Permanence Testing of 3D-Printed Objects Subjected to Fade Testing with Outdoor Sunlight and with High-Intensity Fluorescent Illumination and Evaluated with a Multispectral Camera and Image Analysis System

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Abstract

In the past two decades, 3D printing using polylactic acid (PLA) and other plastics has become widely used for modeling, prototyping, and manufacturing for both professional and amateur applications. Statistics website <www.statista.com> predicts that the global 3D printing market will grow from $12 billion in 2018 to $20 billion in 2021. Like 2D-printed signs, prints, and photos, 3D-printed objects, if placed outdoors or in windows, will be exposed to visible light and UV radiation that can cause colorant fading, surface chalking, crazing, and other degradation (including a loss of brightness in the case of fluorescing colors). Little recent work has been published concerning testing of 3D-printed materials for light fading, ozone resistance, and long-term dark storage stability.[1] To develop a protocol for permanence testing of 3D-printed objects, the authors first developed a 3D-printable test target inspired by the widely-used Macbeth ColorChecker. Fade-resistance testing of samples placed in the 3D color test target was conducted under accelerated fluorescent illumination and exposed directly to outdoor sunlight.

Introduction

The authors have developed a 3D-printed color test target for assessment of color permanence in 3D-printed objects, and for use in a test that could be evaluated with a large data-set multispectral camera and analysis system. The multispectral camera records CIE LAB values similar to a spectrophotometer but measures non-flat objects more accurately – and much more quickly – than is possible with desktop or hand-held spectrophotometers. The large data-set capture time with the MegaVision EV system for 16 spectral bands is just 1 minute and 16 seconds. For capture of 26 spectral bands (including special multi-filter image captures with a filter wheel for analysis of degradation of UV-excitation of fluorescing colorants) is 3 minutes and 15 seconds. The system allows for the capture of more than 10,000 individually addressable LAB data points; capture times are the same regardless of the number of data points specified.

The 3D-printable color test target (Figure 1) was inspired by the widely-used Macbeth ColorChecker. The plastic 3D-printed target includes a holder with 6 columns and 4 rows of indentations into which 1×1-cm 3D-printed cubes or flat, square tiles can be placed. Once installed in the holder, the 3D-printed materials can be subjected to fade testing. The design also includes a protective clear lid with 0.5×0.5-cm openings that hold the test tiles in place during transport, but still allows unimpeded light exposure of the color tiles. The 3D .stl print files for the test target are posted on the Wilhelm Imaging Research website and can be freely used by anyone without cost. Although not intended for 3D printing, a conceptually similar flat customizable camera test target with individual user-installable target patches is available from Image Science Associates.[2]

Figure 1. *Photo of the Ryerson-Wilhelm Imaging Research 3D-printed color test target, one with 1-cm cubes (top right) and the second with 1x1x0.5-cm square tiles (bottom left). The color cubes or flat, square tiles can be 3D-printed and exposed to high-intensity indoor illumination, placed in outdoor sunlight weathering tests, subjected to ozone resistance tests, or to long-term (Arrhenius) dark stability tests. During the course of the tests, the samples are measured spectrophotometrically with a multispectral camera, and image analysis software is used to quantify fading, color balance shifts, staining, chalking, and other types of degradation.*

Figure 2. *Jeremy Littler works in Ryerson University's Digital Fabrication Lab (Digital FabLab) with the Prusa MK2 3D printer that printed the 3D color target. For this project, PLA filaments of various colors were used to print the test target color patches.*

3D Color Test Target .stl Files

A ZIP archive, downloadable from http://www.wilhelm-research.com, contains 4 files in STereoLithography (.stl) format that can be used to make 3D prints of the 4x6-cell color Ryerson-Wilhelm Imaging Research test target:

- *Ryerson-WIR_3D-Printed_Test_Target_Clearcover_2018-07-12 – cover for the target to keep the chips from falling out.*
- *Ryerson-WIR_3D-Printed_Test_Target_FlatCube_2018-07-12 – test patches that can be printed in different colors.*
- *Ryerson-WIR_3D-Printed_Test_Target_TrayWithBevelandRuler.stl – holder for the test patches.*
- *Ryerson-WIR_3D-Printed_Test_Target_TrayWithoutRuler.stl – another design for the holder for the test patches.*

