ of the light system. One can design a range of different complicated, banal, or playful scenarios depending on the level of occupancy, velocity, climate, time of day, etc. In this initial experiment, we tested the following two effects:

figure 7

(a) Snapshot of the light design software. (b) Illustration of the model light design software and physical 1:50 model.

figure 8

(a) One-minute trajectory. (b) Two-minute trajectory. (c) One-hour velocity map. Estimated velocities vectors for people in the square.

Light circle: as an illuminated aura around the occupants, the localized light would secure an illuminated circle of a minimum of 10 meters in diameter. This would allow the occupants to perceive variations in pavement and the faces of people passing by, which in turn facilitates secure navigation and travel across the square.

Light wave: as a playful illumination scenario, we designed a treasure hunt scenario where two of the lights on the square indicate (blue light) the position of a trigger causing a wave of white light to travel across the square. After 10 seconds, a new blue light will emerge in another location. The hypothesis was to create illumination that engaged people in playful and creative situations.

3.3 Resulting Lighting

Summarizing the intensities from the *basis* and *effect* lighting gives the light intensity for each lamp. The resulting lighting presents a light performance that has low intensity in scenarios without people and offers more social and interesting light configurations during times of occupancy, while still fulfilling the functional requirements.

4 RESPONSIVE LIGHT SCENARIOS AND DESIGN METHODOLOGY

The layered model described above only describes the logical organization of the design methodology approaching a responsive light design of an urban square, and also calls attention to a creative process similar to that needed in the development of architectural space. In addition, we need to develop tools to provide techniques where interactive scenarios can be sketched and evaluated in a creative and intuitive design process. To approach the design challenge, a physical 1:50 model of the square was developed (Figure 7b). Simple white LEDs were used to represent the lamps, and by using video input recorded on-site, we were able to test how different response designs would unfold in the square. In this way, we could simulate the light design using real-life video feeds and evaluate response times, rhythms, and placement in relation to the scale of the urban space. Figure 7a shows a snapshot of the screen, where the red dots represent groups on the square and the black circles are the lamps. The diode models were good sketching tools, but to fine-tune the response patterns on-site, a smart phone app was developed so that the architect could monitor activity in the square and adjust light response and color intensities on-site.

figure 9

figure 9

The glowing light scenario.

figure 10
The white aura light scenario.

figure 10

5 EXPERIMENT

The experiment was conducted during the last week of January 2012 from late afternoon into the early evening. At this time the sun sets at 5 pm, therefore collection of data and observations took place from 5 pm until 8 pm. During that period the weather was very cold by Danish standards, ranging from -5 down to -10 degrees Celsius (23 down to 14 degrees Fahrenheit), and very windy. Data was collected by observations and by logging of the results of the computer vision analysis.

6 RESULTS

During the experiment the experience and effect of the four different light scenarios were investigated: ambient, glowing light, white aura, and red treasure hunt. The normal illumination of the square was turned off during the experimental period.

6.1 Scenario 1: Ambient Illumination

The first scenario is a homogeneous illumination of the square. The 16 lamps had a static intensity of 80 percent white light, and no effect was added. This light scenario was similar to what would have been a traditional static illumination of the square, and was motivated by a need to compare the change of flow and social behavior in the square in different light scenarios. It seemed that people did not notice the changed illumination and acted as if nothing were different from usual. When people were asked about the illumination, only a few recognized the changed lighting, even though the lighting before had been very limited.

6.2 Scenario 2: Glowing Light

The intention of the slowly fading white illumination was to create lighting that would illuminate the square in an aperiodic way, leaving the square half lit but always in a process of fading down or up, providing a feeling of overview of the square and supporting the feeling of security (Figure 9). Thus the light system chooses a random lamp and then sets the light level to 10 percent of the maximum level, from which it is then decreased. As a playful chance encounter, a light wave effect was introduced.

6.3 Scenario 3: White Aura

As a simple response pattern, the lamps were set to slowly dim up to 100 percent when a person approached the lamp. Because of the relatively big illuminated area (10 meters) around people, they did not seem to realize the darker square surrounding them. This absolute minimum light scenario allowed the pedestrians to see the ground as well as other people, which were the fundamental functional requirements for lighting described in section 1. Observing from a distance, one could see how people at the edge of the square were pointing toward the "performing" people moving across the square. The simple effect and the large contrast between the surrounding darkness and the light "painted" by the moving pedestrians made the persons natural focal points in the square.

