

Color Calibration Based on Mosaic Stitching of a Color Target as an Alternative to a Single-Shot Approach

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Abstract

Color targets come in different designs, sizes and surface finishes. A high quality color target such as the Next Generation Target (NGT)¹, designed for the Library of Congress, has a glossy finish that makes it sensitive to the light-setup geometry. When the NGT color target is to be captured orthogonally, i.e. both the camera and the light share the same plane and lie on the normal of the target's surface, even with cross-polarization in place it is not possible to completely eliminate the high reflections caused by the camera/light geometry – unlike for less glossy color targets such as the X-Rite SG CC – not even if the camera/light setup were to be tilted at different angles. We are demonstrating in this paper that it is possible, however, to deploy a mosaic approach to capture the NGT color target at a tilted angle, masking out the reflections, and composing a rectified mosaic image out of only the clear parts of the target. The resultant ICC color correction profile for the mosaic image is proved to be viable to put in use and it satisfies all the necessary metrics for ISO level "A" when it comes to color calibration and color accuracy.

Introduction

Color calibration is the process of making the captured images, by an imaging system, and the displayed images on a monitor more accurate in color representation and rendition so that the colors look more in-line with the physical reality and carry more resemblance to the scanned object rather than being heavily post-processed (saturation, contrast enhancement, etc.), which would make it only more pleasant to the eye but not as accurate.

The recommended geometry for a proper acquisition of a color target, according to the ISO standards, is 0°/45° relative between the imaging system, the imaged surface and the light setup [4]. However, what if the color target does not fit fully inside the imaging system's field of view (FOV) such in having a camera with a Macro lens at close range, where the FOV is quite small and would require, usually, a smaller color target. Smaller color targets are, unfortunately, manufactured only with fewer color patches normally (e.g. X-Rite Nano 24 × 40mm with 24 patches, ColorGauge Micro Target 35 × 41mm with 30 patches) compared to the size of richer color targets with more patches (e.g. X-Rite SG CC 21.6 × 27.9cm with 140 patches, NGT 19 × 15cm with 130 patches).

Obviously, more color patches are more desirable than just a few as that will have a non-negligible effect on the color cor-

rection model and the end result of the color calibration process. More colors would allow better representation and more accurate interpolation which would, consequently, allow for a better and more precise coverage of the used color gamut as opposed to using fewer patches.

Cameras are known not to be colorimetric instruments as they do not satisfy Luther-Ives principle [12, 13]. In other words, there is no linear transformation that maps an RGB camera response to the actual colorimetric response of a stimulus [13]. Cameras capture and render colors in what is known to be a device-dependant color space (RGB). The aim of the color calibration process is to make the captured colors less dependent on the used imaging system itself and more related to how they look in reality, and that is by moving the colors into what is known as an independent color space (e.g. CIELAB, CIEXYZ). So, a non-linear transformation will be calculated to move a camera's response signal (RGB) into CIELAB/CIEXYZ of known color values, which are usually spectrally measured and transformed into CIELAB values of a color target².

The Problem

The ISO standards and any other recommendations in the field of color calibration assume the full color target to fit inside the camera's FOV, let alone the geometry between the camera, the light source and the target. i.e. capturing a color target for color calibration in a single shot with optimal 0°/45° geometry. However, in certain applications all the aforementioned requirements may not be possible to fulfill. For example, (a) due to the technical design of an imaging system [2] (see Fig.3), in which the light source and the optical system share the same plane rather than having 45° angle relative to one another, and/or (b) due to the high quality scan requirement where as many details as possible are to be captured with the help of a Macro lens at close range (i.e. smaller FOV), in addition to the desire of using the best possible color target for the color calibration and correction processes – which comes usually with more color patches and only in large sizes.

Using a Macro lens comes with few challenges though. One of them, is the small size of the camera's FOV which does not help much to fit a large color target (e.g. X-Rite SG CC or NGT) when better color calibration and color rendition are sought for high quality scans (e.g. digitizing museum artifacts in high details, small crafted reliefs, etc.). Another challenge is the geometric distortion any Macro lens suffer from.

¹The NGT color target we are using throughout this paper is NGT v1.0.

²For detailed practical step-by-step guidelines consult [4, 3]

We have prepared the following experiment and tested the following approach of scanning at a tilted angle rather than orthogonally, then running homography to re-project the captured images in a certain perspective and finally stitching in a mosaic-fashion the captured data to form a complete ortho-image from the scanned parts of a color target as if the whole color target was captured in a single shot and from an orthogonal view.

