AnyLight: Programmable Ambient Illumination via Computational Light Fields

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ABSTRACT
In this paper we describe AnyLight, a lighting device that uses computational light fields to offer highly programmable illumination for architectural environments. Relying on *integral imaging*—a technique commonly used to realize stereoscopic 3D displays—AnyLight can mimic the illumination effects of various light sources, both real and imagined. A combination of high-output, narrow-beam LED backlight and custom, 3D printed optics give the device the capacity to shoot out strong, targeted light rays from its surface in arbitrary directions. The paper will provide extensive discussions covering the device's technical details, usage scenarios, and possibilities for future extensions; quantitative and qualitative results from our initial evaluation sessions will be reported as well.

Author Keywords
Integral illumination; integral imaging; computational light field; light field display; robotic/responsive architecture; programmable lighting.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION
Integral imaging, a technique originally invented more than a century ago, has found popular use as a relatively simple way to implement stereoscopic 3D displays in the past several decades. Potential uses of the technique are by no means limited to stereoscopic displays, however—and ongoing advances in lighting technology (e.g., LEDs) and the recent introduction of 3D printable optics have now put us in a position where we can easily (and also *cheaply*) explore alternative applications of the technique.

In this paper, we explore one of such alternative uses of integral imaging, namely its potential to realize a highly programmable lighting (*integral illumination*) system for architectural environments. We have developed a prototype system, called AnyLight, which aims to mimic the lighting effects of a wide range of both real and imaginary light sources, e.g., spotlight, chandelier, sunlight, etc. While our prototype is still small in scale, room-sized implementations are theoretically possible by tiling multiple devices in a 2D grid layout. In a room fully furnished with an array of AnyLights, occupants will be able to freely control its lighting, and thereby also its ambience, to a degree unachievable using existing lighting technologies—with as much effort as switching wallpaper images on PCs or mobile devices.

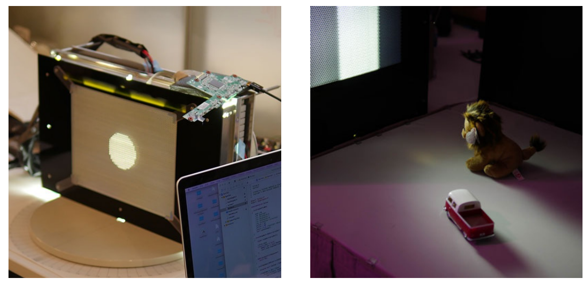

Figure 1. AnyLight: an integral illumination device.

Hardware-wise, AnyLight employs a design similar to that of a conventional, integral imaging-based 3D display, involving a combination of a spatially modulated light source (we use a standard LCD with a custom-designed backlight in our prototype) and lenticular optics. However, the difference in objective between a display and a programmable lighting system—in particular the fact that we cannot determine a fixed *viewing area* for AnyLight—creates distinct technical challenges that we counter through several measures, e.g., a "hybrid" optical design where transparent and opaque elements coexist within a single lenticular sheet. Software-wise, we have developed a simple desktop controller application designed to allow users to intuitively harness the power of AnyLight without needing to understand low-level optical phenomena.

The paper will explain the technical principles underlying the design of AnyLight and illustrate the details of our prototype implementation, highlighting the major technical hurdles and our strategies to overcome them. We will describe several potential usage scenarios of the device within architectural environments, and discuss how the hardware may be optimized to suit different use cases and installment locations. We will also report results obtained from our initial evaluation sessions, including quantitative measurements of hardware performance and informal feedback gathered through a user study.

ISS 2016, November 06–09, 2016, Niagara Falls, ON, Canada
© 2016 ACM. ISBN 978-1-4503-4248-3/16/11...$15.00
DOI: http://dx.doi.org/10.1145/2992154.2992188

The paper's main contributions can be summarized as below:

- Introduces the concept and design of AnyLight, a programmable lighting system for architectural environments based on the principle of integral illumination
- Identifies the key technical challenges the aforementioned concept entails, and delineates strategies to solve them
- Explores the design space of AnyLight, illustrating through examples how the system may be optimized or extended to suit different applications and use cases
- Presents evaluation results that verify the soundness of the AnyLight concept, which should assist future efforts to design similar or derivative systems

RELATED WORK

Stereoscopic Displays

Integral imaging, first described by Lippmann [17] in 1908, is a technique to record and reproduce 4D plenoptic light fields using a planar array of tiny convex lenses. In the final decades of the 20th century, the technique had been revived to realize stereoscopic/multiscopic 3D displays, and a range of new developments has been spurred [37] as a result. Notable examples include the use of slanted 1D lenticulars to increase perceived spatial resolution [4], achieving actual high resolution using a projector array instead of an LCD [18], expanding the viewing angle using an extra, passive optical screen [8], and realizing variable-focus integral imaging using liquid lenses [29]. Recently, 3D printable optics [36] has begun to be used for integral imaging as well [27]. Active development is also taking place regarding the development of light field cameras (i.e., the use of integral imaging to capture 3D content), where lenticular sheets are placed on top of photosensors instead of displays [19, 35].

Besides integral imaging, a number of other techniques to implement stereoscopic displays exist, for example parallax barriers [20], holography [23], polarized glasses [12], volumetric displays [11], and time-multiplexed LCD stacks [32] (a comprehensive overview of existing 3D display technologies can be found in [16]).

Programmable Lighting

The notion of realizing "programmable" lighting using digital technology is an old one—a recurring idea (that has routinely been featured in concept images/videos meant to demonstrate the potential of Ubiquitous Computing) is to use projectors as reconfigurable illumination appliances [15, 21, 30]. However, limitations such as the fixed (and often narrow) projection angle, low spatial resolution, etc. makes their use as ambient illumination devices still rather impractical. On the other hand, simpler, more economic programmable lighting devices such as color-changing LED bulbs [1, 24] have been gaining popularity as part of a *smart home* [7] setup. Smart lighting is also finding usages other than illumination per se, for example visible light communication [13].

