UbiChromics: Enabling Ubiquitously Deployable Interactive Displays with Photochromic Paint

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Pervasive and interactive displays promise to present our digital content seamlessly throughout our environment. However, traditional display technologies do not scale to room-wide applications due to high per-unit-area costs and the need for constant wired power and data infrastructure. This research proposes the use of photochromic paint as a display medium. Applying the paint to any surface or object creates ultra-low-cost displays, which can change color when exposed to specific wavelengths of light. We develop new paint formulations that enable wide area application of photochromic material. Along with a specially modified wide-area laser projector and depth camera that can draw custom images and create on-demand, room-wide user interfaces on photochromic enabled surfaces. System parameters such as light intensity, material activation time, and user readability are examined to optimize the display. Results show that images and user interfaces can last up to 16 minutes and can be updated indefinitely. Finally, usage scenarios such as displaying static and dynamic images, ephemeral notifications, and the creation of on-demand interfaces, such as light switches and music controllers, are demonstrated and explored. Ultimately, the UbiChromics system demonstrates the possibility of extending digital content to all painted surfaces.

CCS Concepts: • **Human-centered computing** → **Ubiquitous and mobile devices**; **Interaction devices**; *Touch screens*; *Displays and imagers*.

Additional Key Words and Phrases: ubiquitous displays, photochromic, interactive display, fabrication, smart environments/connected home, ambient devices/internet of things, prototyping/implementation

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1 INTRODUCTION

Pervasive and ubiquitous displays promise to extend the user interface beyond the physical boundaries of our favorite devices, and into the world around us, allowing for physically larger display surfaces and interactions with digital content. When deployed as a part of an environment's furnishings (i.e. walls, ceilings, floors, and tabletops), ubiquitous displays empower users with invaluable contextual associations with spaces and functions, while offering immediate personalization.

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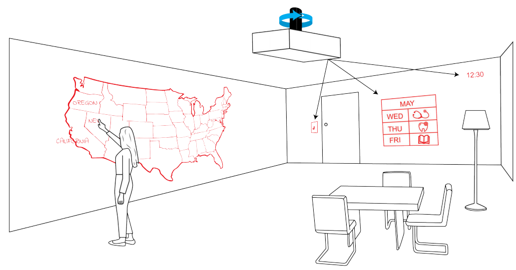

Fig. 1. A conceptual model of a laser projector connected to a servo motor changes the color of the paint on the walls, leaving behind images of various content, on multiple walls. A user can interact with this content, and add to it with an LED equipped pen.

Many research efforts have demonstrated compelling use cases of ubiquitous displays using conventional technology in the form of large-format television screens [9, 28, 42], video projectors [18, 24, 53], and distributed displays [39, 43, 58]. However, these innovative ideas have not seen widespread adoption due to their relatively high cost, cumbersome deployment methods, and need for wired power and data infrastructure. Furthermore, conventional display technologies (e.g., LCD, DLP, Plasma, OLED, etc.) are unlikely to scale to room wide deployment. Since the electronics industry is focused on developing screens with higher pixel density and better image quality, the absolute screen size of an individual unit has begun to plateau due to market forces.

To address these cost and deployability issues, we draw inspiration from the material science community that has explored a wide range of dyes, pigments, and paints that change their physical and optical properties, such as color, based on external stimulation. For instance, thermochromic dyes were used for Hypercolor branded T-shirts [48], which would change color based on body heat. Likewise, there is a large variety of materials that change color based on vibration, light, acidity, and chemical reactions [7]. Additionally, when it comes to the HCI community, retrofitting large surface areas via paint has proven to be an effective means of deploying interactive systems [59, 60]. Therefore, considering that paints are ubiquitously used to coat our living spaces, furniture, clothing, and devices, it is not hard to imagine a world where all surfaces can be augmented and enhanced into color-changing displays.

However, significant challenges must be overcome to take a color-changing material and turn it into a functional display. For instance, the color-changing material needs to be actuated to cause a state change. In the case of electrochromic material, which changes its color when exposed to an electric potential, a layered matrix of row and column drivers must be constructed to create a localized and controllable electric field to actuate a ‘pixel’ of electrochromic material [22]. The need for extra elements and active layers in order to drive and digitally control the color changing material highlights important factors related to cost, scalability, and ease of deployment. This leads to the realization that by physically disconnecting the *medium*, that changes its state, from the *actuator*, that causes the state change, it is possible to dramatically reduce the complexity of constructing ubiquitously deployable, color changing displays.

In this work, we introduce UbiChromics, a system using photochromic material, which is normally white and changes color when exposed to specific wavelengths of light. This color changing *medium* can be easily painted on nearly any surface such as walls, ceilings, floors, tables, etc. at a cost as low as \$0.07/m^2. In order to activate the paint, we developed a long-range *actuator* in the form of a vector laser projector for room-wide coverage. Combined with a custom designed scheduler and Graphical User Interface (GUI), the UbiChromics system can display and continuously refresh multiple custom images, messages, and interactive interfaces on walls and surfaces.

An example of the UbiChromics concept is depicted in Figure 1. Here, the walls of the room have been painted with the low-cost photochromic material, and a specially designed vector laser projector, with a stepper motor swivel, has been mounted to the ceiling. When the laser projector shines the specific wavelength of light needed to activate the photochromic paint, semi-permanent images are drawn onto the wall that last up to 16 minutes. Using the stepper motor, the laser projector can move its effective work area to another section of wall, thereby allowing images to be deposited anywhere in the room, creating a large area display surface. The UbiChromics system can then display and refresh static content, such as pictures, and dynamic images, such as clocks, notifications, and calendars. In order to make the system interactive, a depth camera, co-located with the laser projector, is used to capture user input. The user can then define the location of interactive elements, such as light switches, music players, and environmental controls.

This paper introduces a system for creating low cost ubiquitous displays that can be painted onto nearly any surface, along with a number of novel interaction devices that can be used to make on-demand interfaces and display images. We make the following contributions:

(1) A scalable system for creating large area interactive displays using photochromic paint
(2) A photochromic paint formulation that allows for easy preparation and application
(3) A projected display system that is persistent and does not suffer from transient occlusions
(4) Demonstrations showing interaction modalities and application scenarios that highlight the unique characteristics of the UbiChromics system

2 RELATED WORK

UbiChromics builds upon a rich body of prior work in three distinct areas within Human-Computer Interaction (HCI) literature: ubiquitous displays, including pervasive and passive interfaces; photochromic materials for interaction; and interactive surface-based systems. We now detail prior works from each area and contextualize UbiChromics' contribution relative to those works.

2.1 Ubiquitous Displays

Ubiquitous displays improve the breadth of information available to the user without requiring their direct attention or creating an unnecessary distraction. For example, a simple wall clock exemplifies many of the qualities of calm technology as described by Weiser & Brown [46]: it resides mainly in our periphery, does not overburden the user with information, and relays a sense of familiarity and awareness. Incorporating calm technology principles, works have explored various ways of using visual and physical systems to embed data representations [49].

Within ambient awareness systems, there are tactile works, such as Tangible Bits [16], Nimio [4], and CubeLendar [26], which allow users to interact with physical widgets that provide peripheral awareness and group interactions. Closer to UbiChromics are surface-based displays, which "hide" in the environment and only leave the periphery when activated, promptly returning when deactivated [45]. Some works use aesthetics as displays, such as the Information Percolator [14], and Pixie Dust [27], which use air bubbles in water tubes and acoustically controlled particles, respectively, to encode information and provide an interactive display. Similarly, Water Lamp and Pinwheels [5], uses solenoids to tap on water, and pinwheels connected to DC motors. Furthermore, not all displays are contained within 2-D Cartesian systems: the SandWriter robot [8] draws large scale text and moderate resolution graphics onto beach sand. Commercial works, such as FogScreen [32]'s mist system, use thermally activated methods to create on-demand, portable display systems.

UbiChromics draws upon these works and is able to display passive content (such as static text and art), dynamic content (such as wall clocks and calendars), and interactive interfaces (such as light switches and music players). Similar to previous work, these interfaces and displays can be deployed on demand to surfaces and walls coated in our specially design paint and then recede into the background when the longer needed or can be refreshed indefinitely.