Stitching Approach

The most abundant example of a practical stitching algorithm are panoramic images, that most of the current smartphones are capable of creating on the fly. A stitching algorithm aims to merge a sequence of images, of a scene, taken separately –because the whole scene does not fit into the camera’s FOV all at once– into one complete image better known as a mosaic image (also referred to as the “*stitched image*”).

The sequence of the images must have an overlapping area shared between one another defining the starting and the ending regions of each image with its neighbouring images in the sequence so that the merge looks seamless and free of undesirable artifacts.

A stitched image may suffer from various artifacts though such as *edge vignetting*, *unsharp/out-of-focus regions in the image away from the image center*, *visible seam-lines along the stitched edges* and *a sudden change in brightness along the stitching line (aka. intensity shift)* [8, 16, 18]. These kinds of artifacts would make the final stitched image to look unnatural, let alone the distortion the image data undergo both in terms of geometry and photometry (color information).

Our stitching procedure consists of the following main steps:

1. Image acquisition
2. Image rectification
3. Image merging

The camera captures many images of a certain color target by moving across the color target at a pre-defined angle as it would be described later in the **Methodology** section, which results in different camera poses for each of the captured images. The rectified images are assumed to share the same camera pose though. Therefore, the captured images are not registered based on their features, but rather they are rectified based on a common virtual camera pose, check Fig.1. That means, all captured images are projected onto a common image plane, that is of a virtual camera. i.e. as if all the images were taken by the camera at the same pose, the pose of the virtual camera. All the rectified images are, then, merged in a mosaic-fashion to form what is known as the “*stitched image*” while applying some masking and blending techniques to keep the final image as sharp and as clean as possible that would be explained next.

2D Planar Image Rectification

In computer vision, a *plane-induced homography* maps a set of points from one image to another only when these points, from the two images, share the same real-world plane [9].

A homography is a linear transformation (i.e. a 3×3 matrix transformation with 8 degrees of freedom) in which one image plane P can be moved to another image plane \hat{P} using the following transformation as shown in Eq.1.

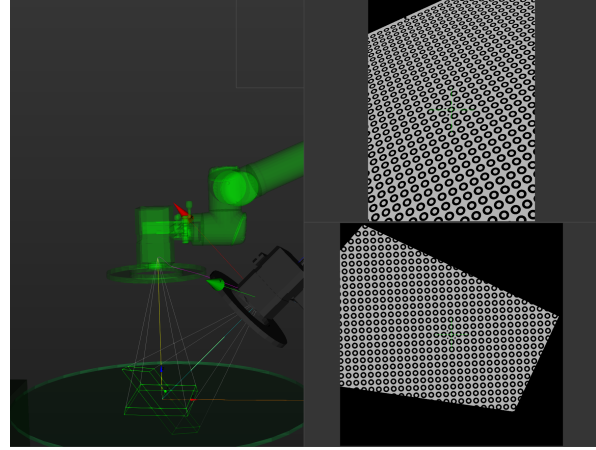


Figure 1: Left side - virtual camera (in green) vs. real camera (in black). Top right - captured image by the real camera. Bottom right - rectified image as if it were taken from the pose of the virtual camera

$$\hat{P} = HP : H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \quad (\text{Eq.1})$$

During the process of moving one image plane to another, a mapping from one image plane to the real-world plane is taking place, check Eq.2, where the scene’s points taken from a real-world 2D plane X, Y (assuming $Z = 0$) are being transformed into the image plane u, v . The mapping from the 3D world to the 2D image can, hence, be also inverted as it is shown in Eq.3.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \Pi \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = [\pi_1 \ \pi_2 \ \pi_3 \ \pi_4] \begin{bmatrix} X \\ Y \\ 0 \\ 1 \end{bmatrix} = [\pi_1 \ \pi_2 \ \pi_4] \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \quad (\text{Eq.2})$$

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = H \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \Leftrightarrow \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = H^{-1} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \quad (\text{Eq.3})$$

After the transformation from the real camera image plane to the real-world plane, now it is possible to map it once again onto the virtual camera image plane. The homography transforming from the real to the virtual image plane is given by Eq.4

$$H_{real \rightarrow virtual} = K_{virtual} \left(R - \frac{t n^T}{d} \right) K_{real}^{-1} \quad (\text{Eq.4})$$

The intrinsic matrices K are determined using the calibrated horizontal and vertical focal lengths in pixels f_u, f_v and the principal points c_u, c_v . The intrinsic parameters of the virtual camera need to be adapted to the increased size of the stitched image.

$$K = \begin{bmatrix} f_u & 0 & c_u \\ 0 & f_v & c_v \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{Eq.5})$$