We do not claim that AnyLight is the world's first system that appropriates integral imaging for programmable illumination; a number of precedents do exist in this area [5, 14, 38]. However, instead of targeting architectural or ambient illumination as we do with AnyLight, in prior efforts only relatively small objects positioned inside a limited, predefined area are illuminated. This is an important distinction; whereas in prior work on integral illumination, only light rays that hit the target objects (more precisely, only light rays that enter the predefined area containing the target objects) need to be controlled, AnyLight needs to have command over *all* rays that emanate from its surface. This presents a unique challenge to the hardware design; we will revisit this fact later in the paper when we discuss the issue of "ghosting" and our tactics to counter it.

Robotic/Responsive Architecture

Within the spatial design professions (e.g., architecture, stage design, interior design, installation art, etc.) lighting has long been considered a key factor that influences the quality of architectural space, and one can find numerous instances where innovative lighting has been used to create distinct spatial experiences [2]. Such regard for the power of lighting is corroborated by environmental psychology literature [3]; lighting is known to have wide-ranging, and often subconscious, effects on our behaviors, thoughts, emotions, etc.

In light of such facts, a building furnished with architectural-scale programmable lighting may well be viewed as a type of *robotic, or responsive architecture* [22]—a class of architectural structures and environments that dynamically alter their shapes and/or appearances using sensors, displays, kinetic actuators, etc. In our previous work [26], we positioned robotic/responsive architecture as one of the key technical approaches that may lead to a world built of *habitable bits*, where the built environment itself becomes infused with the "distinctive plasticity and interactivity of digital bits"—the classic, Weiserian [31] vision of *overlaying* myriad computers on top of the environment is replaced by an inseparable integration of digital technology and the physical environment.

Though we expect AnyLight to be a versatile technology that can provide benefit in a wide range of applications, costs will likely be prohibitive at first for individual, domestic uses, and initially the most practical application domain for the technology may be *media facades* [10, 33]—large-scale LED/LCD displays installed as part of building exteriors, found in commercial city centers all over the world such as Times Square in New York. AnyLight may be used to build more expressive successors to such displays.

HARDWARE

Figure 2 shows the basic hardware configuration of AnyLight. As can be seen, the overall architecture is roughly identical to that of a conventional integral imaging 3D display, employing a combination of an LED backlight, an LCD panel and a lenticular sheet, assembled linearly. Again, as with conventional integral imaging setups, the backlight and the LCD panel can be swapped with other forms of spatially modulated lighting, such as a projector, LED/OLED display, etc. LCD panels are notoriously inefficient (a typical color LCD can only transmit less than 10% of incoming light), and thus our use of an LCD may seem to be a questionable choice, especially considering

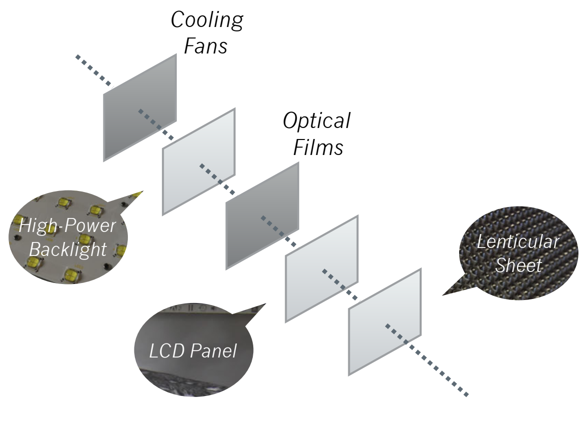

Figure 2. AnyLight hardware configuration.

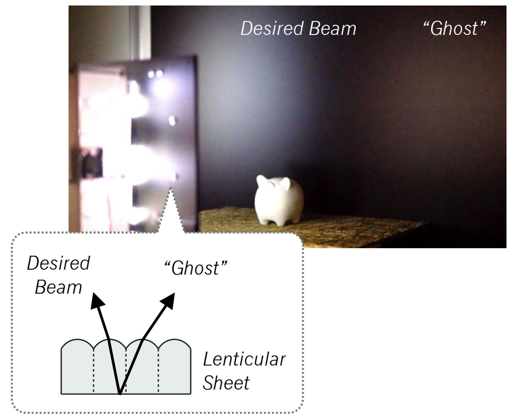

Figure 3. Cross-talk between lenslets, and the resulting ghost.

the decreasing costs of LED matrix displays. However, if we set aside the issue of energy use, no other technology can currently offer the combination of high pixel density, high brightness, low cost, and compact form factor. As we are still in the early prototyping stage, we deemed energy usage to not be as important as the quality of user experience; LCDs are the best option we have now to simulate what LED/OLED-based implementations may be able to provide in the near- to mid-term future, assuming continuous technical advances.

Although the general architecture is similar, several important differences set AnyLight apart from existing integral imaging displays. For example, the power output of the LED backlight is much higher (with an upper limit of 271,200 lumens in our brightest setup), and the printed lenticular sheet sports a custom design that mixes clear and opaque elements. In order to manage the considerable heat generated by the LEDs, we rely on both passive and active cooling technologies, including a set of two powerful fans (24V/2.3A) installed on the back of the device. When assembled, the entire setup measures 43.4 $\times$ 16.5 $\times$ 26.8cm. (We built several versions of the prototype, each with a slightly different form factor; the above measurements were taken from our main setup, which we used in all of our evaluations.)