2.2 Photochromic Materials

There are numerous color-changing materials, including thermochromic materials, which change color when exposed to specific temperatures. Chromoskin uses color change for cosmetic applications [20], Liu et al. explore paper-like thermochromic displays [23], Electronic Origami changes the colors of 3D objects [19], and Yamada et al., explore using an infrared LED array to actively control thermochromic displays [55]. However, these approaches require a individual heating element to activate each 'pixel' of thermalchromic material, thus suffering from the same scalability issues that traditional displays. UbiChromics overcomes the scalability issue by separating the *actuator* from the *medium*, thereby allowing for a single projector to cover an entire living space.

UbiChromics utilizes a photochromic approach, where the material changes color through absorption of optical electromagnetic radiation [40]. One of the most commercially successful photochromic applications is color-changing lenses for sunglasses, which are clear indoors, but darken in the presence of UV light from the sun [40]. Photochromic materials have also been used in novelty applications, such as toys [56] and cosmetics [38]. Recently, there has been significant interest within the HCI community to leverage photochromic materials to convey information and facilitate interaction. Early work within the HCI community explored artistic and environmental applications of photochromic pigments, such as on canvas [10], in writing [13], controlling color-forming pixels in sculpture [11], and creating sunlight-responsive floors [12]. More recent emerging technologies include Photochromic Carpet [37], Slow Display and Shader Printer [35, 36], ColorMod [31], and Photo-Chromeleon [17], which use photochromic material to recolor 3D printed objects, as well as ChromoUpdate [47], which changes individual pixels from one color to another.

The majority of these prior works focus on statically changing the color of small objects, often using long-term photochromic material which requires UV lasers or high intensity UV lamps for activation. In contrast, UbiChromics focuses on room scale applications utilizing a single eye safe laser projector to draw content and interfaces throughout a users living spaces. Additionally, prior approaches largely consist of a single-step interaction (i.e., the user does *something*, the color *changes*, and the interaction *stops*). To some degree, this limitation comes from using solely long-lasting photochromic materials, which can take hours or days to revert. UbiChromics leverages the ephemerality of short-lasting photochromic materials to facilitate multi-step interactions, such as creating an on-demand music interface, pressing the 'play' button to start a song, then drawing and pressing a 'next' button to skip it.

2.3 Surface-Based Interactions

Surface-based interactions have a long, rich history within HCI literature [44]. Many approaches augment the surface using projectors to render widgets and displays [3, 33, 52]. Systems such as WorldKit [53], DIRECT [54], FlowPut [34], and Beamatron [50] add interactivity by using depth cameras for gesture input. In short, these systems do not physically alter the surface but, as a result, rely on hardware in the environment to provide both display and sensing.

Another approach modifies the surface physically by taking advantage of light-routing effects [15, 25, 29, 51], embedding the surface with pressure sensors [1, 6, 21], applying a coating of paint to enable direct interaction and input [59, 60], or embedding the surface with a heat-generating circuit [41]. These systems physically modify the interactive surface; yet, without creating a display mechanism, they require an external display, such as an LCD panel or projector.

Our approach combines elements of both methods, modifying the surface with a photochromic coating to 'hold' the display on the surface and a projectors and camera for rendering and sensing. This allows for flexible mixed-modal interactions, where any combination of sensing and rendering devices can be used. Additionally, programmatic and direct manipulation of the display (such as with a hand-held light source) can be performed simultaneously.

3 PHOTOCHROMIC MEDIUM

The goal of this section is to evaluate several photochromic materials and binders to determine the best recipe for creating a color changing paint suitable for implementing large scale passive and interactive displays. We begin with background information on the different types of photochromic material used in this paper and specifics of their color changing properties. This is followed by material mixing and testing procedures, and discussion of the spectral absorption properties of the materials and measurements of light activation and deactivation. These findings are used to select the optimal combination of photochromic materials and binders that are used to create the UbiChromics paint. Finally a step-by-step recipes of the paints used throughout the remainder of this paper are described.

3.1 Background on Photochromic Material

Photochromic materials' reversible color change is due to a photochemical reaction which occurs when the material is exposed to near-ultraviolet-light (blue-violet) and ultraviolet light. These wavelengths change the shape of the photochromic material's chemical structure, and thus the color. The specific wavelength used for these reactions is dependent on the specific photochromic molecule. In the raw state, the photochromic material is a powder with an off-white color. When dissolved in a clear solvent, the stable-state solution remains off-white, and exhibits color after exposure to near-ultra-violet or ultra-violet light. For simplicity and clarity, we will refer to the white-to-color transition as "activation", and the "color-to-white" transition as deactivation.

Photochromic materials are generally split into two categories, t-type and p-type. T-type is a photochromic material with a temporary color change, which is activated by a specific wavelength of light and the color changes back to white after a short amount of time. P-type is a semi-permanent, bi-stable, material which is activated by a specific wavelength of light and changes back to white when exposed to broad spectrum visible light (white light). The higher the intensity of the white light, the faster the P-type material changes back to white. When used in indoor environments, under typical lighting conditions, p-type lasts longer than t-type. In this work, we explore the feasibility of two t-type materials and two p-type materials, in Table 1, and refer to the t-type material as short-term photochromic material, and p-type as long-term photochromic material.

3.2 Material Testing

The ultimate goal is to use color changing materials as a *medium* for displaying images. Short-term and long-term materials are sold in powder or concentrated paste forms, and thus need to be dissolved in a binder to create a paint. One of the challenges is to determine the best combination of photochromic material and binder that results in a cost-effective, color-changing paint that is easy and safe to create, and can be effectively applied to various surfaces.

Fortunately, the short-term materials (Garnet Red and Red Slurry) changed color out-of-the-box, in their original form (when exposed to the proper wavelength of light). To create a paint, the short-term materials were mixed with the various binders, as indicated in the first column of Table 1. The preferred binders for the short-term materials were the readily available, off-the-shelf,

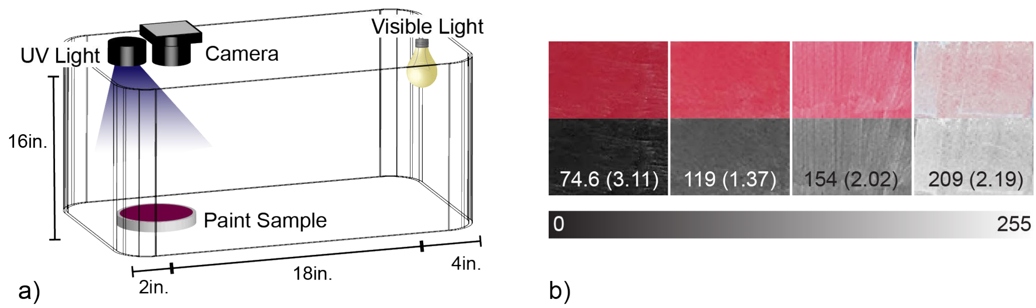

Fig. 2. Panel a) depicts the structure used for collecting images for the gray-scale analysis and testing activation and deactivation time for the short-term and long-lasting photochromic material. Panel b) depicts examples of paint samples in their red form (top) as well as their gray counterpart (bottom). The values on the gray-scale images represent the mean (and standard deviation) of the pixels in the image, where values closer to 0 are darker, and closer to black, while higher values are lighter and closer to 255 or white.

water-based products, since they do not release harmful vapors, and have a short drying time. We found that it was important to select clear or translucent white bases to avoid tinting the paint or effecting the activated color. Many of the solutions formed “well-combined paints”, in which the photochromic materials were thoroughly distributed through the off-the-shelf binder. A few other binders, such as the short-term Red Slurry with White Crayola Glue, formed congealed mixtures, leaving lumps of uncombined material, making them difficult to paint. All the binder materials labeled “Well-Combined” in columns two and three of Table 1 resulted in paintable material with some color changing capability. To determine the best of the binders, the Gray-Scale Analysis described below quantifies the magnitude of the color change. Unfortunately, some of the binders did not mix particularly easily, requiring excessively long mixing times (+6 hours), or were not water-soluble, and thus added an extra level of complexity in terms of application and safety. These were rated as “Overly Complex” in comparison to the easier-to-use water-base binder materials that produced a “Well-Combined” result.