Table 1. Ryerson-WIR Color Test Target Data

Number	Position	Color	Fluores-cence	ΔE2000	C*	ΔC*	L* UV	Scaled L* UV
Control (Reference Sample, Stored in the Dark)								
1	A1	yellow	low		88.3			
2	A2	green	high		22.8		32	100.0
3	A3	blue	medium		55.9			
4	A4	magenta	low		35.6			
13	B1	white	high		3.8		34	100.0
14	B2	black	low		11.7			
15	B3	red	high		46.1		23	100.0
16	B4	orange	high		53.6		24	100.0
Fluorescent Illumination (Cool White Lamps, Bare-Bulb Exposure)								
5	A5	yellow		2.6	77.6	10.7		
6	A6	green		15.0	30.7	-7.9	16	50.0
7	A7	blue		2.1	54.9	1.0		
8	A8	magenta		7.6	27.8	7.8		
17	B5	white		0.6	3.5	0.3	24	70.6
18	B6	black		7.8	4.3	7.9		
19	B7	red		4.4	41.9	4.3	25	108.7
20	B8	orange		2.7	48.7	4.9	23	95.8
		Average		**5.4**		**3.6**		**81.3**
Outdoor Sunlight (Weathering with Rainfall and Snow)								
9	A9	yellow		5.4	66.7	21.6		
10	A10	green		9.5	19.6	3.3	17	53.1
11	A11	blue		3.9	46.7	9.2		
12	A12	magenta		11.1	18.6	17.1		
21	B9	white		5.4	7.0	-3.1	13	38.2
22	B10	black		13.2	3.9	7.8		
23	B11	red		5.5	34.5	11.7	21	91.3
24	B12	orange		7.8	34.6	19.0	20	83.3
		Average		**7.7**		**10.8**		**66.5**

Figure 3. *Charles Wilhelm removes a 3D color target from an accelerated fluorescent test unit.*

Figure 4. *Richard Adams with a 3D color target in the outdoor location where it was exposed to sunlight, rain, and snow for one year.*

Permanence Testing Protocols

3D color test targets were printed at Ryerson University's Digital Fabrication Laboratory (Digital FabLab) with a Prusa MK2 3D printer [3] and a CraftBot 3D printer [4] with a variety of polylactic acid (PLA) filaments of various colors (Figure 2).

For the "raw materials" to build 3D-printed objects, most 3D printing systems utilize filaments made of various polymers, including PLA, ABS, PET-G, PVA, TRU, and Nylon. The filaments are supplied in a wide variety of colors (many of which are highly saturated colors), and it is these colorants incorporated into the filaments that impart colors to the finished object.

Most current 3D printers are capable of printing only one color (one filament) at a time. The Ryerson-Wilhelm 3D Color Test Target allows color tiles to be printed individually using separate filament colors; the color tiles can then be inserted into the 3D-printed test target frame to easily create a multi-color test target. Some printers, including the HP JetFusion 500 Series 3D printers (which uses an inkjet assisted sintering 3D printing process with CMYK color capabilities), the 3D Systems ProJet CJP 660Pro 3D printer, and the XYZprinting daVinci Color FDM 3D printer (which uses in-line CMYK inkjet printing of a special ink-receptive filament to impart colors) and is claimed to be able to print "high-resolution, full color" objects directly with the color information encoded into the printing files. Some 3D-printed objects are spray-painted or otherwise have colorants applied after printing. This is especially common with large 3D-printed objects, or where brilliant, highly-saturated colors with deep blacks are desired. Because of market demand, "Color-Capable" 3D printing systems are certain to become more commonplace in the future.

Regardless of how colorants are incorporated into 3D-printed objects – or are applied as a separate process after printing – the multispectral imaging and analysis procedures described in this paper can be used to quantify color fading, color balance shifts, yellowish staining, chalking, and other types of degradation.