6.4 Scenario 4: Red Treasure Hunt

The hypothesis of this scenario was to establish an unusual illumination that made people stop and confront the lighting in a playful manner. Figure 11 shows a sequence of images visualizing the effect scenario: 1) A person approaches the blue "trigger" light. 2) The person triggers the effect, which sends out a wave of light from the triggered lamp. 3) The light wave travels through the square. 4) The light wave ends, and the trigger point is disabled for 10 seconds before it lights up a lamp again and a new person can trigger yet another light wave. A few people who triggered the light wave noticed it, and when they realized it, the illumination changed based on their presence. Observed from a distance, the slowly fading lamps had a calming, inspiring, and lively effect; one needed to observe very carefully to notice the wave.

6.5 Energy Consumption

The ambient illumination scenario, as reference, yielded an energy consumption of approximately 230 watts for the 16 lamps. The other three scenarios fluctuate in energy consumption due to the deliberate effects and the reactive effects according to the activity in the square. Clearly, the energy consumption of these scenarios is dependent on the light design; in particular, the choice of ambient light contributes significantly to the mean value that the scenario fluctuates around. The glowing light scenario had the greatest energy consumption, around 100 wa tts; this was the scenario with the largest fluctuation, which in some cases almost reached the ambient illumination level. The fluctuations around the mean are due to the light effect being set according to activity in the square. White aura had the overall lowest energy consumption, about 20 watts on average or 11.5 percent of the ambient illumination scenario. This is also the scenario that is most dependent on activity in the square.

7 CONCLUSION

Street lighting is designed to illuminate the square, extending the potential use of public space into the dark hours. Because of recent developments in the fields of sensor and LED technologies, we are now able to modulate the light to any given control paradigm. This study shows new possibilities and design methodologies for applying simple reactive light strategies in a three-layered response model,

figure 11
Energy consumption of the four illumination scenarios.

figure 11

addressing ambient, effect, and resulting lighting aspects for interactive urban lighting. It does this through four experiments using thermal cameras and computer vision analysis that allow designers to detect occupancy and flow patterns in the street. The data is utilized both as input to a real-time light control system and as a mapping of long-term occupancy and flow, allowing researchers and urban planners to access data on the use of urban spaces. In this paper, the evaluation of three interactive light strategies—glowing aura, glowing light, and red treasure hunt—reveal the potential for reactive lighting to be applied in public spaces and present significant energy savings of up to 90 percent. This result shows that dramatic light changes would not make people in transit space change behavior. However, the lighting does change the relation between observers on the edge of the square and people moving in the lighting. The responsive lighting amplifies the performance of the occupants, who become actors on a stage (Goffman 1959), people who attract attention; and it supports the concepts of passive surveillance by Jane Jacobs (Jacobs 1961). The majority of the visitors did not realize the changing of the light at their first visit to the square, but after observing other people perform from a distance, a new participatory novelty emerged. To uncover the full character of the public space would demand further examinations of space routines across seasons, which would allow us to develop deeper knowledge and understanding of social potential in situations with long-term occupancy. To address future challenges of response design in the field of reactive lighting, the authors of this paper suggest an interdisciplinary approach, where technologists and architects work closely together in search of new, robust tools and novel design methods to be tested in the "laboratory of the street."

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FORMAL AND FUNCTIONAL IMPLICATIONS OF DYNAMICS-RELATED SOLAR DESIGN SCHEMES

ABSTRACT

In recent years several solar radiation simulation tools have been developed to assist architects in analyzing the performance of existing building designs. However, it is often unclear how the results of these analyses can help to generate new solutions and thus be truly beneficial for innovation in sustainable architectural design. Recent developments in open source applications that allow links between energy simulation engines and 3D modeling environments open a new layer of understanding. The possibility of better understanding the dynamic interaction between incident solar radiation and building envelopes allows the synthesis of new architectural design schemes. This paper presents the results of a series of experiments based on the case study of a mid-latitude single-family house in Taiki-cho, Japan. The first experiment describes how the incident solar energy interacts with the exposed components of the envelope. The second experiment describes how the energy demand of the building can be partially reduced through the design of passive interventions that are based on the dynamics of the demand. Finally, the third experiment exemplifies how, based on the knowledge extracted from the first two experiments, it is possible to synthesize new dynamics-related solar design schemes that join passive techniques, active technologies, and formal aspects.

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