令和元年度　未来研究ラボシステム　研究成果報告書

研究種目：個人研究　　**研究期間**：平成 30 年 10 月～令和元年 9 月

研究課題名：色の変化できる素材を使って日常物の持続可能性を高める研究

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研究成果

This project presents a method to create re-programmable multi-color objects that are made from a single material only. The goal of this project has a little bit shifted from the original research goal, i.e., instead of modifying the fabric color to the 3D printed or arbitrary objects.

The key idea of this project builds on the use of *photochromic inks* that can switch their appearance from transparent to colored when exposed to the light of a certain wavelength. A major limitation of using photochromic materials, however, is that they are single-color only, i.e., each material can only transition from transparent to one color and back to transparent. In this research, we found that by *mixing cyan, magenta, and yellow (CMY) photochromic dyes* into a single solution and leveraging the different absorption spectra of each dye, we can control each color channel in the solution separately. Since this approach uses only a single solution, we can transform single-material fabrication processes, such as coating, into high-resolution multi-color techniques. As shown in Figure 1, our approach allows to change the 3D printed color as many time to different colors.

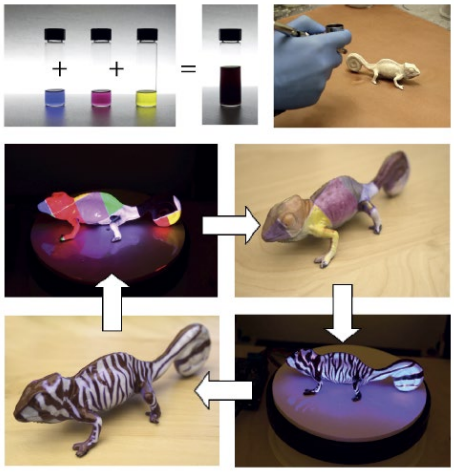

Figure 1 Overview of the research goal. It allows mixed CMY photochromic dyes together to create our multi-color ink. After coating, we use a UV light source and a projector to control each color channel on a pixel-by-pixel basis, resulting in high-resolution texture that can be reapplied multiple times.

WORKING PRINCIPLE

When cyan, magenta, and yellow photochromic colors are mixed together into a single solution and the solution is activated with UV light (i.e., all three color channels are fully saturated), the resulting color is black. This is consistent with the CMY color mechanism. To activate colors other than black, we need to deactivate one or more color channels. Deactivating the cyan color, for instance, would result in red since only yellow and magenta remain activated. To deactivate each color channel individually, we can leverage the fact that the deactivation peak (i.e., the absorption peak) of each photochromic color is at a different wavelength (Figure 2). Since all of the deactivation wavelengths are within the spectrum of visible light (between 390 nm to 790 nm), we can use a standard projector to supply one deactivation wavelength each.

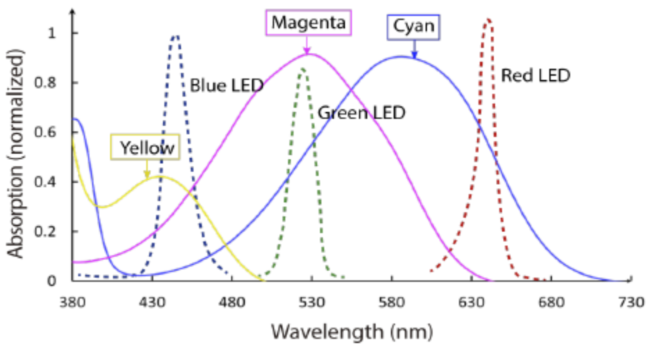

Figure 2 The absorption peak of each photochromic dye is at a different wavelength (line), and the activation spectrum (dash).

To be able to choose photochromic dyes that minimize overlap between different color channels, we determined the absorption spectrum for each photochromic dye. For this, we mixed 0.1 wt% of each dye in ethyl acetate using a magnetic stirrer for 1 hour at 500 RPM and then filled the solution into quartz cuvettes with a 1 mL path length. We then radiated the solution under UV light until the photochromic inks were fully activated and then placed the cuvettes in a spectrophotometer (Varian Cary 5000 UV-Vis-NIR spectrophotometer) to determine the absorption spectra. The result for all available photochromic dye we have shown in Figure 3.