Accelerated Light-Fading Tests

Fade-resistance testing of samples in the 3D color target was conducted under accelerated fluorescent illumination (Figure 3) and in outdoor sunlight (Figure 4). After being exposed to 25 klux fluorescent light for 24-hour, 1-week, and 1-month intervals, the samples were measured with a MegaVision EV Multispectral camera and image analysis system[5] as shown in Figures 5, 6, 7, 8, and 9, and delta-E color difference values were calculated.[6]

C* chromaticity and ΔC* chromaticity differences were calculated (Table 1) and graphed (Figure 5) to compare the

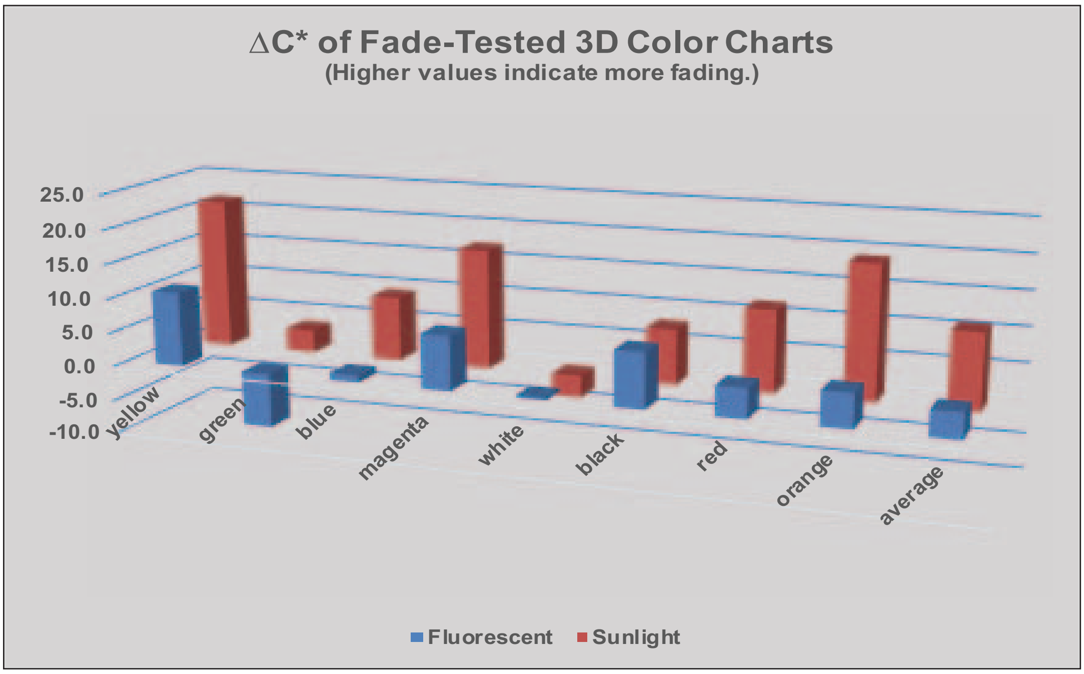


***Figure 5**. Graph of the change in chromaticity (C*) of color patches exposed to fluorescent light and outdoor sunlight. The samples illuminated with sunlight (red) showed the greatest decrease in chromaticity due to light fading.*