The transformation from the measured real camera pose $T_{real \rightarrow world}$ to the defined virtual camera pose $T_{virtual \rightarrow world}$ is given by Eq.6:

$$T_{real \rightarrow virtual} = T_{virtual \rightarrow world}^{-1} T_{real \rightarrow world} = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \quad (\text{Eq.6})$$

Where t is the translation vector and R is the rotational matrix. The plane equation with the plane normal n given in the real camera coordinates and with the distance d from the real camera to the plane is written as in Eq.7:

$$n^T t_{real \rightarrow world} + d = 0 \quad (\text{Eq.7})$$

It is necessary to keep in mind, in order to run these transformations successfully, a camera calibration for the intrinsic and extrinsic parameters is required. Given the known distortion parameters as a result of the camera calibration, all the captured images would be corrected, subsequently, for any radial and tangential distortion. Images are, then, rectified when being transformed into the stitched image.

Depth of Field Masking and Vignetting

The unsharp regions of the rectified images are masked out based on the depth of field (DOF), a volume projected onto the captured plane [17]. The DOF volume is a slice of the pyramidal FOV volume that lies between the near and the far planes. The mask is not binary since the sharpness decreases, rather, gradually (Figure 2).

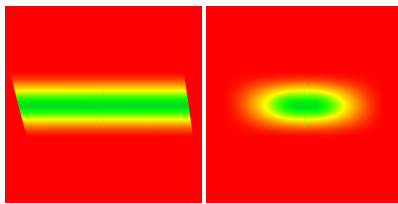


Figure 2: (a) A depth-of-field (DOF) mask, (b) DOF mask with vignetting.

The masked images are blended together into one stitched image using the weighted average method. The weighted average is the weighted sum of the images normalized by the sum of the weights. The weight of each pixel depends on its proximity to the center of the image. The farther a pixel is from the image center, the less it is weighted (vignetting effect).

Methodology Technical Design

The technical nature of a high resolution scans imposes on us the use of a Macro lens sometimes. In addition to the technical design of our scanning system that imposes yet another constraint regarding the geometry of the light in relation to the imaging system. The system uses a light source directly attached to the camera lens' body, better known as a ring-light due to its design, check Fig.3.

The ring-light is a ring varying in diameter with respect to the used lens, it has an opening in the middle where the camera

lens fits in and where the polarization filter is to be mounted. The ring-light is composed of tiny LED's fixed next to each other covering the whole surface area of the ring-light. The color correlated temperature (CCT) of the used LED's is D50 [7].

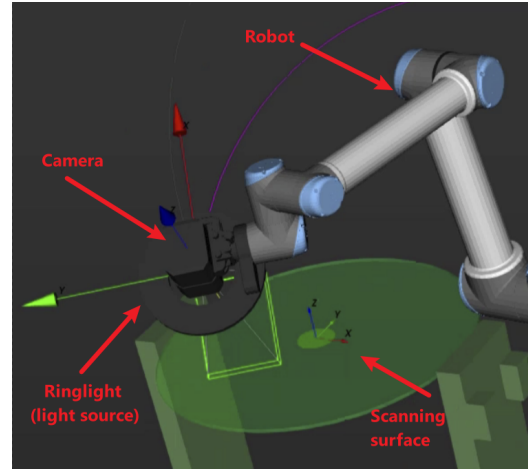


Figure 3: Our system design. Acquisition mode

Because of the geometry between the ring-light and the optical system a set of polarization filters were necessary to deploy so to cut out any direct and undesirable reflections and specularities that would obscure the photographed object. One circular polarization film is fixed on top of the ring-light directly (on top of the LED's), and one circular polarization filter in front of the lens to create a complete cross-polarization effect [10, 14]. Cross-polarization has non-negligible effect on the process of color calibration and hence on the accuracy of color both in terms of lightness and Chroma components depending on the scanned material [6].

A camera is fixed at the end-effector of a robotic arm. Finally, there is also a scanning table, better known as a turn-table as it can be controlled by a software for rotational movement, it is where the scanned object is to be placed on top.

Experiment

First, setup #1 Fig.4, we have prepared an anchor point to use as a reference and to compare against that complies more with the recommended ISO standards [4] in terms of light source (D50) and the scanning geometry $0^\circ/45^\circ$ with no polarization filters. We have chosen the exposure parameters (aperture, shutter speed and ISO number) based on a gray patch that has a $CIELAB(L^*) \approx 65$.