The mixed solutions were evaluated pictorially, with the setup shown in Figure 2 Panel a). This requires a light proof box, equipped with a white light (270 lux), a UV light (365-405 nm), a camera, and a paint sample. Each paint sample is placed in the same position, with a camera collecting images of the samples. The camera maintains constant exposure levels to ensure true color values. The samples were fully activated, a photo of the samples was taken, converted to gray-scale, and then converted into a numerical representation, by taking the mean and standard deviation of the images, as shown in Table 2 and Table 3.

The values in the table represent the mean gray value (and standard deviation), where values closer to 0, are closer to black, and thus have more contrast; and values closer to 255, are closer to white, and thus, have less contrast. The standard deviation represents the variation in the paint sample; the higher the value, the more variation in the sample. Examples of these images and their corresponding values are shown in Figure 2 Panel b). From Table 2, the Garnet Red provided more contrast than the Red Slurry, and that the congealed solutions tend to have higher standard deviations. Since the Rust-Oleum Clear Gloss mixed with the short-term Garnet Red gave the highest contrast, different ratios of the Rust-Oleum Clear Gloss with the short-term Garnet Red were evaluated to determine which ratio worked best. Table 3 shows the concentration that worked best with the Rust-Oleum Clear Gloss and short-term Garnet Red was the 1:6 ratio; the 1:4 ratio was too thick to paint onto a surface, providing a higher standard of deviation, and the 1:8 ratio had lower contrast. The cost of the short-term Garnet Red was also lower than the short-term Red Slurry, at \$0.28/g compared to \$0.80/g, covering 2.3 cm^2/g compared to 0.39 cm^2/g, and thus, UbiChromics uses the short-term Garnet Red as the short-term material of choice.

The two long-term materials from Yamada Chemical were also tested with a number of solutions/binders, as listed in Table 1. The materials responded similarly in solutions, and thus most of the testing was done with DAE-0004 (red) since it is lower in cost than DAE-0068 (purple-red). The combinations not tested with DAE-0068 are labeled as "Not Tested" in Table 1. Neither material changed color with the water-based, off-the-shelf binders, nor after a solution of material dissolved in acetone or THF had dried, and are thus labeled "Not Dissolved" and "Inactive Dry", respectively. Nor were we successful in achieving a color change with the recipe using 3D printing materials outlined in [31], nor with the Sartomer CN120C60 3D printing resin, and as such, are labeled "Unsuccessful" in Table 1. However, based on [17], we experimented with DupliColor Matte Finish Clear Coat, and found that dissolving the photochromic material in it resulted in a color change. This solution was too thin to paint with a brush or a roller, and is labeled as "Subpar Texture". Adding Mia Secret Clear Acrylic Powder to the DupliColor paint created a viscous solution that worked best for painting, and is marked the "Ideal" solution for long-term photochromic materials. Since there was only one viable solution for the long-term material, we did not evaluate the gray-scale values of the samples.

Table 1. Summary of Material Mixing with Short-Term and Long-Term Photochromic Material

Off-the-Shelf Binder	**Photochromic Material**			
	Short-term Garnet Red	**Short-term Red Slurry**	**Long-term DAE-0004**	**Long-term DAE-0068**
Rust-Oleum Ultra Clear Gloss	Well-Combined[1]	Congealed [2]	Not Dissolved[3]	Not Dissolved[3]
Golden GAC 100	Well-Combined[1]	Well-Combined[1]	Not Dissolved[3]	Not Dissolved[3]
KILZ KLEAR Primer	Well-Combined[1]	Congealed[2]	Not Dissolved[3]	Not Dissolved[3]
Clear Elmer's Glue	Well-Combined[1]	Congealed[2]	Not Dissolved[3]	Not Dissolved[3]
White Crayola Glue	Congealed[2]	Congealed[2]	Not Dissolved[3]	Not Dissolved[3]
Valspar Satin Clear Latex	Well-Combined[1]	Well-Combined[1]	Not Dissolved[3]	Not Dissolved[3]
DupliColor Matte Clear with Acrylic	Overly Complex[4]	Overly Complex[4]	**Ideal**[5]	**Ideal**[5]
DupliColor Matte Clear	Overly Complex[4]	Overly Complex[4]	Subpar Texture[6]	Subpar Texture[6]
Acetone	Overly Complex[4]	Overly Complex[4]	Inactive Dry [7]	Inactive Dry[7]
Tetrahydrofuran (THF)	Overly Complex[4]	Overly Complex[4]	Inactive Dry[7]	Inactive Dry[7]
ColorMod Recipe [31]	Overly Complex[4]	Overly Complex[4]	Unsuccessful[8]	Not Tested[9]
Sartomer CN120C60	Overly Complex[4]	Overly Complex[4]	Unsuccessful[8]	Not Tested [9]

[1] Resulted in a color change in a paintable form
[2] Resulted in a color change, however, the solution was congealed and not suitable for painting
[3] Did not dissolve the photochromic material to create the color change
[4] Excessive for the short-term materials, as they activate out-of-the-box
[5] Only combination with long-term material to provide a color change in a paintable form; thus marked ideal
[6] Successfully changed color, but was too thin to paint with a brush or roller
[7] The solution no longer changed color when the solvent dried
[8] We were unsuccessful at getting a color change with this solution
[9] Not tested due to cost

3.3 Spectral Absorption Properties

A material's absorption spectrum identifies its activation and deactivation wavelengths, shown in Figure 3. Our testing of photochromic materials with their binders formed insignificant, straight,

Table 2. Short-Term Material Mixing with Various Off-the-Shelf Binders Gray-scale Analysis

	Golden GAC 100	KILZ KLEAR Primer	Clear Elmer's Glue	White Crayola Glue	Rust-Oleum Clear Gloss	Valspar Clear Latex
Short-Term Garnet Red Mean (SD)*	110.2 (2.09)	93.9 (1.98)	97.5 (2.02)	74.3 (3.15)	**62.8 (2.43)**	71.2 (2.65)
Short-Term Red Slurry Mean (SD)*	139.0 (1.47)	127.5 (3.81)	140.3 (1.80)	125.0 (6.74)	85.5 (6.42)	121.7 (1.92)

* Gray-scale measurements are unit-less.
These values represent the gray value on a scale of 0 (black) to 255 (white).

Table 3. Rust-Oleum Clear Gloss Paint with Various Ratios of Short-Term Material Gray-scale Analysis

	1:2	1:4	1:6	1:8	1:10
Short-Term Garnet Red Mean (SD)*	153 (1.36)	151 (0.829)	**159 (0.533)**	162 (1.12)	170 (3.58)

* Gray-scale measurements are unit-less.
These values represent the gray value on a scale of 0 (black) to 255 (white).

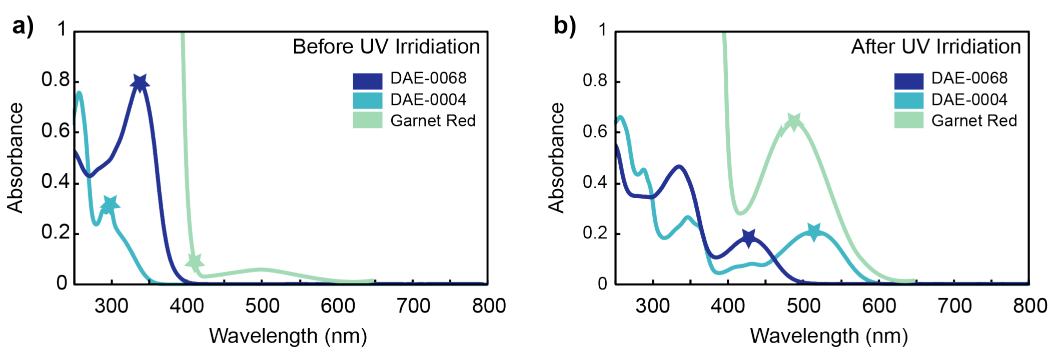

Fig. 3. Absorption data from long-term Yamada DAE-0068, long-term Yamada DAE-0004, and short-term Qingdao's Garnet Red. Panel a) shows the wavelengths at which the different materials activate and panel b) shows the wavelengths at which the long-term Yamada materials deactivate. Data courtesy of Yamada. Optimal activation and deactivation wavelengths are indicated by asterisks.

horizontal lines, with no indications of an activation wavelength. Thus, the absorption spectra of materials without additives are provided with permission from the manufacture. This figure shows that UV light sources activate the long-term photochromic materials, and near-ultraviolet light activates the short-term Garnet Red.