DEVELOPING THE PHOTOCHROMIC COATING

To make the method directly applicable to physical objects (as the goal of this research), we developed a re-programmable photochromic coating that can be airbrushed onto the surface of objects. To do so, we dissolved cyan, magenta and yellow photochromic dyes directly into a transparent lacquer. Before mixing the three photochromic dyes together, we first mixed each dye separately in lacquer (BSP307). For the three separate mixtures, we used 0.05 wt% cyan, 0.05 wt% magenta and 0.3 wt% yellow, respectively. These concentrations were chosen based on the deactivation times of each dye. We then mixed the resulting liquids by equal volume to achieve our multi-color coating. Before applying the coating to an object, we primed the surface of the object with spray paint to avoid subsurface scattering of the projected light. We first sprayed each object with black paint (drying time: 30 min), and then subsequently sprayed a white paint layer (drying time: 24 hours). After this, we sprayed our photochromic coating onto the surface of the object using an airbrush system (Iwata HPCS). The saturation of the sprayed ink can be increased by applying a second layer of ink after letting the first layer dry for 20 minutes. The ink is then fully dried after ca. 24 hours. Figure 4 shown the coating and activation results.

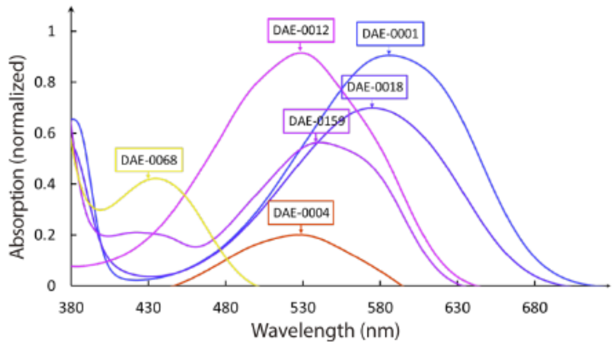

Figure 4 Absorption spectra of the photochromic dyes in the visible wavelength range.

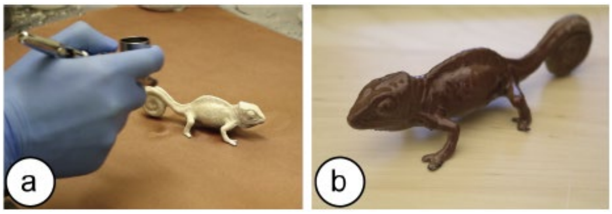

Figure 3 (a) Appling the photochromic coating and (b) the resulting coated object after UV activation.

ALGORITHM TO COMPUTE DEACTIVATION TIMES

We found that once we placed the photochromics further away from the projector (i.e., visible light source) such as at a projection distance of 30 cm to allow the projected image to be in focus as the shortest focal point, the available color gamut reduced. Figure 5b shows the result acquired when projecting the R, G, B sequence compared to the target result. The difference is due to the change in light intensity, which we will explore in more details as the follow up work. By determining a relationship between projector distance and deactivation time, this could enable us to add 'projector distance' as a variable into our system to accommodate different placements of the objects to be re-colored.

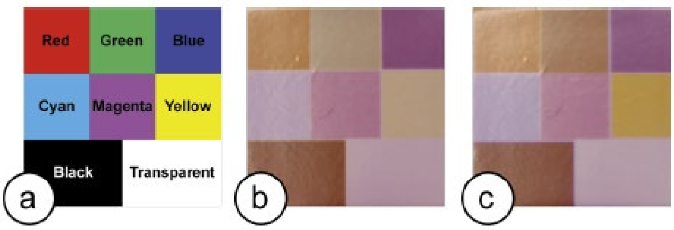

Figure 5 (a) Expected results. Result from (b) the naive approach and (c) obtained optimization.

To achieve as close as possible to the target result shown in Figure 5a, we capture the activation times of each dye when exposed to each of the wavelengths R, G, and B, respectively from the projector. The saturation level of each projected R, G, B color bar linearly increased from left to right over time until it reached the right edge of the cube (Figure 12). This procedure created a color gradient from

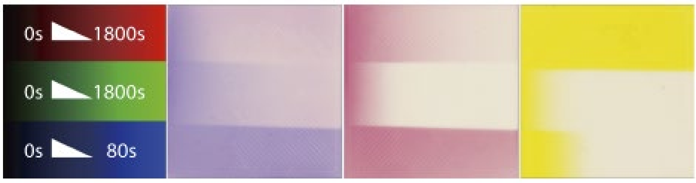

Figure 6 Effect of exposure time of R, G, B projector channels on C, M, Y coating.

fully saturated dye (left) to increasingly desaturated dye (right) and intermediate saturations in between. We then extracted the relative saturation level by capturing a photo of each cube under white light, converted the photo to the CMY color space, and plotted the saturation per color channel as the relative saturation decrease over time. The experiment found the relative saturation levels over time for each dye and each of the projector's color channels. While each of the projector's R, G, B LEDs deactivated its primary photochromic color channel, the activation time varied significantly from 32 seconds for the yellow dye under blue light to 620 seconds for the magenta dye under green light and