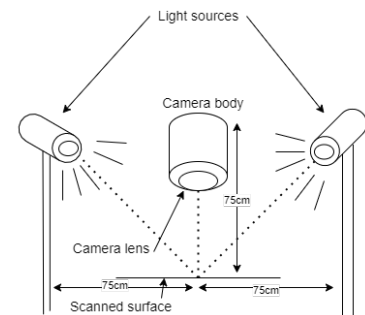


Figure 4: Setup#1 to define a reference anchor measurement for color calibration and metric calculations.

Two external light sources were mounted on both sides of the scanning table and tilted nearly 45° towards the scanned target.

Two color targets were selected for the experiment, namely X-Rite SG CC (#140 color patches) and NGT³ v1.0 (#130 color patches).

Next, setup #2, we removed the external light sources and mounted the ring-light on the camera lens returning the system to its default design, in which it usually operates, and with all the corresponding polarization filters in place. An illustration of the system design is shown in Fig.3

NGT color target has a very reflective and shiny finish making it with orthogonal acquisition geometry, even when it fits completely in the camera's FOV, impossible to scan cleanly in full with our system setup even with a perfect cross-polarization fixed in place and even if the camera/ring-light were to be tilted at an angle (i.e. when the light shines directly towards the target at a perpendicular angle 90° , one could clearly see the reflections of some of the ring-light's LED's), check Fig.5 – On the other hand, it is completely possible to scan X-Rite SG CC with the same setup with the help of cross-polarization eliminating by that all possible reflections completely.

For that reason, it is necessary in our system whether we are using a normal 72mm lens or a 100mm Macro lens to find another alternative to be able to scan the NGT color target rather cleanly and in a way that still guarantees ISO standards level "A" of color accuracy.

A stitching approach comes very handy in this situation, by taking multiple images at a certain angle ($45^\circ < \theta < 90^\circ$) to create one final image (mosaic) contains the full color target after performing a perspective correction to produce an ortho-image. However, a couple of questions arise here:

- What about the color accuracy of such approach?
- How much will the color calibration process would be impacted?
- Would the color calibration result be any comparable to the standard approach $0^\circ/45^\circ$?
- How viable is the resultant color correction to put in use?

We have decided, at this stage, to run an extensive tests rather on a normal 72mm lens first before moving to the Macro setup as the problem of the reflections NGT-v1.0 color target depicts -when being scanned perpendicularly with our system and that what we are trying to solve- is independent of the lens type.

So to summarize the experiment's setup hardware:

- A PhaseOne iXG 100MP camera body with 72mm lens.
- Two external light sources with D50 CCT.
- A ring-light full of LED's with D50 CCT - attachable to the camera lens.
- Brandless circular polarization film for the visible domain $380 - 780nm$ - to be fixed in front of the ring-light.
- A Circular polarization filter (Marumi) for the visible domain $380 - 780nm$ - to be fixed in front of the camera lens.
- An NGT v1.0 and an X-Rite SG CC color target⁴.

³NGT: Next Generation Target. Available via <https://www.avianrochester.com/nextgentarget.php>

⁴Ground-truth CIELAB values were measured spectrally beforehand using a Barbieri spectrophotometer LFP qb for each.

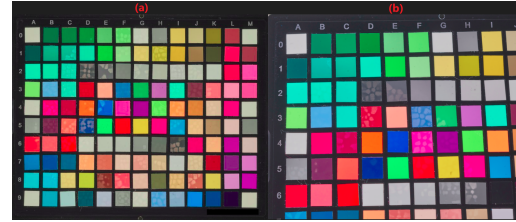


Figure 5: The reflections NGT shows despite the cross-polarization setup by (left:a) a perpendicular scan $0^\circ/90^\circ$ and (right:b) a $0^\circ/75^\circ$ geometry. Reflections seem to be inevitable due to the strict geometry the ring-light and the camera has in relation to each other.

Data Acquisition

The camera white-balance was set first with the help of a neutral gray patch, and the exposure settings (aperture, shutter speed, ISO number) were chosen based on a neutral gray patch as well with $CIELAB(L^*) \approx 65$ for both setups. The aperture was fixed to $f/11$ and ISO number to 100 always. In setup#2, the exposure was chosen so that the gray patch has $CIELAB(L^*) \approx 65$ at the angle of 65° as it turned out, heuristically, it yielded the best results while moving the camera across a color target while scanning it.

For data acquisition in setup #2, the robot was instructed to tilt at varying angles $45^\circ \leq \theta < 90^\circ$ to capture the needed data for evaluation. Despite the fact that, NGT color target still shows some reflections if the angle is not steep enough, look at Fig.5.