The amount of time for a material to activate and deactivate is important to building applications. Measuring these time variables requires the use of the setup shown in Figure 2, following similar procedures as the gray-scale analyses. The difference is that the UV light activates the paint sample for 3 minutes with the white light off, and then the UV light turns off and the white light is turned on for 24 hours. Although this does not affect the short-term photochromic material, the same steps were performed for all the paint samples. The images taken from the camera during this time were

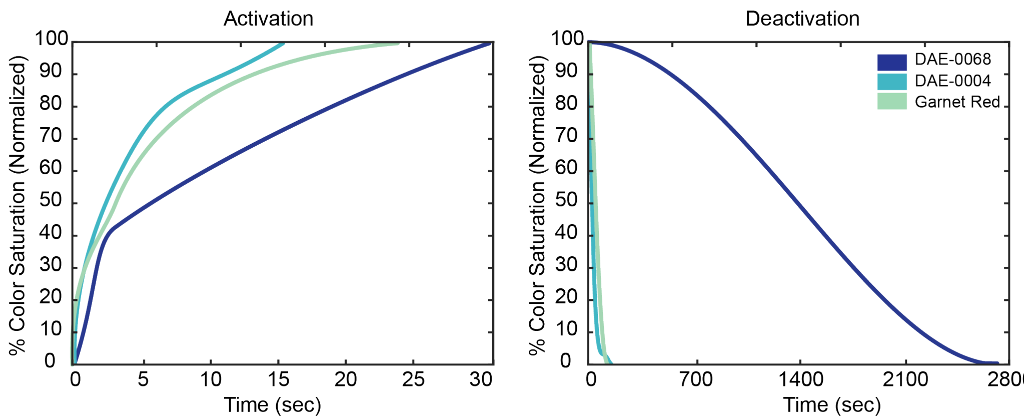

Fig. 4. Activation and deactivation times from the long-term Yamada DAE-0068, long-term Yamada DAE-0004, and short-term Garnet Red. The short-term material lasts for approximately 16 minutes, while the long-term Yamada Red material (DAE-0004) lasts for about 20 minutes, and the long-term Yamada Purple Red (DAE-0068) material lasts for about 6 hours.

converted to gray-scale, averaged, and plotted, as shown in Figure 4. The point at which the values begin to plateau for greater than 1 minute is used as the cut-off for activation or deactivation time.

From 100 % activation, the short-term material lasts for approximately 16 minutes, while the long-term Yamada Red material (DAE-0004) lasts for about 20 minutes, and the long-term Yamada Purple Red (DAE-0068) material lasts for about 6 hours. However, exposing the short-term material for only 80 ms will cause it to appear for 45 seconds. The difference in time constants is important because it allows for different interaction modalities. For example, the short term material could be used for short term information such as scratch paper, whereas the long term material could be used for longer lasting information such as daily calendars.

3.4 Light Activation

This work explores light sources, specifically, long-range, free space laser *actuators*, to activate photochromic paint. Figure 3 Panel a) depicts the optimal wavelength to activate a particular photochromic material, however, availability and cost of the light sources should also be considered in determining which is used as an *actuator* to change the color of the paint in the end applications.

For example, the short-term material activates strongly at wavelengths below 410 nm. Fortunately, the consumer electronics industry has produced a wide number of optoelectronics with wavelengths of 405 nm. With the commercial success of Blu-ray players that use blue (or more accurately violet) lasers for reading discs, the cost of 405 nm laser diodes has fallen dramatically over the last decade and are readily available.

When choosing a light source for an application, it is important to consider how the wavelength, intensity, and the usage model can potentially impact both eye and skin safety. While UV light sources where used in the initial testing of the photochromic material, **no UV light sources** are used as *actuators* when building the UbiChromics system, described below. Instead, low-power, visible-light lasers have been used to ensure eye and skin safety. That said, laser sources present a unique challenge since the light is focused in a beam and not a defuse source. Lasers are classified based on their output power; Class 3R (or IIIa) are low-powered and considered safe when handled carefully, with an output power between 1 and 4.99 mW. These devices rely on a person's natural aversion response to bright light, where they turn away and/or blink, limiting exposure time. Class 3R, laser pointers, with a wavelength of 405 nm, are readily available and very effective at activating the photochromic material anywhere in a room. That said, additional precautions, such as mounting the laser projector on the ceiling to limit direct exposure to a user as well as employing a depth camera to turn off the laser when a user is present, have been implemented to add as secondary level of protection.

3.5 Summary of Material Selection Criteria

Both, the evaluation of the various photochromic materials and binders to make paintable solutions, as well as exploring various lights for activation, guided our interactions and use of interactive devices. A summary of these findings is as follows. From Table 1, the two ideal mixtures with the long-term photochromic material were identified (mixing the photochromic material with DupliColor Matte Clear with Acrylic), and a number of promising mixtures were identified for short-term photochromic materials. To narrow down the short-term photochromic material choices, from Table 2, the Garnet Red mixed with Rust-Oleum Clear Gloss provided the highest concentration, and was further evaluated to determine the best mixing ratio. From Table 3, Garnet Red mixed with Rust-Oleum Clear Gloss in a 1:6 ratio worked best. Since ultra-violet light sources are not eye safe for long-range applications, the long-term photochromic material is limited to interactions with near-contact activation, as described in the Future Work section of this paper. The interactions described in the Applications section of this paper use eye-safe lasers with short-term Garnet Red photochromic material for long-range activation and interaction.

3.6 Final Recipes for Short-Term and Long-Term Photochromic Paint

Based on the experiments, the best recipes for creating usable short-term and long-term photochromic paints are as follows. Short-term paint requires 1 part photochromic material to 6 parts Rust-Oleum Clear Gloss by weight, stirred for 1 hour at 500 RPM. The long-term paint requires 19 g of DupliColor Matte Finish Clear Coat to 0.2 g of photochromic material to 0.8 g of Mia Secret Clear Acrylic Powder, stirring for 1 hour at 500 RPM. After the mixing, the paint can be applied with a foam brush or roller. The installer should refrain from shining UV light on the paint while its drys, as it causes permanent yellowing.

4 PHOTOCHROMIC ACTUATOR

With the photochromic material in a paintable form and the types of light sources needed to activate the paint identified, we now turn our attention to creating of photochromic actuator that enables users to create on-demand displays, and interactive controls and tools on nearly any surface. For room scale applications we a developed a custom vector laser projector, with depth camera to detect user actions and identify images drawn on to the photochromic paint using free hand actuators such as the smart-pen described in Section 6.

Video projectors and cameras have long been used in the field of HCI to distribute images over large surfaces and capture users' hand and body position for remote collaboration, 3D reconstruction, and to create interactive white boards. However, the size of the image is still limited by the field-of-view of the projector, and objects can temporarily occlude the projector casting shadows on the surface and making interactions difficult. UbiChromics offers the opportunity to overcome both these issues. Since the photochromic paint can hold an image for a few minutes to several hours, it is possible to deposit an image on one section of wall, then programmatically rotate the projector with a stepper motor to deposit images throughout the rest of the room. This significantly reduces the cost per area of the display compared to traditional approaches, but has the drawback of slow

Fig. 5. Panel a) A custom modified 405 nm laser vector projector, which provides wide array coverage from long distances. Panel b) A view of the laser projector and depth camera mounted to the ceiling. Panel c) The ceiling mounted laser projector projecting an image, a music menu, onto the wall. Panel d) A closeup of the music menu projected onto the wall.

update rate and being monochromatic. Secondly, transient occlusions can occur when an object blocks the light from a normal projector. This is overcome with UbiChromics, since the image resides on the surface rather than being reflected off of it.