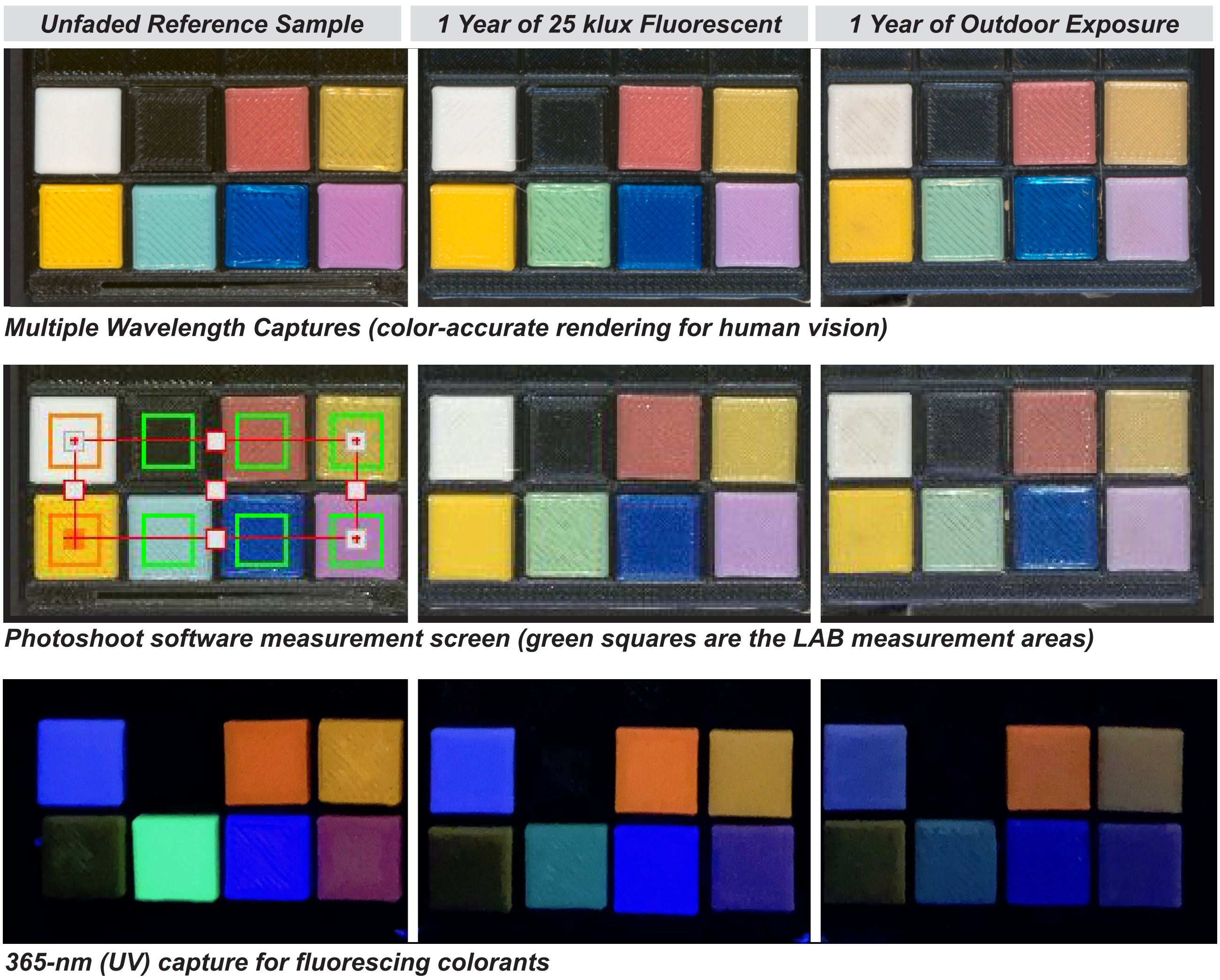


***Figure 6.** Top: 3D-printed color test targets captured by the MegaVision EV camera (left to right): control, fluorescent illumination, outdoor sunlight. Middle: Screen capture showing 4x2 measurement grid used to read LAB values in the MegaVision PhotoShoot software. Bottom: The same three 3D color targets (control, fluorescent, and sunlight) photographed under 365-nm UV illumination. Note that considerable degradation of the fluorescent dye has occurred in four of the most stable colors (white, green, orange, and yellow).*

chromaticity differences for the fluorescent- and sunlight-faded color patches with the control.

Testing the Degradation of UV-Excitation of Fluorescing Colorants

Some of the PLA colors used to print the target patches for this project contained significant levels of UV-excitation components, as revealed by examination under UV illumination (Figure 6). To assess degradation of the UV-excited components, the 365-nm TIFF file created by MegaVision Photoshoot software that was opened in Photoshop. The colors that were observed to have "high" levels of fluorescence (green, white, red, and orange) were measured with Photoshop's Grayscale Information Palette (scale, 0–100%) and the cursor. Measurements of the fade-tested target (Table 1, column 7) were scaled (column 8) with reference to the control target.