At each angle the algorithm will plan and decide the number of images required to capture based on the overlapping factor and the scanned surface diameter. Images were saved in their raw format (IIQ) to be converted later into 16-bit TIFF using COPE conversion engine that belongs to CaptureOne⁵ software with no alteration that would inflict the raw data. The following parameters were used during the conversion process:

- Gamma: linear scientific curve.
- Input ICC: no color correction.
- Output ICC: ProPhoto RGB.
- Output format: 16-bit TIFF.

We chose to export the 16-bit TIFF and move from the camera ICC profile into a more standardized output ICC profile *ProPhoto RGB* rather than keeping only the camera profile embedded as the guidelines in [3] says, because of the experiment implementation that expects an Image in ProPhoto RGB color space. *ProPhoto RGB* preserves the original RGB color information and is more adequate to carry out the necessary color transformations related to the color calibration procedure [15]. *ProPhoto RGB* fulfills as well the recommendations described by the ISO standards as a large color gamut larger than the calibration target itself [4].

The exported TIFF's were stitched, then, together after running homography and perspective correction as explained previously. The final mosaic stitched image was saved back in 16-bit TIFF with ProPhoto RGB color profile embedded.

At this stage, the image is ready for profiling. The RGB values will be extracted out of each of the color patches for creating

⁵<https://www.captureone.com>

the corresponding ICC profile using *ArgyllCMS*⁶. Then, the resultant ICC profile (color correction) will be applied on the TIFF image so we have the color corrected image of the color target, Fig.6. We will, then, convert it into JPEG format while embedding the *ProPhoto RGB* as the output ICC profile. The image is now ready for the color evaluation and assessment by extracting the color values once again -after correction- and moving them from *ProPhoto RGB* into CIELAB color space using the appropriate formulae and the necessary transformations, that are out of the scope of this paper to list all the details for, however you may refer to [11, 1]. An overview of the workflow is illustrated in Fig.7.

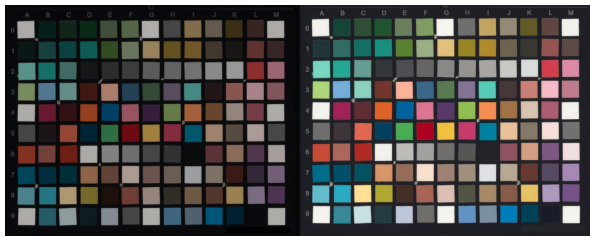


Figure 6: Example of the end mosaic stitched color target (NGT v1.0). Left: Gamma linear and before color correction. Right: after successful color correction [Avg(DE00) = 1.23 and Max(DE00) = 4.15].

Result

Tables 1 & 2 show the statistics of the used color targets after scanning at varying angles and with different overlapping factors/percentages, perspective correction, stitching, color profiling and finally color correction. The header reads (*Angle°/Overlap%*). The tables show 5 different metrics to assess and evaluate the color correction process according to the ISO standards level "A" for photography and archiving systems [5].

- DE00: color difference deltaE2000.
- RMS Noise: Root Mean Square Noise of a gray scale.
- WB DE(ab): White-Balance Chroma difference of a grayscale.
- TRC(L*): Tone Response Curve measured for CIELAB(L*) values of a grayscale.
- Gain Mod.: Gain Modulation describes the variation in the CIELAB(L*) slope of the TRC(L*).

Last column in both tables with the label "Single Shot" (indicated by †) is the statistics against which all the other measurements are to be compared. "Single Shot", setup#1, measurements were captured in complete accordance with the ISO standards, i.e. external light sources were mounted at nearly 45° angle relative to the scanned surface 0°, a camera was mounted orthogonal to the scanned surface with no polarization elements as shown earlier in Fig.4. Measurements that are indicated by "*" are those that satisfy all the aforementioned ISO standards metrics in the table and fall within the ISO standards level "A" apart from the single shot.

In Tables 3 & 4, we are showing the statistics of testing the resultant ICC color correction on a different set of colors (different color target), different from the one was used for creating the

color correction model. It shows the viability of putting the resultant ICC color correction profile in use for a different scan under the same conditions. More insights to follow next.

Discussion

It is evident that even when a color target has to be stitched, homographed, and mosaicked from multiple images to form one-image with an orthogonal view (Fig.6), it is still possible to fulfill the ISO standards level "A" in terms of color accuracy reproduction. Though, one needs to pay attention to other metrics other than just looking at the color difference (DE00) mean and max values. For instance looking at Table 1, for the NGT target, one notices an increase in the RMS Noise when the angle get closer to 90° moving from 0.72 at 45°/60 up to 1.49 at 85°/60 (noise is nearly doubled). The White balance Chroma difference also undergoes noticeable change from a max value of 1.9 at 45°/60, 65°/50 and 65°/30 to 3.0 at 85°/60. The tone curve (TRC) gets worse and worse the closer the angle to 90° which is reflected in the gain modulation⁷ especially in the min value that is deviating farther away from 1.0. X-Rite SG CC shows less significant changes in comparison to NGT v1.0 target at varying angles.