An idealized, "true" integral imaging display can simulate the presence of any 3D object/environment positioned beneath its surface. Similarly, AnyLight can simulate any light source(s) positioned beneath the LCD panel, albeit within practical limitations regarding physical size, power output, spatial/angular resolutions, field of view, etc.

Busting "Ghosts"

Bluntly speaking, it is not a mistake to describe the AnyLight hardware as merely an integral imaging display with a significantly more powerful backlight. However, naively increasing the power output of an integral imaging display produces unwelcome optical effects, which we refer to as *ghosts*.

Ghosts are a result of *cross-talk* between neighboring lenslets on a lenticular sheet. Figure 3 illustrates how such cross-talks arise; here, the right-side LCD pixels underneath each lenslet are illuminated, which should result in a narrow beam of light emanating leftward from each lenslet. However, as light from the illuminated LCD pixels can also travel rightward into the neighboring lenslet, another, somewhat weaker beam of light emanates from each lenslet as well—thereby creating a *ghost*. The top photo in Figure 3 shows AnyLight shooting out a leftward, circular spotlight (realized by only turning on the rightmost pixels beneath lenslets located in the central area of the AnyLight LCD), with a ghost clearly visible to the right. Note that even with the same hardware configuration, whether and how strongly ghosts appear will differ based on the illumination effect produced by AnyLight, which in turn is decided by the 2D pixel pattern shown on the underlying LCD. As a general rule, ghosts are weakest (usually nonexistent) when only pixels under the central region of each lenslet are illuminated (so light is emitted roughly perpendicular to the LCD screen) and become strongest when pixels near the perimeter of each lenslet are illuminated. Another fact worth mentioning is that ghost rays always emanate outside the lenslet's angle of view.

This phenomenon of ghosting is not unique to AnyLight, but is shared among integral imaging systems in general—the *repeating* of content on lenticular postcards (often sold as souvenirs at tourist destinations) is caused by the same cross-talk, for example. Nevertheless, the issue is of much higher importance for AnyLight, than it is for other systems. As illustrated in Figure 4, stereoscopic displays have predefined *viewing areas* from which viewers see the display, and conventional integral illumination systems have predefined *projection areas* in which objects to be illuminated are placed. Light that does

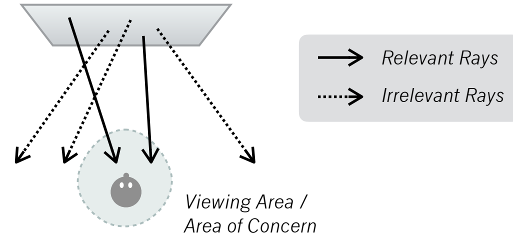

Figure 4. In conventional integral imaging setups, only rays that enter "areas of concerns" need to be controlled.

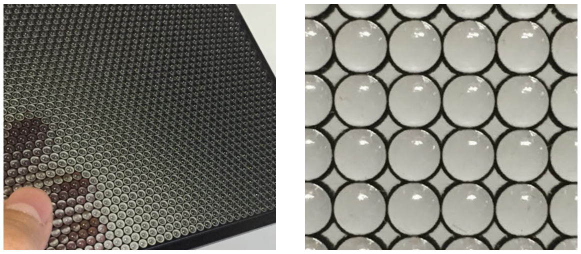

Figure 5. Hybrid lenticular design with clear and opaque elements.

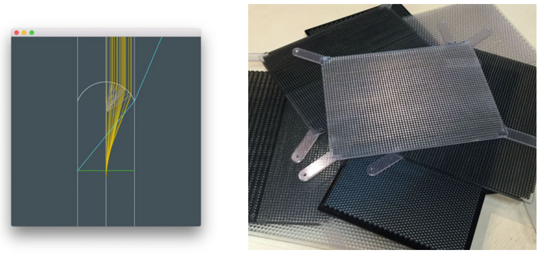

Figure 6. Optimization software and resulting lenticular designs.

not enter these *areas of concerns* is considered irrelevant and thus does not need to be controlled (note that "ghost" rays always fall into this category, as areas of concerns are naturally designed to exist within the lenslets' angle of view). Ambient illumination systems like AnyLight do not have this luxury as we cannot define any specific areas of concern, and hence *all* rays coming out of the device are relevant; they either need to be controlled, or in cases where that is not possible they need to be at least suppressed.

In order to reduce ghosting as much as possible, in our implementations we employ the following two techniques:

Hybrid Lenticulars

There are several variations to lenticular sheets used for integral imaging; a 1D array of narrow, cylindrical lenses may be used where content only needs to change along a single axis, or a 2D array of circular lenses (e.g., fly-eye lens) can be used if it needs to change along both the x and y axes. In any case, the lenticular sheets are wholly made out of transparent, optical grade glass or plastic. However, as we have seen in Figure 3, within lenticular sheets entirely made out of clear materials there is no mechanism to curb the cross-talk between lenslets, and consequently the creation of ghosts.

For AnyLight, we take advantage of 3D printing to design and fabricate custom lenticulars with opaque "walls" built around each lenslet, in effect optically isolating the lenslets from each other (Figure 5). The sheets are printed using a Stratasys Connex 3D printer, with clear parts made of VeroClear (refractive index = 1.47) and opaque parts made of VeroBlackPlus. The opaque, black walls absorb incoming light, and hence prevent inter-lenslet transmission of light rays. (3D printed lenticulars with similar designs have been described in [28], although not for illumination purposes).

The LCD panel in our prototype was sourced by taking apart an Asus MB168+ 15-inch external display, with a screen resolution of 1920 × 1080px and a pixel pitch of 0.179mm. We designed each lenslet to have a diameter exactly 20 times the pixel pitch (3.58mm), and made variations of the sheets with two different wall thicknesses (0.179mm and 0.358mm). We also tested using a grayscale LCD (Totoku MS25i2) in one of our alternative implementations; in this case the system loses the ability to adjust the color of light rays, but the light output will be significantly higher due to the lack of color filters. (In a typical color LCD, the color filters alone shut out two thirds of the incoming light).