Results

Accelerated Light Fading

Table 1 shows the C* chromaticity values and ΔC* color differences between the unexposed control and the targets exposed to sunlight and fluorescent light for one year. (Positive numbers indicate a greater reduction of chromaticity.)

The ΔC* measurements (column 6) show that exposure of the 3D-printed color patches to fluorescent light and sunlight resulted in fading, as reflected in the reduction in chromaticity values. (The green patch gained slightly in chromaticity upon exposure to fluorescent light.)

Degradation of UV-Excitation of Fluorescing Colorants

The UV reflectance values of the 365-nm exposure (column 7) and scaled values (Column 8) show the extent to which the UV brighteners faded upon exposure to fluorescent light and sunlight. On average the fluorescing components "faded" to 81.3% of their original levels on exposure to fluorescent light and to 66.5% on exposure to sunlight.

Permanence Testing Using a High-Resolution Multispectral Imaging and Analysis System

MegaVision has developed a multispectral imaging system that employs a high-resolution monochrome area sensor array (50 megapixel CCD array with a file size of 100 MB at 16 bits per wavelength recorded); files are saved in uncompressed RAW format. Image capture time is 4 seconds per frame; a 16-band image capture requires about 1 minute and 15 seconds.

The MegaVision system uses narrow-band LED's, ranging from near UV to IR, in place of white light as the illuminant (nominally covering the 350–1000 nm range of silicon detectors). This arrangement improves by one or more orders of magnitude the efficacy of the light energy illuminating the scene (important, for example, where damage to delicate museum objects from light exposure is a concern) and eliminates the many problems associated with changeable filters in the optical path. Ten of the nominally nineteen (or more) spectral bands cover the visible range; additional spectral bands, including in the UV and IR regions, can be employed if desired.

The LED illumination system typically includes 50,000-hour-rated LED's with up to nineteen specific wavelengths, including:

UV: 365, 385, 400 nm

Visible: 420, 450 470, 505, 530, 560, 595, 615, 630, 655 nm

Infrared: 700, 735, 780, 850, 940, 1050 nm

Figure 7. *Richard Adams (left) and Charles Wilhelm expose the three 3D color targets on the MegaVision EV multispectral camera in order to capture LAB measurements of the color patches. Photos taken with white setup and red, green, and UV exposures.*

Figure 8. *Henry Wilhelm adjusts the MegaVision EV Multispectral Camera. The EV is a spectral imaging system that employs a 50-megapixel monochrome CCD with a configurable LED array of up to 19 narrow-band LEDs (visible in upper right corner: UV 365, 385, and 400 nm; Visible 420, 450, 470, 505, 530, 560, 595, 615, 630, and 655 nm; and IR 700, 735, 780, 850, 940, and 1050 nm) in place of white light as the illuminant.*