It is worth noticing that, even the used anchor point "Single Shot" for this experiment that is more conforming with the ISO standards in respect to the geometry, the capturing and profiling procedures, it is still challenging to completely fulfill all the specified metrics within the defined thresholds and limits. For instance, X-Rite SG CC at $\min(TRC(L^*)) \approx 4.2$ the value is quite out of the defined limit for ISO standards level "A". One of the grayscale patches, namely J6 with a reference value of $CIELAB(L^*) \approx 89$ will be mapped, while profiling, into $CIELAB(L^*) \approx 93^8$ -even using another ICC profiling software for proof-checking, a similar error would show up however for a different gray patch (e.g. using *BasIColor* input to create an ICC profile would map patch E5 a little bit higher throwing it also outside the ISO standards level "A" tolerance threshold E5 : 96 → 98.5). On the other hand, no such problem would occur when we use our approach of scanning, stitching and profiling a mosaicked image of the SG color target.

Looking at the NGT "Single Shot", it shows a noticeable Chroma difference (measuring neutrality) in $WB - DE(ab)$ of 2.87 while if the NGT is to be scanned at an angle and stitched it shows better neutrality that amounts to only 1.9 for the measurements that fall within the ISO level "A" limits.

Our approach of stitching and profiling proves to deliver better color correction statistics that are closer to the ISO recommendations for the highest level (level "A") especially for a challenging target such as the NGT that requires very careful lighting setup and geometry, otherwise it is impossible to scan cleanly without undesirable shiny reflections.

Tables 3 and 4 show the result of different sets of tests and validation that have been conducted for both approaches *Single Shot vs. our stitching mosaic approach*.

Table 3 shows the result for our stitching approach illustrating its viability of using the resultant color-correction on another scan under the same conditions. After capturing both targets -

⁷Gain modulation value should be ideally 1.0 for all gray patches

⁸Different experimental data with lower exposure settings -lower than recommended- showed more conformant statistics with the ISO standards level "A" where all the metrics are within the defined tolerance

⁶<https://www.argyllcms.com>

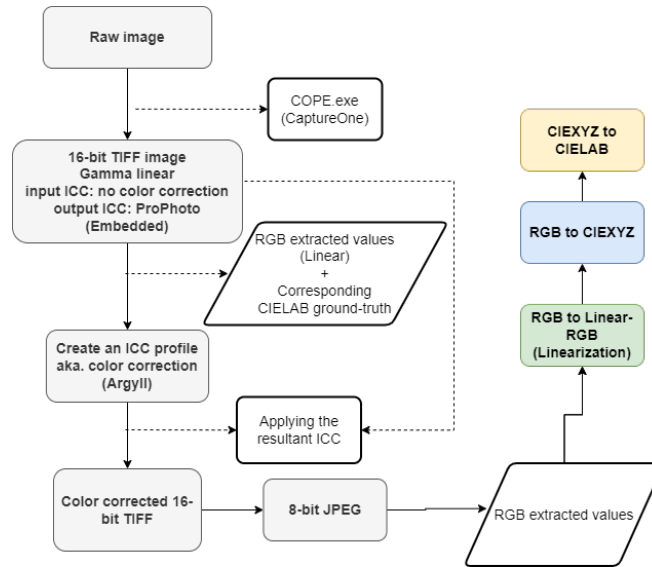


Figure 7: Steps of converting and moving color data from the raw format up until the final color corrected color converted into CIELAB color space for calculating the color difference (DE00).