4.1 Laser Projector Hardware

The laser projector, shown in Figure 5 Panel a), is a modified Laserworld DS-1000RGB vector projector that has been repurposed to include a 405 nm laser pointer, with the other two channels disabled. The laser pointer is an eye safe Class 3R (or IIIa) with a listed output power less then 4.99 mW. Instead of projecting a 2D image like typical consumer electronic projectors it instead uses orthogonal galvanometer mirrors to programmatically steer the 405 nm laser beam. The Laserworld projector has an Ethernet connection and communicates via the ILDA protocol (a standard by the International Laser Display Association). Pre-defined shapes and sprites, such as ASCII characters, can be uploaded to the projector via Laserworld's Showeditor software and stored on the laser's internal SD card. Using the laser to render images onto the photochromic display, we can programmatically call the shapes to create a wide variety of images at ranges of up to 3 meters(~10ft), allowing for wide coverage area.

As mentioned previously, the laser projector was mounted to the ceiling, as shown in Figure 5 Panel b). Since the laser projector is mounted to the ceiling, it must be tilted down, so that the laser point makes contact with surfaces coated in photochromic material, and in this case, angled such that it could project on two walls, a table top, and any object within that vicinity. With the laser tilted down and towards two walls, images may appear skewed. We programmatically correct for this skewing, as described in the Scheduler 4.2.2, section of Laser Projector Software.

4.2 Laser Projector Software

To control the virtual objects rendered by the laser projector, and detect users actions with the depth camera, we developed a software pipeline depicted in Figure 6. The system takes inputs from API calls or directly from users via a web interface that specifies what objects are drawn at what time and where in the room. The system also takes real-time input of the state of the interaction space from the depth camera. Next, the Scheduler manages the virtual objects that need to be rendered and refreshed based on the decay time of the photochromic paint and the total number of required virtual objects that need to be rendered in the room. Finally, the pose estimation block determines if users are in the field of view and if they are interacting with any of the virtual objects.

4.2.1 User Interface and Back-end. To allow end-users to control laser output, we created a drag-and-drop web interface, shown in Figure 7. We provide a variety of widgets that users can place

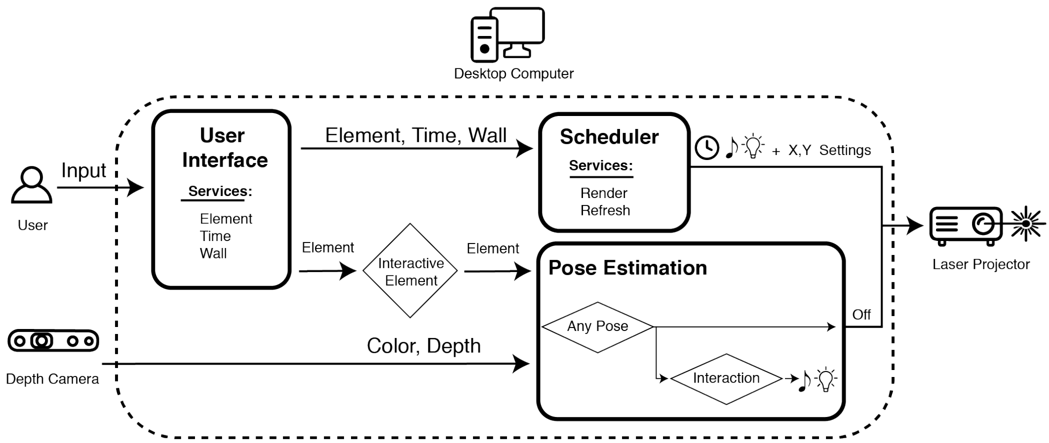

Fig. 6. The laser projector-camera software flow diagram shows the UbiChromics system takes inputs from a user and depth camera. The user may select an element, which wall to project it onto, and how long the projection should remain on the wall from the user interface. The user input and color and depth information from the camera are processed on a desktop computer, which calculates the proper settings for the laser.

onto photochromic painted walls in their environment: a light switch, a music control panel, a clock, and a custom text input box. Once a widget is selected, its image appears overlaid on an image of a wall to provide a preview of how the widget will look once rendered by the laser. Users can click and drag the image of the widget to adjust it's position on the wall, and optionally input a length of time that the widget should be displayed (default is 60 minutes). Finally, users press a confirm button to send a request to the laser to draw the widget. This sends an API request containing the details of the widget placement, which calls the corresponding move and draw functions to the laser. The web interface was built using Vue.js [57], and Flask [30] was used to implement the backend web server and laser request API.

4.2.2 Scheduler. The scheduler is a Python script processing the API request and handles the specific functions used to send commands to the laser. Since the color of the activated photochromic material fades over time, the scheduler refreshes and manages elements enabled by the user interface. Thus, there are two roles for the scheduler: 1) render elements selected in the user interface 2) manage the re-rendering of those elements. Meanwhile, the scheduler is also a task scheduler, to schedule elements such that projection of one element does not interrupt another projection. Rather, elements are queued until the laser finishes projecting the previous elements.

The scheduler tracks the inputs from the user interface, including the element type (clock, light switch, menu, etc)), its x, y coordinates, the time for it to remain active, and the wall number on which it is to be projected. The scheduler uses this information to select which image to render from the SD card, map the interface to the laser x,y coordinates, and adjust the image size and rotation to account for skewing. Alternatively, free-form images can be drawn directly from Python, but the scan time is usually slower. Once the element is placed, the scheduler refreshes the element every so often based on the element's deactivation time, described in the Evaluation section. Thus, the scheduler refreshes each element as necessary, and continues to refresh elements until the user-specified time for each element to remain active has elapsed. For example, if a user selects the clock element, and specifies 60 minutes, the clock will update the time every minute for 60 minutes.

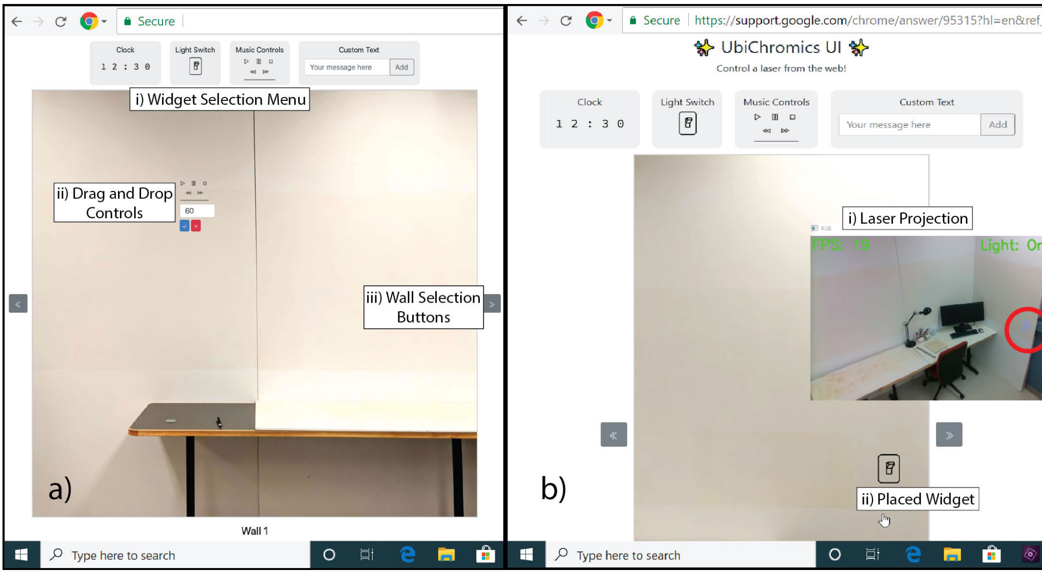

Fig. 7. The panel depicts the process a user would take to project and interact with various wall elements. Panel a) The web interface for laser control: i) users can select from a variety of widgets to render on walls, ii) once selected, users place widgets with drag-and-drop controls, iii) users can change which wall they would like to render widgets to. Panel b) The web interface after a widget has been selected: i) the laser immediately begins projecting to the corresponding wall and location, ii) placed widgets appear overlaid onto an image of the wall, and can no longer be edited.