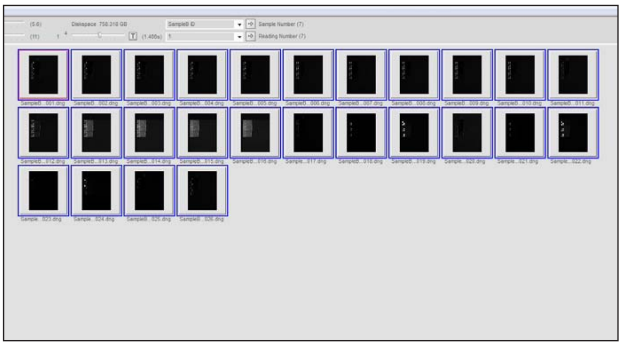


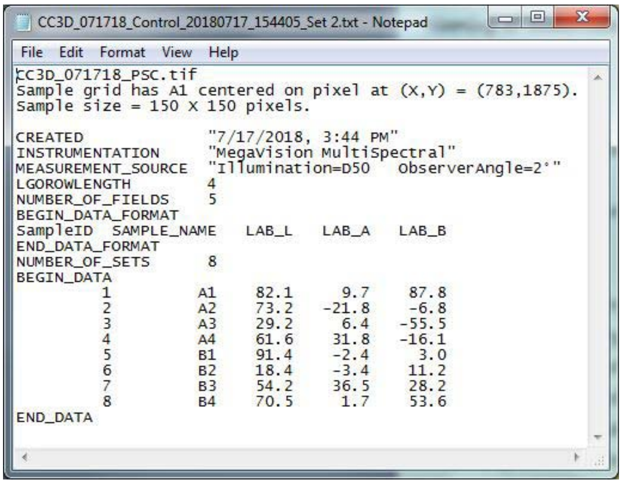
Figure 9. *Multispectral image capture from the MegaVision EV shows 26 RAW (or DNG format) files captured at wavelengths from 365–1050 nm. With a 50-megapixel monochrome sensor, each capture file is 102 MB, with all 26 files amounting to 2.7 GB. Without the use of the filter wheel, 16 captures total 1.6 GB.*

To date, the MegaVision EV multispectral camera has primarily been used in the cultural heritage field, including making very accurate color reproductions of manuscripts and works of art. The camera is being used for imaging historical documents at the Library of Congress in Washington, D.C., including drafts of the United States Declaration of Independence. The system is also being used by the Israel Antiquities Authority in Jerusalem <www.antiquities.org.il> for high-resolution, multi-spectral imaging of the 2,000-year-old Dead Sea Scrolls.

The MegaVision EV multispectral camera is fitted with a specially designed 120mm f4.0 UV-VIS-IR hyperspectral lens that is apochromatic and maintains the same focus point over the full range of wavelengths from 350 to 1050 nm.

Use of a Color Filter System in Quantifying the Degradation of UV-Excitation of Fluorescing Colorants

MegaVision's Color Filter Wheel (CFW, Figure 12) provides front-of-the-lens filtration for a range of color image capture and scientific imaging applications. The CFW contains either one or two coaxial filter wheels; each wheel has 4 filter ports. The 61-mm filter ports enable vignette-free use with a wide range of optics, including MegaVision's 120-mm hyperspectral lens. Standard 67-mm rings on both wheel housing ports facilitate external interfaces with standard filters, lens shades, and other modifiers. The CFW can be fitted with a range of gel, polyester, resin, or thin (up to 2 mm) glass filters. A standard single-wheel configuration includes one clear opening and red, green, and blue color separation gel or polyester filters. In dual-wheel configurations, each wheel is independently controlled and incremented, so arbitrarily selected filters from each wheel may be super positioned.



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CC3D_071718_Control_20180717_154405_Set 2.txt - Notepad
File  Edit  Format  View  Help
CC3D_071718_PSC.tif
Sample grid has A1 centered on pixel at (X,Y) = (783,1875).
Sample size = 150 X 150 pixels.