NGT v1.0	ISO (A)	Angle/Overlap						*		*		† Single Shot	
		85°/60	85°/50	85°/30	75°/60	75°/50	75°/30	65°/60	65°/50	65°/30	45°/60	90°	
DE00	mean (≤ 4)	1.08	1.06	1.19	1.17	1.18	1.19	1.12	1.12	1.12	1.23	1.04	
	max (≤ 10)	4.35	4.45	4.51	4.06	4.28	4.28	4.17	4.18	4.31	4.15	4.05	
RMS Noise	max (≤ 1.6)	1.43	1.49	1.77	1.49	1.5	1.57	1.01	0.98	1.01	0.72	0.4	
WB DE(ab)	mean	1.11	0.99	1.06	1.2	1.22	1.23	1.06	1.1	1.08	1.18	1.12	
	max (≤ 3)	3	1.73	2.88	2.67	2.69	2.75	1.9	1.9	1.9	1.9	2.87	
TRC(L*)	min(-2)	-3.94	-5.05	-4.26	-3.18	-3.35	-3.48	-2.05	-1.82	-1.98	-1.49	-0.82	
	max(+2)	1.73	0.78	1.31	1.44	2.27	2.27	1.33	1.46	1.41	1.46	0.43	
Gain Mod.	min(0.7)	0.69	0.69	0.72	0.75	0.7	0.71	0.82	0.83	0.82	0.85	0.96	
	max(1.3)	1.12	1.1	1.12	1.3	1.21	1.22	1.16	1.18	1.17	1.1	1.07	

Table 1: NGT v1.0 statistics of the stitched and perspective-corrected color target at different angles and with different overlap percentage ($Angle^\circ/Overlap\%$) compared to standard profiling (indicated by '†') that adheres more to ISO recommendations $0^\circ/45^\circ$. Columns marked with '*' indicate the measurements that satisfy ISO level 'A' for color evaluation.

SG CC	ISO (A)	Angle/Overlap				† Single Shot	
		65°/60	65°/50	75°/60	85°/60	90°	
DE00	mean (≤ 4)	1.03	1.03	0.95	0.99	1.05	
	max (≤ 10)	4.44	4.29	4.25	4.15	4.31	
RMS Noise	max (≤ 1.6)	0.48	0.49	0.41	0.34	1.27	
WB DE(ab)	mean	0.93	1.02	0.74	0.99	0.86	
	max (≤ 3)	2.06	2.83	2.21	3.12	2.29	
TRC(L*)	min(-2)	-0.71	-0.71	-0.44	-0.75	-4.23	
	max(+2)	1.01	1.07	0.79	0.6	0.87	
Gain Mod.	min(0.7)	0.88	0.88	0.94	0.93	0.98	
	max(1.3)	1.05	1.05	1.09	1.03	1.30	

Table 2: X-Rite SG CC statistics of the stitched and perspective-corrected color target at different angles and with different overlap percentage ($Angle^\circ/Overlap\%$) compared to standard profiling (indicated by '†') that adheres more to ISO recommendations $0^\circ/45^\circ$. Columns marked with '*' indicate the measurements that satisfy ISO level 'A' for color evaluation.

NGT v.1.0 and X-Rite SG CC- with the aforementioned and described method of taking multiple images of a color target and then stitching them together in a mosaic fashion to form one complete image of the intended color target, each of the color targets were used to produce a color-correction ICC profile (train-

ing data). Then, the resultant ICC color-correction ICC profiles would be applied and validated on the other stitched color target (testing data). i.e. the ICC color-correction profile created using the NGT target would be validated on the X-Rite SG CC target and vice versa. In Table 4 the standard approach was followed

	Stitched Targets	NGT v.1 ICC		SG CC ICC		ISO (B)
	ISO (A)	NGT v.1	SG	SG	NGT v.1	
DE00	mean (≤ 4)	1.32	2.95	1.09	2.93	mean (≤ 5)
	max (≤ 10)	4.24	7.95	5.09	7.5	max (≤ 15)
RMS Noise	max (≤ 1.6)	1.07	3.11	0.52	2.82	max (≤ 2)
WB DE(ab)	mean	1.17	1.6	0.99	1.48	max (≤ 4)
	max (≤ 3)	1.88	5.48	3.16	5.39	
TRC(L*)	min(-2)	-2.76	0.8	-0.71	-6.2	min(-3)
	max(+2)	1.49	6.94	1.38	-0.21	max(+3)
Gain Mod.	min(0.7)	0.81	0.91	0.9	0.68	min(0.6)
	max(1.3)	1.14	1.19	1.11	1.16	max(1.4)

Table 3: Extra tests and validation. Scanning both color targets (NGT v.1 and X-Rite SG CC) under the same conditions, then stitching both of them and creating an ICC color correction profile for both, then testing each of the created ICC profiles on the other color target as shown in the table.