In designing lenslets we followed an approach similar to that described in [27], and wrote a custom numerical optimization program that employs a Monte Carlo method to minimize focusing errors among rays passing through different points on the lens surface. The program supports designs of both spherical and aspherical lenses, and we have made a series of custom lenticulars, as shown in Figure 6. We will report the comparative performances of these lenses later in the paper.

Narrow-Beam Backlight

Unfortunately, even if the opaque walls succeed in absorbing 100% (i.e., no reflection) of inter-lenslet rays we will still see some level of ghosting, as light rays can traverse freely within the thin, clear layer of glass protecting the LCD panel (Figure 7). Taking off this glass layer, or embedding walls inside this layer may perhaps be possible but is impractical and thus we rely on a different approach, that is to modify the backlight to limit the angle with which light rays are emitted.

Figure 8 shows our backlight. We use a total of 240 Lumiled LUXEON M high power LEDs, which can be switched on/off in batches of 8 to enable local dimming (which contributes to more efficient energy use, and also higher contrast). Covering the LEDs are several layers of optical sheets—diffuser, prism sheets (one each for x and y directions), and 3M DBEF (Dual Brightness Enhancement Film), respectively—a routine configuration found in many off-the-shelf LCDs. We handpicked the sheets from a group of alternatives to find the combination that produces the narrowest beam possible; however in reality we found little variance in performance among the options (it appears that products on the market are already optimized for LCDs, and are manufactured to similar specifications). Thus we were unable to limit beam angles to our desired levels with optical sheets alone (we will report performance details later in the evaluations section).

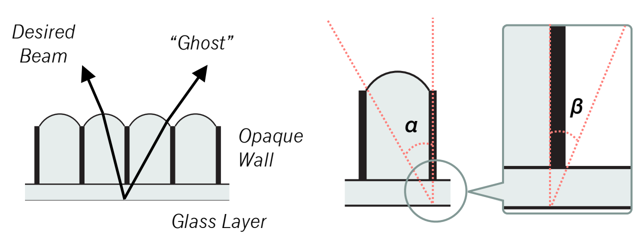

Figure 7. Cross-talk arising from glass protection layer.

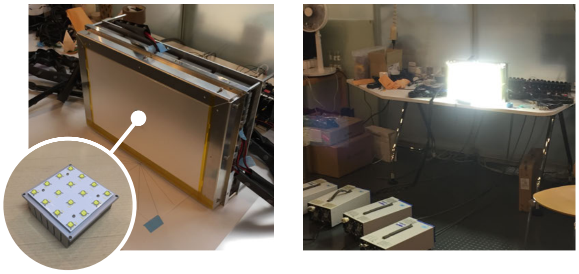

Figure 8. LED backlight.

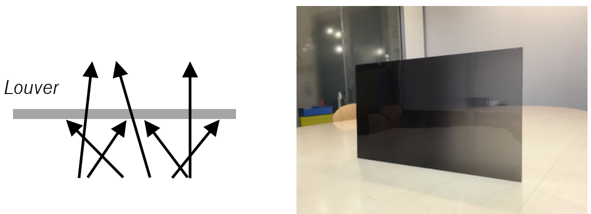

Figure 9. Limiting beam angle with louver film.

A number of optical arrangements exist that can further limit the beam angle. However, to maintain the compact form factor and the low cost of the prototype, we chose to simply add an extra sheet of *louver film* in front of the DBEF sheet. Commonly marketed as privacy filters for PC/smartphone screens, louver films absorb all light entering at angles greater than its *cutoff* value (Figure 9). Although this approach has the virtue of easy installation, owing to its reliance on absorption louver films are inevitably less energy efficient than refraction-based or reflection-based optical arrangements (e.g., using collimators). Exactly how much we should limit the beam angle is a design decision that depends multiple factors, but the louver's cutoff angle should be somewhere between α and β in Figure 7; choosing a value close to β will produce less ghosting but reduce overall light output, whereas a value close to α has the opposite effect. Any value outside this range will either lead to a needless increase in ghosting ($> \alpha$), or a similarly needless reduction of light output ($< \beta$). For our implementations, we used a 3M louver film with a cutoff of ± 30 degrees.

Our current implementation relies on an LCD, but as we mentioned earlier we expect them to be eventually replaced by superior technologies, e.g., LED matrix displays. Many of such technologies will negate the need of a backlight, but the issue of ghosting and requirement for limiting beam angles will still persist; thus experimental results obtained through our prototype will still be relevant to such future designs.

SOFTWARE

Figure 10 illustrates the relation between on/off states of LCD pixels and the emitted light ray. Here, the vector (x, y, z) can be computed using the following equations, in which n_{air} and n_{lens} denote the respective refractive indices of air (1.00029) and the lens material (1.47), and h represents lens height. The

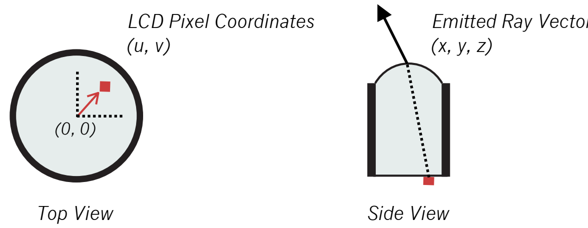

Figure 10. Relation between LCD pixel position and emitted light ray.

color of the ray will mirror that of the LCD pixel. Computing the inverse, i.e., determining which pixel needs to be lit up to produce the desired light ray, is equally straightforward.

$$x = \frac{-u}{\sqrt{u^2 + v^2}} \cdot w \tag{1}$$

$$y = \frac{-v}{\sqrt{u^2 + v^2}} \cdot w \tag{2}$$

$$z = \sqrt{1 - w^2} \tag{3}$$

Where:

$$w = \frac{\sqrt{u^2 + v^2}}{\sqrt{h^2 + u^2 + v^2}} \cdot \frac{n_{lens}}{n_{air}} \tag{4}$$

The AnyLight software continuously modulates the LCD pixels to obtain the desired light output, while shutting down the backlight locally for any region in which all pixels are black, i.e., $(R, G, B) = (0, 0, 0)$. (The hardware is capable of more sophisticated backlight dimming, but we currently use binary on/off for simplicity's sake.) Cooling fans are not controlled by the software—instead they are kept running whenever the system's main power is turned on.