CREATED              "7/17/2018, 3:44 PM"
INSTRUMENTATION      "MegaVision MultiSpectral"
MEASUREMENT_SOURCE   "Illumination=D50   ObserverAngle=2°"
LGOROWLENGTH         4
NUMBER_OF_FIELDS     5
BEGIN_DATA_FORMAT
SampleID  SAMPLE_NAME   LAB_L   LAB_A   LAB_B
END_DATA_FORMAT
NUMBER_OF_SETS       8
BEGIN_DATA
        1        A1     82.1     9.7    87.8
        2        A2     73.2   -21.8    -6.8
        3        A3     29.2     6.4   -55.5
        4        A4     61.6    31.8   -16.1
        5        B1     91.4    -2.4     3.0
        6        B2     18.4    -3.4    11.2
        7        B3     54.2    36.5    28.2
        8        B4     70.5     1.7    53.6
END_DATA
```

Figure 10. *This CGATS standard file of LAB color readings is the output of the MegaVision Photoshoot software. The readings correspond to the 8 green rectangles in Figure 7.*

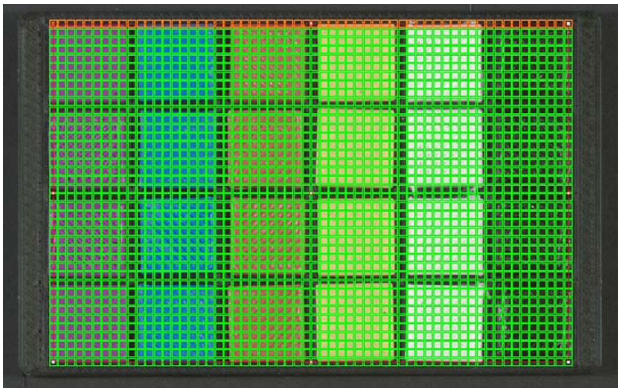

Figure 11. *The MegaVision multispectral camera can be thought of as a high-resolution spectrophotometric camera. With separate captures of the image at each LED wavelength (the Image Stack),* ***each*** *pixel of the 50-megapixel sensor is able to export full LAB data. It is quite practical to have ten-thousand or more LAB data points for test targets with large-data sets (the capture time remains the same regardless of the number of data points), or when capturing data from a highly detailed 3D-printed object – for example, a full color rendering of a human face. With successive captures over time, the fading and staining of full tonal scale skincolors — as well as other colors — can be measured as fading and color shifts progress.[7] The Megavision camera can be mounted on a tripod and, accompanied by the LED lamp panels, can be used in the field to image objects – including large-format graphics, photographs, and paintings – on location. All that is required is that the captures be done at night, in dark room, or in an otherwise dark location.*

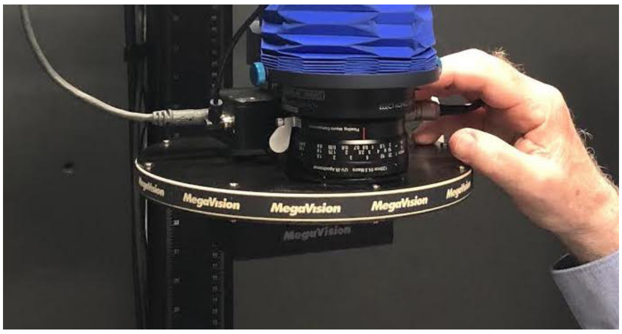

Figure 12. *A closer view of the MegaVision EV camera showing the filter wheel that can be used to isolate selected wavelengths of illumination in order to quantify degradation of UV-excitation of fluorescing dye and pigment colorants. The filter wheel is also extensively used in the examination of cultural heritage objects.*

The CFW increments to an adjacent filter position in about 1 second. Smooth acceleration and deceleration ensure minimal vibration and motion transients.

CFW control and utilization are completely integrated into MegaVision's image capture software application, PhotoShoot. When used with MegaVision's narrow-band multi-spectral imaging system, the CFW provides the capability to not only render color images of great accuracy, but also to quantify and discriminate between the reflectance and fluorescence components of the color in the images.

When integrated into MegaVision's multispectral imaging system, the CFW plays a crucial role in discovery. Features that are not visible often leave invisible traces that can be discriminated from the background by fluorescence. Often, the fluorescence is weak, and without the filter wheel the weak fluorescence signal is swamped out by the strong excitation light. Filtering the excitation light can enable the discovery of invisible features. Alternatively, some features transparent to visible light may reflect UV radiation which cannot be seen by humans, but can be detected by a silicon sensor. To this end, the CFW is commonly fitted with both a UV-pass filter and one or more UV-blocking filters.

Summary

The Ryerson-Wilhelm 3D Color Test Target provides an easy-to-print color test target incorporating multiple 3D-printed colors for use in assessing the color permanence and fluorescing colorant degradation with 3D-printed objects.

The colorant degradation analysis procedures described here are also applicable for spray-painted 3D-printed objects and with other types of post-printing application of colorants. The 3D color test target was specifically designed for comprehensive, large data-set multispectral imaging and analysis systems; however, if necessary, it can also be used with desktop and hand-held spectrophotometers.