	Single Shot	NGT v.1 ICC		SG CC ICC		ISO (B)
	ISO (A)	NGT v.1	SG	SG	NGT v.1	
DE00	mean (≤ 4)	1.04	2.25	0.92	2.27	mean (≤ 5)
	max (≤ 10)	3.97	6.22	3.43	6.68	max (≤ 15)
RMS Noise	max (≤ 1.6)	0.38	0.81	1.52	1.06	max (≤ 2)
WB DE(ab)	mean	1.13	0.72	0.61	1.09	max (≤ 4)
	max (≤ 3)	2.87	1.32	1.41	1.6	
TRC(L*)	min(-2)	-0.64	-1.27	-4.95	-2.69	min(-3)
	max(+2)	0.44	1.19	1.22	1.1	max(+3)
Gain Mod.	min(0.7)	0.94	0.98	0.99	0.82	min(0.6)
	max(1.3)	1.06	1.08	1.3	1.29	max(1.4)

Table 4: Extra tests and validation under standard geometry $0^\circ/45^\circ$. Scanning both color targets (NGT v.1 and X-Rite SG CC) under the same conditions, then creating an ICC color correction profile for both and testing each of the created ICC profiles on the other color target as shown in the table.

using a "single shot" with geometry $0^\circ/45^\circ$ to create and test the ICC color-correction profiles.

The two Tables 3 and 4 show very similar trend and almost very comparable results. By looking, for instance, at the color difference *DE00* our stitching approach shows slightly increase in the mean and max error, where the mean is moving up to ≈ 3.0 and the max up to nearly $\approx 7.5 - 8.00$, whereas for the single-shot approach the error for the mean(*DE00*) is moving up to ≈ 2.25 and the max up to ≈ 6.5 .

The more noticeable change is affecting rather the grayscale patches, which are more sensitive to light fall-off and direction. For instance, $max(TRC)$ goes up to nearly ≈ 7.0 when correcting stitched SG CC target using the ICC profile of a stitched NGT v.1.0 target and that is caused by rather the dark patches of the grayscale like (J5) being mapped/corrected to have $CIELAB(L^*) \approx 10.0$ while its reference value measures to $CIELAB(L^*) \approx 17.0$ resulting in $\Delta(L^*) \approx 7.0$. The neutrality of the grayscale patches are also affected when correcting one stitched target using the other and that is apparent by observing the Chroma component *DE(ab)* that moves up to ≈ 5.5 .

Keep in mind that, the grayscale patches are very sensitive to the light direction, fall-off, and distribution. In addition to the fact that, using a stitching approach (composing a color target out of multiple and different images with different light fall-offs) can be challenging regarding choosing the parts that need to be stitched

and the used algorithm for averaging for example. It has been also proven while experimenting that, the NGT v.1.0 target is less challenging and less tricky than the X-Rite SG CC target while scanning and profiling especially when it comes to their grayscale accuracy reproduction and that could be due to many factors, one of them is the nature of their texture and the finish, in addition to the distribution of these patches across each of the targets and hence the light falling distribution.

Conclusion

Taking multiple images at an angle different from 90° of a color target and then correcting for their different perspectives and then stitching only the sharp and clear parts of them together to form one mosaic clean image with an orthogonal view, that is to be used for color profiling, can, with careful attention, pass ISO level "A" (i.e. the highest) in terms of color reproduction and accuracy.

NGT color target (v1.0) has a very reflective finish, which makes it impossible to scan in an orthogonal manner when the light source and the imaging system share the same plane, even with perfect cross-polarization in place the target still shows undesirable and visible reflections. Hence, scanning such kind of color target (material) by capturing multiple images at a certain angle $45^\circ \leq \theta < 90^\circ$ and stitching the clean parts into one mosaicked image seems to be a very practical solution that yields very com-

parable results (in some cases even better) to that if the target were to be scanned and profiled in accordance with the ISO standards recommendations (i.e. Single shot with $0^\circ/45^\circ$ geometry) as the statistics above can testify.

Our proposed stitching approach shows that the resultant ICC color-correction profile is very viable to use for color correction as it was shown in Table 3. Though, it is advised to pay extra care and attention if the scanned material/object is rather composed of mostly gray shades, which could be more sensitive to the light fall-off.

Furthermore, Our stitching and calibration approach produces very similar and comparable outcomes to the usual reconstructed 3D surface/texture as the proposed stitching approach resembles the mosaicking technique used in photogrammetry and other image-based 3D reconstruction software for texturing 3D models. Which makes it promising for color-correcting 3D objects, that proved to be very challenging so far for accurate color correction of their surface texture due to their (arbitrary) geometry and how usually fixed lighting setups would interact with the object's curvature.

Our system and technique of scanning uses a ring light attached to a moving camera and extracts only the sharp and the well-lit parts from each captured image, and thus ensuring comparable lighting conditions across all the extracted image parts during the whole scan of a 2D/3D object. As a result, we are able to compose at the end a homogeneous mosaic texture featuring an overall even light distribution that makes color-correcting for a texture of a 3D model more applicable.

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