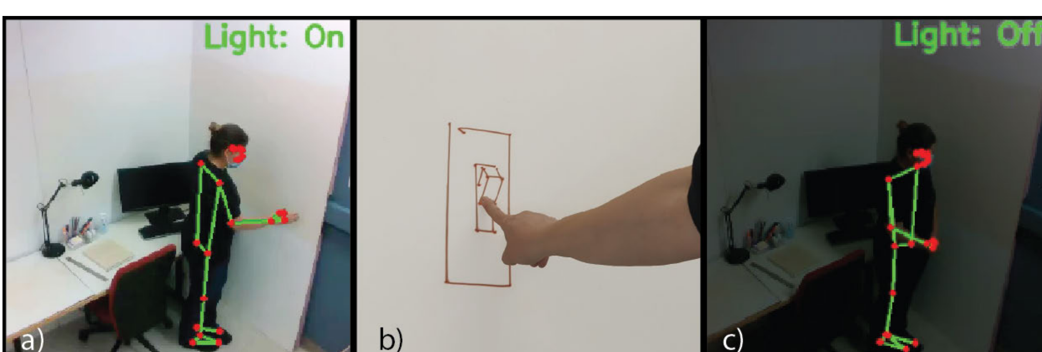

Fig. 8. Panel a) The pose detection of a user touching an element on the photochromic wall. Panel b) The color change of the light switch shape on the photochromic wall. Panel c) The interaction, lights turn off, that occurs from touching the element on the photochromic wall.

Indirect light, such as light coming through windows, with or without tints or filters, has not been shown to activate the shot-term photochromic material. Nor has lighting in different environments been shown to alter the deactivation time of the short-term photochromic material. Although many environments use white light, which includes 405 nm, the light diffuses such that it does not affect the painted surfaces.

4.2.3 Pose Estimation. In order to enable users to interact with the UbiChromics display, a depth camera is used to track pose and hand proximity to interactive features. The depth camera is an Intel Real sense D435i. The depth camera provides color and depth images to the computer. Using the color images and MediaPipe's BlazePose [2], we track eight of the 33 key points it extracts: the wrist, pinky, thumb, and index finger for both hands. We then extract the depth data for these key points and determine if they are within the thresholds for the various interactive elements, and if so, perform the interaction. For example, in the case of a light switch projected on a wall shown in Figure 8, BlazePose would identify the hand, and determine if it is within the light switch threshold. The depth data then determines if the hand is in fact touching the wall/light switch to turn off the light. Pose estimation occurs only for the interactive elements enabled by the user interface.

Additionally, to increase user comfort and add an element of safety redundancy, we used the depth camera to check for changes in the depth field, and restrict laser output to those regions, effectively eliminating The possibility of the laser being incident on a user.

5 EVALUATION

To understand the feasibility of using the UbiChromics system as a ubiquitous display, we ran a series of experiments to 1) determine the minimal color contrast for text readability on a photochromic painted wall, 2) evaluate the effect of varying the activation time of the photochromic material on the length of time images are displayed, and 3) evaluate the number of characters that can be displayed. In other words, we used these experiments to evaluate how well the 405 nm laser projector performs at actuating surfaces painted with the short-term photochromic material, and thus, to determine its effectiveness as a ubiquitous display.

5.1 User Study

We conducted a user study to determine the minimum acceptable color contrast for text readability between the original wall color and activated red paint color. We recruited 10 participants, ages (22+/-3 years), 9 men and 1 woman. Participants were asked to keep glasses or contact lenses on if they wore them on a regular basis. The laser was placed seven feet away from the wall for this task , and participants stood nine feet away from the wall displaying the reading content, as shown in Figure 9 Panel a). Each session was video recorded and took, on average, 20 minutes to complete.

Participants were asked to read a random series of 15 5-letter words and express their confidence level for reading the word on a 1 to 5 Likert scale (where 1 is not confident and 5 is very confident). One word was displayed at a time, for 15 increasing lengths of time, from 1 second, up to 80 seconds. Words were allowed to fade completely from the wall in between reading exercises.

We asked participants to verbally announce any and all letters they could visualize, and observed that participants could begin to identify letters correctly at 10 % color activation, and as indicated by a 5 on the Likert scale, could correctly and confidently identify whole words at 30 % color activation, as shown in Table 4. All of the participants were able to correctly identify 100 % of the words at and after 25 seconds of activation. From these results, we used 30 % color contrast as the deactivation threshold for the laser projector evaluation described below, use this to determine the point at which the laser should refresh text and images on the wall so that they are constantly perceivable.

5.2 Line and Character Rendering Evaluation

In order to determine the laser/wall system's efficacy for being a ubiquitous display, we evaluated the laser to gauge how many characters it could project on the wall. To make this evaluation more universal, we looked at characters as a factor of line length. This way, we could consider images such as the shape of a Mona Lisa line drawing, or more traditional characters, such as letters and numbers. This evaluation requires the measurement of deactivation as a function of line length and

Table 4. User Readability Test - Likert Scale Results

Activation Time	1 (Not Confident)	2 (Slightly Confident)	3 (Moderately Confident)	4 (Confident)	5 (Very Confident)
1 second	100 %	0 %	0 %	0 %	0 %
2 seconds	80 %	10 %	10 %	0 %	0 %
3 seconds	70 %	0 %	20 %	10 %	0 %
4 seconds	40 %	20 %	10 %	20 %	10 %
5 seconds	30 %	20 %	20 %	10 %	20 %
10 seconds	0 %	10 %	10 %	40 %	40 %
15 seconds	0 %	10 %	0 %	10 %	80 %
20 seconds	0 %	0 %	10 %	10 %	80 %
25 seconds	0 %	0 %	0 %	0 %	100 %

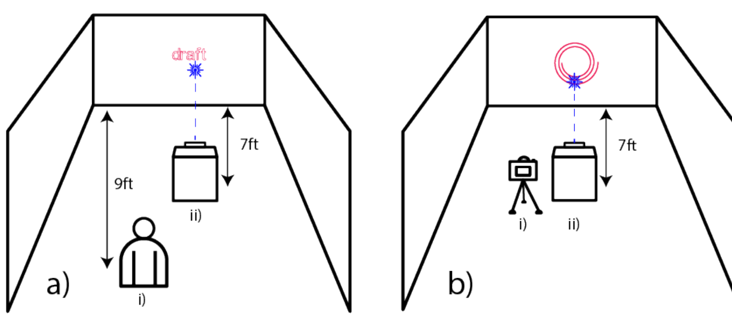

Fig. 9. Panel a) The user study setup used to determine the minimum color threshold needed for individuals to read characters on the photochromic wall, where i) is the participant and ii) is laser projector + depth camera. Panel b) The experimental setup used to determine minimum line length that can be projected, where i) is the DSLR camera for recording the paint as it fades and ii) is the laser projector.

activation time. Thus, varying projected line lengths and the time that those lines are activated, we can measure how long the images remain displayed.

For the evaluation, we placed the laser projector seven feet away from a wall, as shown in Figure 9 Panel b), and projected spirals of varying lengths, from 22 inches to 233 inches, for 5, 10, 25, and 50 seconds. To vary the lengths, we changed the size of the spirals using the laser's size parameter. The values of the line lengths were then calculated based on the projected spiral's measurements. The activation times were selected based on the results of the user study, where a number of individuals could read text at 5 seconds, most could read text at 10 seconds, and all individuals could read text at 25 seconds. We tested for 50 seconds of activation as well to test a much greater range of line lengths.