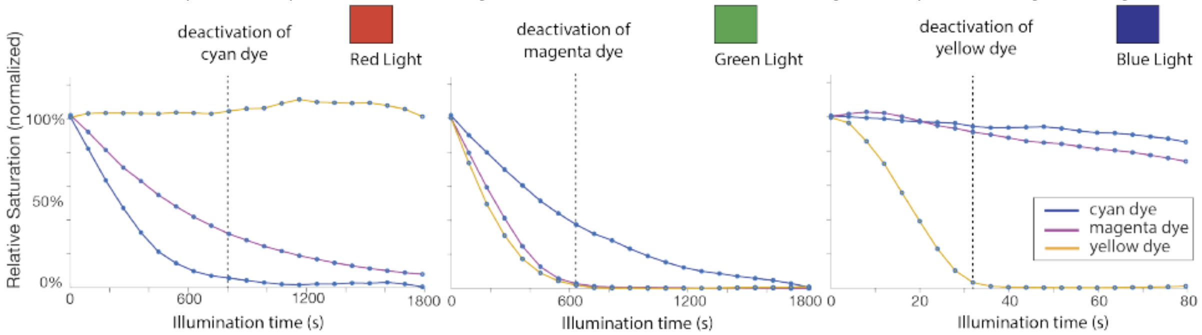

Figure 7 Deactivation times of the photochromic dye per light channel (R, G, B). We consider a dye to be deactivated when it drops below 5% saturation.

800 seconds for the cyan dye under red light, respectively. Figure 7 shows the results obtained from the experiment. We used the data on relative saturation level over time as input into our approximation algorithm. To minimize the global error rate across all three channels, we calculated all the time to illuminate each color channel through projector, then estimated color of a coated surface, which are a linear factors on the saturation reduction in relation to the illumination time per color channel. As showed in Figure 6c, or greatest enhancement is in the yellow color, a result of our optimization algorithm, which prioritizes the red LED over a combination of the red and green LED (as predicted previously) to deactivate the cyan and magenta dyes (because the green LED also deactivates the yellow dye).

AVAILABLE COLOR GAMUT

Finally, we investigated the available color gamut we could achieve with the photochromic dyes. To determine this, we placed a white cube coated with the CMY solution and fully activated it with the UV light until the coating appeared black. To sample the available color gamut, we took 5 images at evenly spaced deactivation times across the maximum deactivation length, i.e. for red/green: 1800s and blue: 45s. This created 5x5x5 sample images. After each light exposure, we used a camera to capture an image of the resulting outcome. We then converted the image into the CMY color space and extracted the mean value of each color channel using an OpenCV script. As shows in Figure 8, the captured texture colors of this experiment shows the available color gamut in CIE chromaticity diagram. Our color gamut has its greatest impact in the area between the three primary photochromic colors.

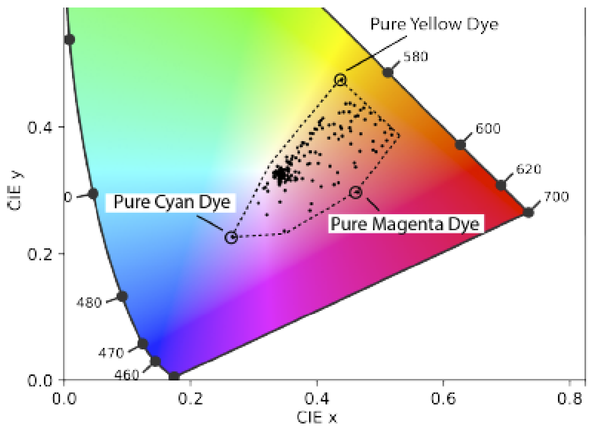

Figure 8 Achievable color gamut of our photochromic coating in the CIE chromaticity diagram.

CONCLUSION

In this research, we demonstrated how we can use photochromic dyes mixed into a single solution to create re-programmable multi-color textures that are made from a single material. We investigated the potential improvement over the color gamut and the optimization parameters for the colors activation that maximize the visible color while minimized overlap in deactivation wavelength. In addition, we also demonstrated how to create a mixture solution that provides even saturations in each color channel. For the future work, we plan to further increase the capabilities of our system by collaborating with material science researchers to develop improved photochromic dyes and extending our fabrication methods to 3D printing with filaments and resins.

キーワード： photochromic, digital fabrication, human-computer interaction

研究経費（R1 年度）の内訳

備品費	消耗品費	旅費	謝金	その他	合計
円	166,240 円	52,760 円	円	33,000 円	252,200 円

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発表論文等（令和 2 年 3 月 31 日現在）

研究代表者および主な共同研究者の研究業績のうち、本研究課題に関連するもののみを、現在から順に発表年次を過去に遡って記入してください。

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〔その他〕

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