User Interface

As we have just seen, running AnyLight is simply a matter of dynamically modulating LCD pixels, and writing the driving software can hence be a quite straightforward process. However, to make the system usable we will also need an easy-to-use user interface. Directly manipulating pixel values to control light rays is an incredibly complex task, difficult even for those with deep knowledge of lenticular optics and the intricate details of our prototype hardware. We need an interface that provides a proper level of abstraction, while retaining the system's distinctive high degree of freedom.

Figure 11 shows our user interface application. States of each LCD pixel are completely hidden from users, and instead they choose a light source from several alternatives (e.g., spotlight, spherical light) and adjust parameters such as position, number, orientation, color, etc. by clicking and dragging on a 3D rendering view showing models of light sources, emitted rays, and the device's surface panel. The application automatically modulates LCD pixels to simulate the virtual light sources on the screen as accurately as possible. One drawback of this interface is that, due to its reliance on real-world metaphors, the

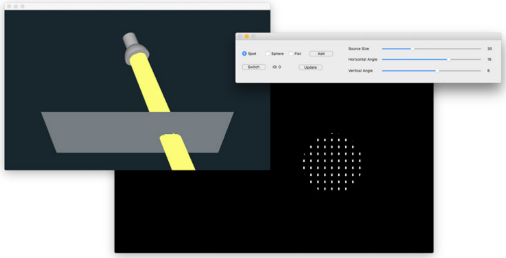

Figure 11. User interface application.

application is unable to produce purely imaginary lighting effects that cannot be synthesized using a combination of actual light sources. Although the application only supports manual controls at this stage, we are also interested in fully automatic lighting adjustment, e.g., making a spotlight continually track a person or an object.

APPLICATIONS

We expect AnyLight to have potential uses in a wide range of settings, some of which are listed below.

Home/Office Lighting The device may act as a more versatile lighting system for living/working environments, possibly assisting with relaxation, concentration, etc.

Media Facades The device may serve as a more interactive and dynamic alternative to existing media facades in urban centers, providing both commercial and aesthetic values

Stage Lighting The device may be used as a dynamically reconfigurable stage lighting, giving scenic designers higher degrees of artistic freedom

Photography The device could possibly serve as a substitute for existing lighting equipment in photography studios

Therapy The device may potentially be used in light therapy [6], for treating Seasonable Affective Disorders (SADs)

Not all of the above applications will become practical simultaneously. For example, commercial uses like media facades should become viable sooner than individual ones, and some applications will naturally be more demanding than others in terms of technical specifications (e.g., stage lighting will need higher power output compared to normal ambient lighting).

Theoretically, an integral illumination device can simulate the presence of arbitrary objects, including but not limited to light sources, situated within a virtual 3D space underneath the device's surface. Though there needs to be a series of improvements regarding spatial/angular resolutions, light output, etc., allowing ourselves to be a bit speculative, we can envision a future room with a large AnyLight device covering the entire ceiling—which can quickly switch from showing a simulated twilight sunbeam that can actually be blinding, to rendering a virtual Bohemian chandelier that actually looks breathtaking (perhaps a partial realization of Sutherland's *ultimate display* concept [25]). Note that since integral illumination is a variant of integral imaging, AnyLight can function as a display as well; users can look up to the ceiling and see realistically visualized light sources, not just their resulting effects. (Again, however, this is contingent on future technical advances—our current prototype's low spatial resolution makes for a terribly crude display at the moment).

The difference between integral illumination and the existing *projectors-as-illumination* ideas [30] may warrant a brief discussion. Roughly speaking, integral illumination can produce effects akin to a 2D grid of projectors, albeit with higher spatial resolution, lower angular resolution, and much lower cost of implementation. Light rays emitted from a single projector all originate from essentially the same point in space; consequently its capacity to produce variable directional lighting is severely limited. This is easy to understand if we consider its use in photography sessions; a task as simple as switching the direction of light cast onto the subject cannot be fulfilled with a single projector-based lighting.

Application-Specific Lenticular Design

An ideal integral illumination device would be universal—the same optical design would provide equally good performance in all situations and scenarios. However, real-world design of such devices involves a number of performance tradeoffs, and a universal optical design may well be one that only achieves mediocre performance for all situations.

By making use of the freedom of design offered by 3D printed lenses, we can customize the lenticular optics of AnyLight to provide better performances for specific uses, situations, and installment locations. Below we provide several examples to demonstrate this potential, along with photographs of custom lenticulars that we have actually fabricated (Figure 12). (Note that the experimental lens designs described here have not yet been tested, and we make no guarantee that they will perform as planned in practice.)

Wider/Narrower Angle of View

When considering indoor uses, an ideal lenslet for AnyLight will have an angle of view just wide enough to cover the entire area that needs to be illuminated; anything wider will amount to a waste of angular resolution (unless we are pursuing some artistic indirect lighting effects). For example, installing AnyLight overhead in a large room with a low ceiling would benefit from a wider angle of view, whereas one installed in a tiny room with a high ceiling would call for a narrower angle. For spherical lenslets, the general rule is that a large curvature radius widens the angle of view, while a smaller radius narrows it down—which will also make the lens taller, if optimized to minimize focus errors.