A video of the wall was recorded as the color faded, to determine the initial level of color contrast, defined from 0 % (wall color) to 100 % (fully activated), and how long before the image deactivated. The lighting and exposure was held constant to maintain consistency throughout the testing. We

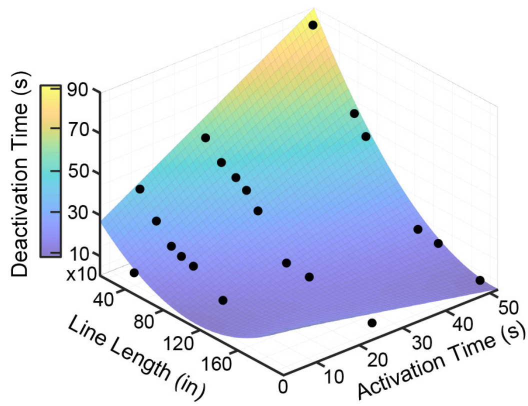

Fig. 10. The results of the laser study (black circles) with a second degree polynomial mesh model, represented by Equation 1. The model shows deactivation as a result of line length and activation; as line length increases, and activation time remains constant, deactivation decreases; as activation time increases, and line length remains constant, deactivation increases.

used the results of the user study to define the point at which the image was considered faded. In between each experiment, the images faded completely.

The results of the line evaluation were limited to color contrasts above 30 % based on the visibility threshold from the user study, and are represented in Figure 10 by black dots. As expected, the smallest image, with the shortest line length, coupled with the highest activation time, achieved the highest contrast, at 100 %, the darkest the paint can get when activated. Although not shown, the largest image, that with the longest line length, coupled with the shortest activation time, achieved the lowest contrast, at 0 %, which is the base wall color, indicating no color change occurred.

With this information, we can predict how many characters the laser can project. The minimal color contrast used to count a character and consider it visible is 30 %, based on the user study. With this information, we developed Equation 1 using three variables: D_t for deactivation time, L for line length, and A_t for activation time. In the experiments, we altered line length and activation time to see the change in deactivation times. Thus, to predict deactivation, the equation is setup to solve for D_t, deactivation time, using variables L and A_t, line length, and activation time. This allows users to quickly select the best parameters for the system they are developing. The coefficients for these factors were determined by MATLAB's curveFitter toolbox.

$$D_t = 251.1 + -5.196 * L + 13.77 * A_t + 0.02349 * L^2 + -0.08711 * L * A_t \tag{1}$$

A mesh representation of the model is represented in Figure 10, as well as the raw data from which the model is built, indicated by the black circles. The model shows that as line length increases, and activation time remains constant, deactivation decreases. This means that a larger image (represented on the right side of the Figure) will not last as long as a smaller one (represented on the top side of the Figure) if they are both activated for 50 seconds. On the other hand, as activation time increases, and line length remains constant, deactivation increases. This means that an image projected for 50 seconds (represented on the right side of the Figure) will last longer than an image of the same size projected for 10 seconds (represented on the left side of the Figure). While more data than this was collected, not all combinations of time and line length met the visibility threshold, and were thus eliminated from the model. For example, the largest image, defined as a

Table 5. Line Length to Character Conversion

Element Type	Physical Size	Line Length
One Letter	3" x 3"	17"
Light Switch	3" x 4.5"	24"
Clock	18" x 6"	68"
Music Menu	14" x 14"	70"
Mona Lisa	18" x 24"	270"

line length of 233 inches did not appear when activated for only 5 seconds. Thus, that region of the model is excluded from predictions as well.

With Equation 1, we can tell if the laser can handle refreshing a clock, music menu, and light switch, or just a clock and light switch. The conversion from line length to number of characters is dependent on size of characters/images. For the application demonstrations found in this paper, the character/image to line length conversions are found in Table 5. Of course, this is a limitation with the laser, and not the paint or using it for ubiquitous displays. To achieve more characters, one could add more lasers or implement other actuators, as discussed in the Future Work section.

6 APPLICATIONS

UbiChromics can be used in a number of ways to create ubiquitous displays and when paired with a depth camera can form a variety of interactive applications. This section explores of number of application domains to demonstrate the utility of the UbiChromics concept, including static images displaying text and art, dynamic images such as clocks and notifications, as well as interactive elements such as music controls and light switches.

As shown in Figure 7, to carry out these applications, a user would begin by selecting the element of interest from the web interface, and dragging and dropping it to a location on the wall of choice. The user may then select how long they would like the element to remain active. The time to remain active refers to the time in which the laser would re-render the image to keep it from fading. In the background, the the interface and backend pass the element, x,y coordinates of the element, wall number, and time to remain active to the Python scheduler, and pass just the element to the Python pose script. The scheduler then projects the element in the specified location, while the pose script awaits interactions for interactive elements, such as the music menu and light switch. Below is a further description of each of the elements and how they represent the usability of photochromic ubiquitous displays.

Static Element: Notifications There are a number of notifications individuals check on a daily basis including social media, emails, phone calls, and calendar events. Many of these require the user's short-term attention. Thus, notifications lend themselves to be displayed on photochromic paint with a short deactivation time. If the notification needs to last longer, the usage policies can direct the laser projector to re-render the images to keep them from fading. With the laser programmed via Python, we can customize messages or show alerts for various programs that display messaging notifications, phone calls, or calendar events. Figure 11 Panel a) shows the laser projection of a text message onto a wall coated with photochromic paint.

Static Element: Images Similar to notifications, people enjoy having custom art work displayed, and like to change it on a regular basis. Photochromic-coated walls allow users to do that without the need to repaint their walls, hang new wallpaper, or mount new artwork. In fact, users could use other deep-violet light sources to interact with and add to wall art, as shown in Figure 11 Panel b).

Fig. 11. The panel depicts various technology demonstrations. Panel a) A static notification. Panel b) A static line drawing of the Mona Lisa which users can modify using hand-held light sources. Panel c) A dynamic clock which updates every minute. Panel d) An interactive music menu. Panel e) An interactive light switch.

Dynamic Element: Wall Clock Photochromic paint is continually reconfigurable, and the quick deactivation time lends itself well to creating continuously refreshed elements, such as a wall clock, which needs to update every minute. A digitally reconfigurable clock on a photochromic-coated wall allows a user to quickly place the clock anywhere without mounting, creating nail holes, or pulling a phone out of a pocket while busy with another task. Furthermore the wall clock can be dynamically re-located to different locations and even follow the user throughout the environment ensuring that there's always good line of sight to the clock. This is shown in Figure 11 Panel c). The same benefits apply to creating similar elements, like custom countdown timers when cooking.

Interactive Element: Music Controls Screen sizes have been growing across all form factors, including smartphones and tablets, to enable easier viewing and greater immersion. However, the size of these devices is restricted by cost and portability. UbiChromics achieves the large-scale interaction, at low costs, by taking advantage of large existing surfaces, such as walls and tables. With a simple coat of paint, UbiChromics makes way for expanding menus, such as the music menu depicted in Figure 11 Panel d). We envision similar interactions for productivity applications (e.g., word processor, calculator), where users often access special symbols and algebraic operations that are found only in menus. These elements also double as social widgets that can be used by multiple people, such as a photochromic jukebox or collaborative writing environment.

Interactive Element: Light Switch As homes become smarter, devices, such as smart thermostats, retrofit traditional analog dials with touch screens. However, this still restricts the interaction space to statically-located physical manifestations (i.e., your thermostat remains in the same place on your wall indefinitely). For this reason, the use of photochromic surfaces and laser projectors give way to intelligent materials, and further enable smart environments. Augmenting the environment with intelligent photochromic surfaces provides users with the ability to control their surroundings, from anywhere in their home, without having to install various devices. This also allows users to use one surface for many widgets, and changing the widgets as their preferences change.

Pairing the system with a depth camera allows us to use hand tracking for interactions. One such application we demonstrate is the light switch, as shown in Figure 8 and Figure 11 Panel e). We envision similar interactions with other stationary widgets, like thermostats, where a projected circle can behave as a dial, increasing or decreasing the room temperature.

7 LIMITATIONS

While UbiChromics offers the opportunity to display digital content on nearly any surface, there are a number of limitations that should be understood and addressed to guide future work.