The 3D-printed test targets and the multispectral imaging and analysis procedures described here can be used with a broad range of accelerated aging tests, including indoor and outdoor light exposure and weathering tests, predictive multi-temperature thermal aging (Arrhenius) tests, water-resistance tests, high-humidity and cycling humidity resistance tests, and tests for resistance to ozone and other atmospheric pollutants.

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[1] For an important early research paper on this topic, see: Maja Stanic and Branka Lozo, "Permanence and Color Stability in 3D Ink-jet Printing" Technical Program and Proceedings – IS&T's NIP26: The 26th International Conference on Digital Fabrication, pp. 541–544, Sept. 19–23, 2010.

[2] Image Science Associates, ColorBuild Mini Target, retrieved from http://www.imagescienceassociates.com/mm5/merchant.mvc?Screen=PROD&Store_Code=ISA001&Product_Code=CB24MINI&Category_Code=TARGETS

[3] Prusa MK2 3D printers and Prusa filaments are supplied by Prusa Research SRO, Partyznska 188/7a, Prague, Czech Republic 17000. Prusa also has a distribution office in the United States. https://www.prusa3d.com

4] CraftBot 3D printers and filaments are supplied by CraftUnique, Salgotarjani Street 12-14, Budapest 1087, Hungary; https://craftbot.com

[5] MegaVision, Inc., P.O. Box 60158, Santa Barbara, California 93160; telephone: 805-964-1400; http://www.mega-vision.com/cultural_heritage.html

[6] Henry Wilhelm, Ken Boydston, Kabenla Armah, and Barbara C. Stahl, "Use of a Multispectral Camera System and Very Small, Comprehensive 'Micropatch' Test Targets for Full Tonal Scale Colorimetric Evaluation of the Permanence of Digitally-Printed Color and B&W Photographs," Proceedings of "Imaging Conference Japan 2011," pp. 131–134, The Imaging Society of Japan, Tokyo, Japan, 2011.

[7] Henry Wilhelm and Dmitriy Shklyarov, "Evaluating the Image Permanence of Full Tonal Scale Human Skintone Colors in Photographs Using the CIELAB Colorimetry Based WIR i-Star 'Retained Image Appearance' Metric," Technical Program and Proceedings – IS&T's NIP23: The 23rd International Conference on Digital Printing Technologies, pp. 743–748, Sept. 16–21, 2007.

Author Biographies

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Henry Wilhelm *is Director of Research at Wilhelm Imaging Research, Inc. in Grinnell, Iowa, USA. Wilhelm has authored or co-authored more than 30 technical papers presented at conferences sponsored by the Society for Imaging Science and Technology (IS&T), the Imaging Society of Japan (ISJ), and the American Institute for Conservation (AIC) in the United States, Europe, Japan, and other countries. He was one of the founding members of American National Standards Institute (ANSI) Committee IT-3, established in 1978. The Committee is now known as ISO Working Group 5/Task Group 3 (a part of ISO Technical Committee 42). Working together with Yoshihiko Shibahara of Fuji Photo Film Ltd. in Japan, Wilhelm served as Co-Project Leader of the "Indoor Light Stability Test Methods Technical Subcommittee" of ISO WG-5/TG-3. ISO International Standard 18937 – Imaging Materials – Photographic reflection prints – Methods for measuring indoor light stability (58 pages) was published in January 2014. Wilhelm is currently serving with Shigeo Suga of Suga Test Instruments Co., Ltd., Tokyo, Japan, as Co-Project Leader for the development of the new ISO 18937-3 accelerated test methods standard for LED illumination sources.*

Jeremy Littler *is the Lead for Emerging Technologies at Ryerson's Faculty of Communication and Design (FCAD). He is a desktop 3D printing/fabrication specialist and was the lead designer of FCAD's FabLab (fablab.ryerson.ca). Littler utilizes a wide range of FDM and SLA printers for multi-material 3D printing projects. These capabilities will be further expanded in the new Creative Technologies Lab being developed at Ryerson University.*

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