Directional Lenticulars

Not all installations of AnyLight call for light to be spread out equally in a radially symmetrical manner, 360 degrees around the device. For example, a ceiling light installed near a corner of a room may only need to emit light in the direction opposite to the walls, and an AnyLight media facade might not need to shoot out light upwards into the sky. In such situations, more efficient use of spatial resolution may be achieved by adding directionality to the lenslets—i.e., modifying their designs so that light from LCD pixels will only be refracted in directions that are necessary under the context of installation. We have

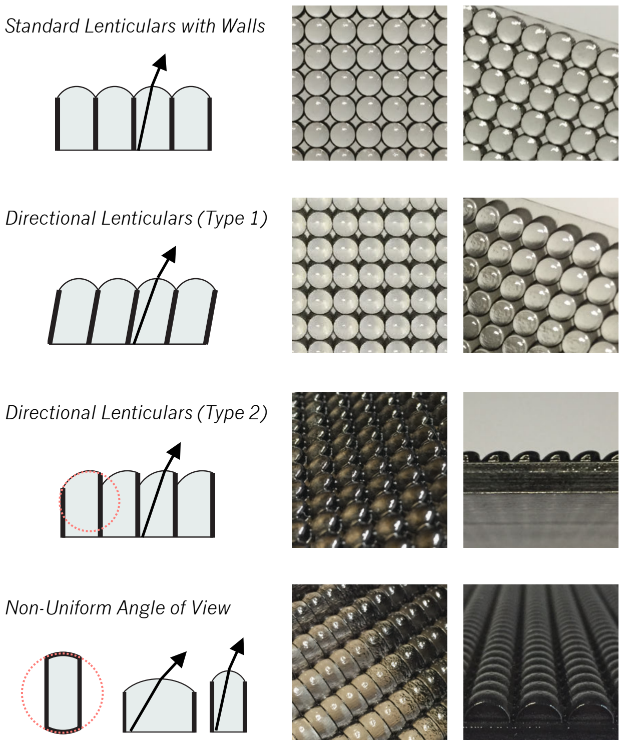

Figure 12. Application-specific lenticular sheets.

designed two alternative lenticulars that may fulfill this function: one where the cylindrical base of each lenslet is slanted diagonally, and another where each lenslet is actually a non-concentric cutout from a larger lenslet shape.

Non-Uniform Angles of View

We have already discussed how the angle of view of the lenslets may be adjusted to accommodate for differences in room geometries, but problems arise for rooms with with vastly different dimensions along the x and y axes—for example a long hallway. In such cases, it might make sense to design lenslets with different angles of view for each direction. We designed one lenticular sheet that may provide this function; the rectangular lenslet shape was derived by carving out a sliver from a larger, radially symmetrical lenslet.

Combining Different Lenslets

Lenslets laid out on a single lenticular sheet do not necessarily need to be uniform in design, and we can mix different lenslets to realize unique illumination effects, compensate for the weakness of each design, etc. For example, by using a combination of lenslets whose angles of view are slanted outward in different directions, we can give AnyLight a wider angular coverage than is possible with uniform lenslets.

EVALUATIONS

To test the validity of the AnyLight concept and our prototype design, we have performed the following two evaluations: 1) quantitative performance measurement of our prototype hardware, with a particular focus on assessing the effectiveness of our *anti-ghosting* measures, and 2) an informal, unstructured user study to gather qualitative feedback on the user interface and overall thoughts regarding the AnyLight concept.

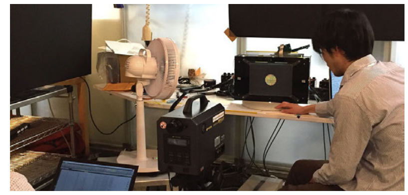

Figure 13. Measuring luminance values.

Hardware Performance Measurement

Using a setup as pictured in Figure 13, we measured the luminance values of light emitted from our AnyLight prototype at varying angles (-80° to 80°, at 5° intervals), under the 13 conditions outlined below.

1–5: Prototype simulates front-facing spotlight, using lenticular sheets ABCDE, respectively

6–9: Prototype simulates side-facing spotlight, using lenticular sheets ABCD, respectively

10, 11: Backlight only (no lenticular sheet), with and without louver film

12–14: Prototype simulates side-facing spotlight, with louver film, using lenticular sheets ABC, respectively

Here, lenticular sheets A through C all share the same spherical lenslet design, with a curvature radius of 1.933mm and a 64.17° angle of view. Lens A is wholly transparent (no walls), whereas Lens B and C contain opaque walls with thicknesses of 0.179mm and 0.358mm, respectively (i.e., 1× or 2× of the LCD's pixel pitch).

Sheet D has a slightly different, but still spherical lenslet design, taller than sheets A through C (6.153mm, as opposed to 4.859mm for ABC) and with a curvature radius of 2.227mm, 49.17° angle of view, and and walls of 0.179mm thickness.

Sheet E is our only sheet with aspherical lenslets, which theoretically should result in significantly lower focusing errors. The lenslets have a 64.18° angle of view and 0.179mm walls.

All lenslets have a diameter of 3.58mm, and are arranged in a rectilinear manner on the lenticular sheets. Distances between lenslets are identical for all sheets with no walls or 0.179mm walls (i.e., sheets ABDE), while sheet C has a wider gap between lenslets to make room for the thicker walls.

Figure 14 shows the performance measurement results.