In order to cover the largest surface area possible, it is desirable to have a single light source that can activate the photochromic paint over long distances. This work proposes the use of a ceiling mounted, 405 nm (deep blue) laser projector to achieve this goal. Thus, laser safety is an important factor that must be addressed when designing and deploying the UbiChromics system. In the United States, the American National Standards Institute (ANSI) provides guidelines for the amount of power and specific wavelengths that can be used safely by the general public. For example, Class 3R (or IIIa) lasers (used in consumer laser pointers) must have an output power no greater than 4.99 mW, and must be in the visible wavelengths from 400 nm to 700 nm. These low-power lasers do not pose a risk to skin, and are considered eye safe when handled carefully due to our natural aversion response to bright light.

This upper limit on output power, and the restrictions on the light wavelengths that can be used in free space, place important constraints on the usage and performance of UbiChromics. For example, it is not possible to simply increase the output power of the laser to decrease the photochromic paint's activation time, or make the paint's maximum contrast darker. To address this issue, we conducted the evaluation in Section 5 to determine the amount of "line length" and equivalent text that can be drawn on the photochromic surface given the limitations of our projector. To further increase the amount of information that can be rendered, multiple vector laser projectors could be used, or alternatively, 2-D projectors could be modified to specifically emit 405 nm light, thereby rendering detailed gray scale bit maps onto the photochromic surface.

Furthermore, these safety limitations also restrict what type of material can be effectively used in our system. Given that the long-term photochromic material requires UV light for activation, and that there are no eye safe UV lasers (because they are invisible and do not illicit the natural aversion response to bright light), it is not possible to use UV light sources in long-range (free space) usage scenarios such as a laser projector mounted on the ceiling. However, this does not mean that it is impossible to use long-term material for UbiChromics. As described in the Future Work section, there are a variety of eye safe UV-LEDs that can be used in near contact situations, opening up the possibility for mobile interactions with photochromic material.

All light based systems, whether they are vector laser projectors used in this work or traditional 2-D projectors used in class rooms, suffer from occlusion when an object or person blocks the light from reaching the screen/surface. UbiChromics clearly outperforms traditional projectors in this regard since the image is held on the surface of the paint for a period of time. Thus, making our system robust to short term transient occlusions. However, there is a limited amount of time an image can be held on the paint, and if the user inadvertently blocks the line-of-sight of the projector for long enough, the system will not be able to refresh the image and the interface may fade away. While this is an inherent limitation of the system, it is possible to construct a mechanism that will alert the user that an occlusion problem is occurring through audio or alternative visuals.

As presented in the evaluation in Section 5, there is an inherent trade-off between the amount of paint that can be activated and the contrast of that color transition. Stated plainly, to make a word or image darker the laser must dwell on the paint longer to cause more transition. This means that there is less time to draw other words and images before they fade away. While it is largely an inherent limitation of the vector laser projector technology used, this work does have a trade-off between the amount text that can be displayed and the readability of the text. Equation 1 can be used to determine this limit, however, we have not seen this trade-off to be a practical limit for the applications is demonstrated in Section 6.

8 FUTURE WORK

While this work has primarily focused on creating the underlying mechanisms needed for room scale ubiquitous and interactive displays, such as photochromic paint as a *medium* and a visible vector laser as an *actuator*, there are a number of alternative usage scenarios and technology choices that can unlock new system capabilities and user applications. For instance, in Section 3, we conducted a study to evaluate which forms of photochromic paint would best be suited for

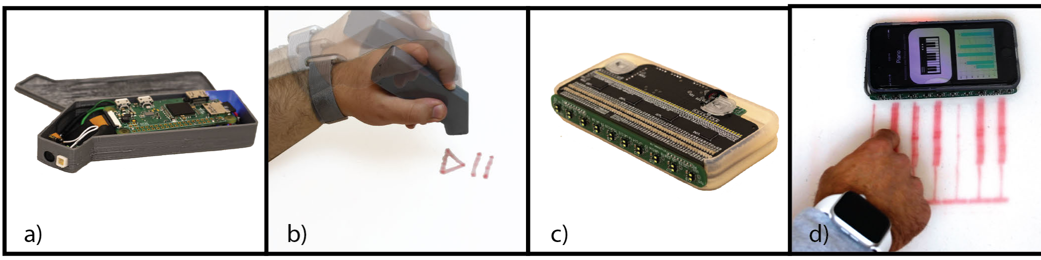

Fig. 12. Panel a) The smart pen 3D printed case, which includes a camera and UV LED. Panel b) The smart pen used to draw and interact with a play button. Panel c) The smartphone case components including LED arrays, mouse sensors, and a time of flight array. Panel d) The smartphone projecting a game controller on a photochromic surface.

room scale applications, where the paint would need to be actuated from a single source over long distances. As discussed, the long-term DAE-0004 and DAE-0068 photochromic materials require UV light for effective activation. Since there are no eye safe UV lasers that are suitable for free air optics, we chose not to use that material in the above room scale applications. However, if we re-envision the *actuator* to be a mobile device that is carried with the user, it opens the possibility to use the actuator at near contact distances, making it feasible to use low intensity, eye-safe UV LEDs. To explore the potential of mobile UbiChromics actuators, initial prototypes of a smart-pen with a built-in camera and a smartphone case with an array of UV LEDs have been developed.

Pen and paper has long been a natural way to express one's self and to communicate with others. This can easily be done on photochromic surfaces with an UV LED enabled pen or a commercially available 405 nm laser pointer. To add interactivity to the classic pen usage scenario, we created the smart pen shown in Figure 12 Panel a), which contains a UV LED mounted on a contact switch, which is activated when pressed against a surface, and a small camera connected to a Raspberry Pi Zero. This combination allows a user to write on a photochromic enabled wall or table and then use the camera to capture the content that has been written. As a demonstration of the type of interfaces that can be developed, Figure 12 Panel b) shows a user drawing a play and pause button. To select one of the controls the user brings the pen back slightly so that the fish eye camera can see the extent of the drawn object, and then the user taps the symbol that corresponds with their selection choice. In this example, the user is tapping on the play button to initiate music.

Smartphones are a compelling platform to use as actuators since they are typically carried with users throughout most of their day, and have local compute and wireless communication capabilities. The smart phone case shown in Figure 12 Panel c) enhances the capabilities of the phone by adding an array of UV LEDs that can be sequentially actuated as the user sweeps the phone across the table. In order to ensure the images are not skewed or deformed by variations in the speed at which the user swipes the phone, two PMW3360 optical motion sensors are used for tracking. Once a user has deposited interactive elements, like buttons, sliders, and knobs, on a UbiChromics enabled surface, an array of 10 VL53L0X time-of-flight (ToF) sensors positioned along the side of the phone are used to detect the location of the user's finger in 2D space. As an example, Figure 12 Panel d) depicts a user playing an interactive piano application. First, the user slides the phone across the table, which allows the UV LED array to activate the paint to draw a piano. Then, the user can play the keys on the piano, which are detected by the time of flight sensors, causing the phone to play the corresponding notes. This has the advantage of extending the interaction surface beyond the bounds of the phone screen.

9 CONCLUSION

This paper presents UbiChromics, a method of creating ubiquitous, room-scale, and interactive surfaces using photochromic paint for less than a penny per square foot (\$0.07/m^2). An evaluation of different types of photochromic materials and binders has been done to select the best paintable forms of both long-term and short-term photochromic paint. In order to create room scale interactive displays, our custom developed short-term photochromic paint has been selected and applied on a variety of surfaces and walls in our lab for testing. In order to activate the paint over long distances, a custom modified 405 nm vector laser projector has been created. Our custom design software stack allows users to define their own static images, passive displays, and interactive elements through a web interface. Then the scheduler controls when and where images will be created and can refresh them indefinitely as needed. Finally, the software stack includes a pipeline to take camera images and track user interactions with drawn interfaces on the wall such as a light switch. An evaluation of the readability of text under various activation scenarios has been done to determine the amount of text that can be deposited and continuously refreshed throughout a room given our systems operating specification. Finally, a number of demo applications have been developed to show the utility and potential for the UbiChromics concept. Ultimately, UbiChromics demonstrates the possibility of extending digital content to all painted surfaces, potentially opening up a wide range of ubiquitous computing applications.

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