The top five graphs show the results for conditions **1** through **5**. A clear, strong peak can be observed for all five conditions, demonstrating how our prototype can direct light in small angles, as per our design intentions. In the graph for condition **1** we can see two small peaks at wider angles (around ±50°), presumably caused by ghosting. These peaks are diminished in conditions **2** to **5**, which demonstrate how the opaque walls

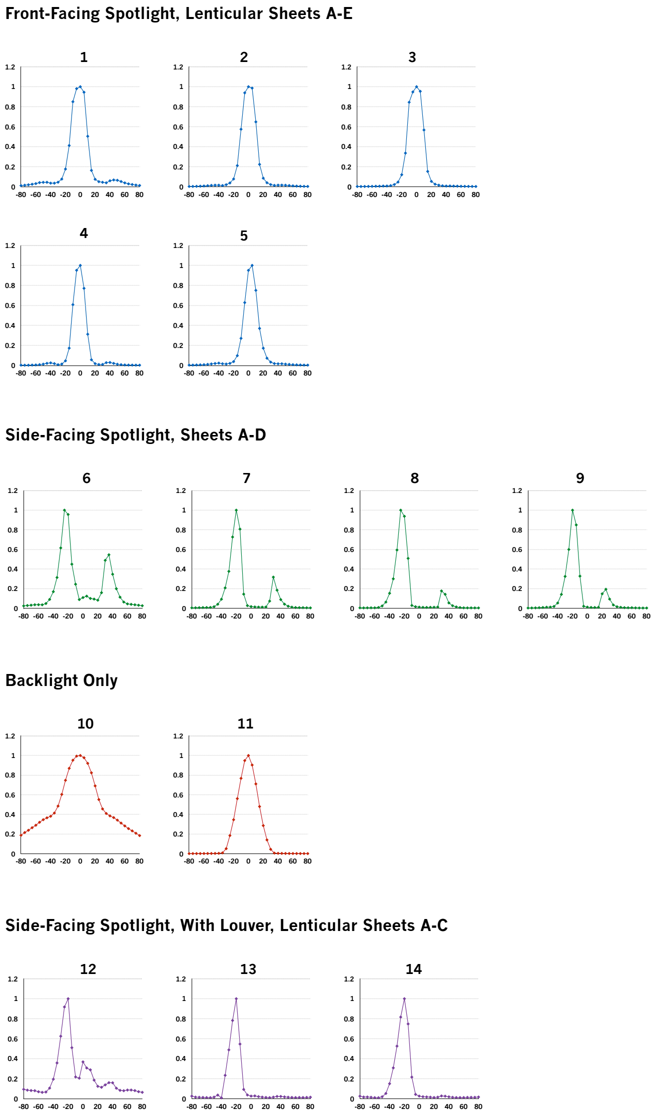

Figure 14. Performance measurement results. Horizontal axis denotes angle (in degrees), vertical axis denotes luminance value (standardized).

successfully suppress ghosting by cutting down on cross-talk between lenslets. Results for condition **5** (sheet E, aspherical lenslets) do not show any clear advantages over the other conditions; theoretically the low focusing errors of the aspherical design would lead to a narrower, clearer peak, but perhaps the limited accuracy of our 3D printer (30 microns) had hindered the lens from fulfilling its intended performance.

The next batch of four graphs shows the results for conditions **6** to **9**. With spotlights cast in a side-facing manner, these are the conditions most susceptible to the formation of ghosts. As expected, we can see significant *ghost peaks* in addition to the main peaks created by simulated spotlights. Comparing conditions **6**, **7**, and **8**, we can readily see how effective the walls are in suppresssing ghosts—unsurprisingly, thicker walls and wider gaps between lenslets yield even better suppression performance. Comparing the results for conditions **7** and **9**, we can see how taller lenslets lead to weaker ghosts, which again is in line with our understanding of how ghosts are formed.

The graph for condition **10** shows measurements taken using the backlight only; as can be seen, the backlight emits a moderately diffuse light in all directions. Comparing this with the graph for condition **11**, we can see how a simple addition of a louver film can give a strong directionality to the light. (Note that luminance values in the graphs are standardized; in absolute values, using the louver film has led to an approximately 30% drop in luminance at the 0° direction.)

The final batch of graphs shows the results for conditions **12** to **14**. We can see how ghosts can be all but eliminated using both a walled lenticular design and a louver film, although the sizable drop in luminance from the louver film holds true here as well.

Informal User Study

To collect some initial feedback about our user interface software and general reception towards the AnyLight concept, we gathered 8 subjects (6 male and 2 female, ages 20–30, median age 26) to conduct an informal user study. In terms of technical proficiency the subjects were sort of a mixed bag, including engineering students and self-proclaimed "luddites". The study did not have a clear structure; subjects were invited into a room one at a time (one or more of the authors stayed in the same room for the duration of each study), received a brief introduction to AnyLight, and were asked to freely interact with the prototype through our user interface application. Subjects were instructed to provide feedback anytime during the study through speech (we took notes of all conversations), and also immediately after the study through a written report. The duration of the study was 20 to 30 minutes per subject. We will discuss some of our findings below.

On the User Interface

Overall, reactions to our interface were mixed. While none of the subjects gave truly negative feedback toward our software per se, many explicitly questioned our decision to use a desktop app as a controller; three of the subjects suggested the use of levers, joysticks or other physical interfaces, one suggested a large touchscreen, and two others suggested an augmented reality interface and mid-air gesture control, respectively. The strong preference for *Natural User Interfaces (NUIs)* [34] and the spontaneous ways in which it was raised by subjects came as a surprise to us—it appeared to us that the subjects saw the desktop app as an awkward filter preventing them from more directly engaging with the immediate, physical functionality offered by AnyLight. However, it must be noted that subjects were wildly diverse with regards to the exact type of *natural* interface they think would be suited for AnyLight, suggesting the need for several iterations of trial and error before we can settle on a single design approach.

If we set aside the skepticism regarding our choice of a desktop application platform, subjects were overall positive about the ease of use of the software itself, though we received several complaints regarding the perceived lack of freedom with which lighting effects can be designed. (Our application does not allow users to design freeform light sources from scratch;

they can only pick a source type from a predefined list of options and then adjust its parameters).

On the Overall Concept

Subjects' responses toward the overall concept were positive, with numerous suggestions about its potential uses in theater, theme parks, nightclubs / concert halls, high-end retail stores, etc. Interestingly, only one of the subjects spontaneously gave home/offices as a suitable setting for the device, and generally subjects seemed to view AnyLight as a device to create *spectacle*, rather than something that can subtly enhance everyday life as per our original intent.

While we doubtlessly take these results seriously, there is one factor that we believe, in hindsight, may have influenced subjects' views on this topic. During the test, when subjects were first presented with the user interface app, the default screen always showed a single spotlight emitting a brightly-colored beam; subjects were first instructed to try to move around and change parameters of this spotlight, before switching to other types of light sources. This first encounter may have colored subjects' opinions, and perhaps we would have received different responses had we begun with a different light source as the starting point.

DISCUSSION

Evaluation results show that our prototype generally works as well as we had expected. However, the prototype is too small to qualify as an architectural illumination device, and thus we have yet to gain good insights regarding the true user experience of AnyLight. To make the most out of AnyLight's ability to freely control not only the color/intensity but also the directions of light rays, the device needs to be fairly large relative to the illuminated objects. Thus our prototype can render various eye-catching effects when illuminating reasonably small objects, but when used as a ceiling light in a real architectural environment its expressive power becomes reduced to such a degree that the effects are no more striking compared to what can be done using a common LCD/DLP projector.

We will need to create a larger prototype—preferably around 2m $\times$ 2m large—before we can conduct more detailed studies and make accurate assessments of AnyLight's potential as an ambient illumination device.

Figure 15 shows some examples of lighting effects produced by AnyLight, and also several of the different hardware setups we have implemented so far.

CONCLUSION AND FUTURE WORK

In this paper we have introduced AnyLight, a novel illumination device that uses the principle of integral imaging to offer highly programmable ambient illumination in varied environmental settings. We described the overall design of the system and our current LCD-based implementation, proposed several measures to tackle the issue of "ghosting", and illustrated potential use cases for the system and how the technology may be extended to suit different scenarios and objectives. Evaluation results demonstrate that our prototype works as intended, and also verifies the effectiveness of our anti-ghost tactics. In

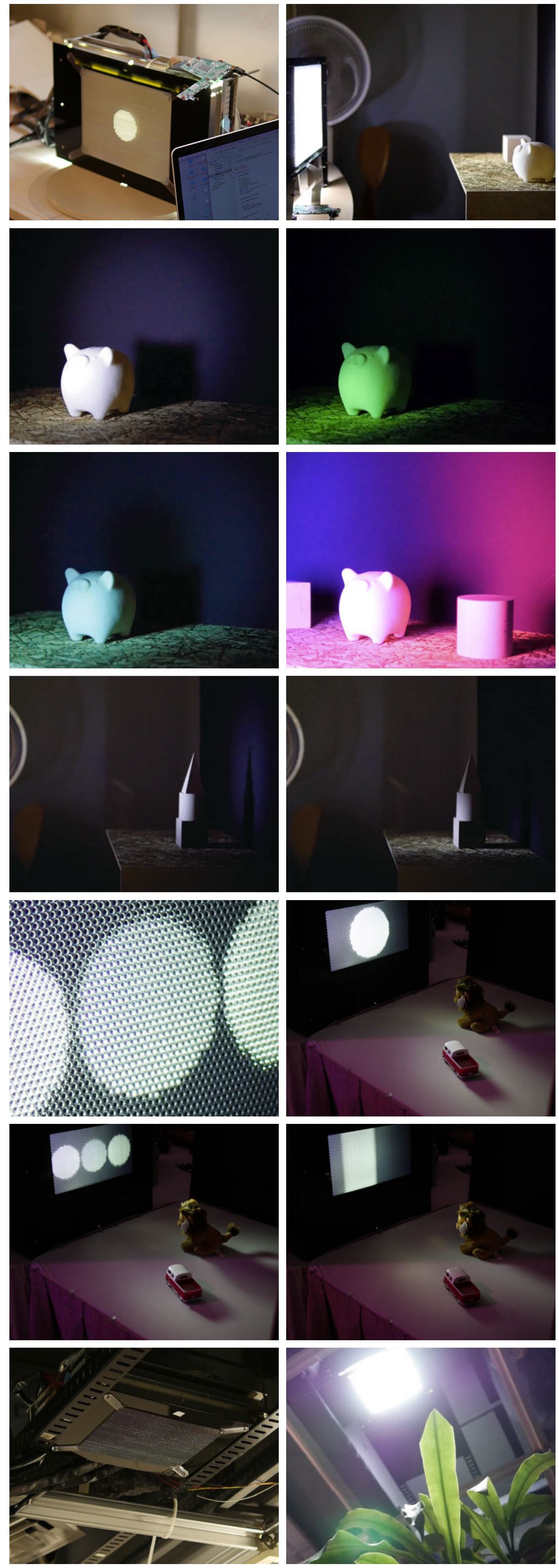

Figure 15. Photographs of AnyLight prototypes and lighting effects.

the user study, subjects were generally supportive of the overall concept of AnyLight, and offered helpful feedback regarding the design of the user interface.

One serious flaw with our current, LCD-based prototype is its energy inefficiency; solving this issue is critical if we wish to bring this technology to the market. We are currently working on a specialized backlight design that would allow it to focus light rays into a narrow beam without the use of a louver, and also discussing with manufacturers of LED displays to investigate the possibility of abandoning LCDs altogether.

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