Improving skin color accuracy in DLP-based 3D reconstruction

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ABSTRACT

Color accuracy is crucial in several domains such as biomedical imaging, cosmetics, and multimedia. Digital Light Processing (DLP) with LEDs has increasingly become a popular lighting source in 3D scanning systems. Although DLP provides advantages in 3D reconstruction, it poses challenges in maintaining color accuracy. Our research focused on using hybrid lighting to improve the color accuracy of DLP-based 3D sensing systems. We developed an empirical dataset featuring skin tones captured under multiple lighting environments, including variations in indoor ambient lighting. Through qualitative and quantitative evaluations of color differences, we conclude that including auxiliary lighting with DLP is beneficial for color accuracy, particularly in biomedical imaging and other applications in which color accuracy is essential.

Keywords: Color accuracy, Digital Light Processing (DLP), light sources, image color processing.

1. INTRODUCTION

Color accuracy is crucial for various applications, including biomedical, cosmetic, and multimedia, but it can be difficult to achieve in complex lighting situations.[1] LED-based digital light processing (DLP) projectors are a common primary light source in 3D scanning devices.[2] However, these projectors can cause color-related issues like chromatic aberration, spectral imbalance, and color temperature variation.[3] These factors can negatively impact color representation and require calibration for accurate imaging. Color measurements depend on the light source and the subject matter's optical properties.[4–6] DLP lighting can result in low color accuracy due to interactions with other light sources like indoor ambient light.[7,8] To address this, computational color constancy techniques are used to correct color in complex lighting conditions.[9,10] Despite advancements in these techniques, achieving high color accuracy in specialized applications such as medical imaging remains challenging, such as accurately reproducing skin color tones due to the skin's complex absorption, reflection, and scattering properties.

In many applications of 3D imaging, the color texture image is acquired simultaneously with the projected patterns used to recover surface topography.[11,12] One common method is Fringe Projection Profilometry (FPP) which uses uniform white light from a Digital Light Processing (DLP) projector or ambient light by projecting a black image. In high-speed imaging, exclusive DLP lighting is often used. However, the texture image may exhibit color accuracy problems.[13] When color accuracy is crucial, such as in skin imaging, a calibration procedure is necessary to ensure accurate color measurements.[14,15] Studies have shown that color calibration typically fails due to lighting conditions rather than the camera sensor.[16] Consumer-grade sensors are usually suitable for color imaging under typical lighting environments but may fail with narrowband lights such as single-color LEDs. LED lighting can also be problematic for visualizing specific skin colors. Therefore, LED-based DLP projectors, which use tri-color LEDs operated in sequence, may not be sufficient for skin color measurements despite being designed for improved color accuracy.

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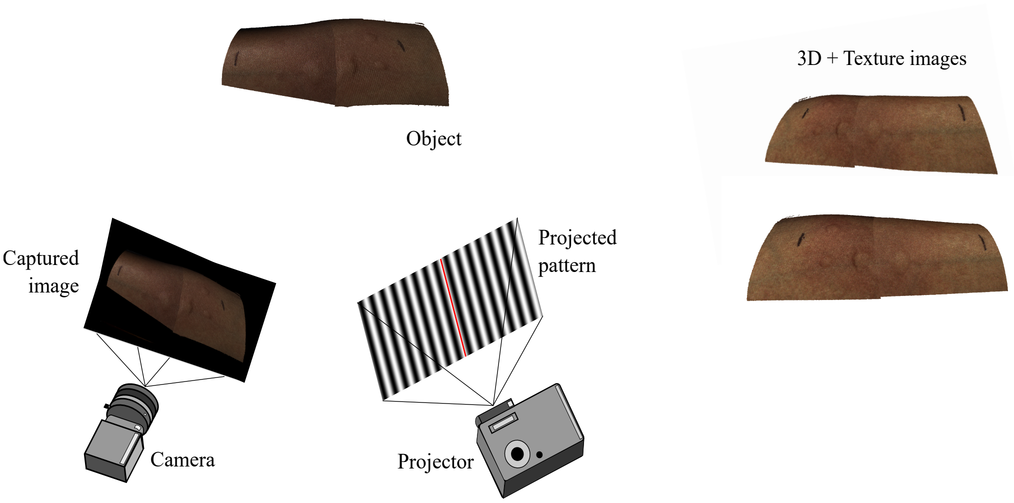

Figure 1: **A typical structured light system in a biomedical application**. A fringe projection profilometry setup composed of a camera-projector pair. When obtaining the texture image of the scene either by averaging the fringes or projecting a white pattern, there are color reproduction problems.

In our research, we examined the accuracy of skin tone colors in a 3D measurement system based on DLP technology under different indoor lighting conditions. We selected color patches from a Munsell color chart to represent skin tones and inspected them under various illuminants, including DLP lighting. Our hybrid lighting approach allowed us to reduce color inaccuracies and create a dependable framework for future research and applications in 3D imaging.

2. MATERIALS AND METHODS

A two-step method was implemented to evaluate the color accuracy of the DLP-based FPP 3D imaging system in relation to lighting effects. Twenty-three color patches were selected from the Munsell ColorChecker chart to represent a range of skin tone. Our experimental setup featured a Basler acA1300-60gc GigE camera and a Dell M115HD DLP projector in an observation booth designed to evaluate the color accuracy under various lighting conditions. The setup utilized a range of illuminants, including D65 (6500 K), P15 (4100 K), and F (2800 K), to simulate typical indoor lighting[17] and its interactions with the DLP light source. The optimal lighting setup for accurate skin-color reconstruction was determined through experimental measurements and colorimetric analysis. We ensured consistent lighting to minimize specular reflections for precise color measurements.

To comprehensively gather skin tones, we utilized the spectral information obtained from the NIST dataset,[18] which was collected under D65 illuminant conditions. We calculated the sRGB components from these data, thereby enabling us to consistently and dependably represent various skin tones under standard lighting conditions. We selected 23 skin color patches from the Munsell ColorChecker chart[19] for our analysis and captured them under different lighting conditions, as described in Table reftab:tabla1. Specifically, we captured patches under DLP projector illumination exclusively (category I), in combination with other light sources (category II), and without DLP illumination (category III). To ensure device-independent color constancy, we applied a chromatic adaptation transform to convert device-dependent RGB coordinates to the sRGB standard.

After completing the data acquisition process across a range of lighting scenarios, colorimetric analysis was performed by comparing the acquired data to the reference color values. In this analysis, we utilized the ΔE_{00} color-difference metric[20] as our chosen method. We computed the average ΔE_{00} color-difference values and their standard deviations for each lighting setup listed in Table 1 to determine the most accurate and consistent conditions. Although achieving the lowest average ΔE_{00} value may indicate a specific optimal scenario, it is

Table 1: Illuminant combinations used in the experimental lighting scenarios.

Category	**Lighting source**	**Abbreviation**
I.	Only the digital light projector	DLP
II.	Digital light projector and D65 illuminant	DLP + D65
	Digital light projector and P15 illuminant	DLP + P15
	Digital light projector and F illuminant	DLP + F
	Digital light projector with D65 and P15 illuminants	DLP + D65 + P15
	Digital light projector with D65 and F illuminants	DLP + D65 + F
	Digital light projector with P15 and F illuminants	DLP + P15 + F
	Digital light projector with D65, P15, and F illuminants	DLP + D65 + P15 + F
III.	D65 illuminant	D65
	D65 illuminant with P15 illuminant	D65 + P15
	D65 illuminant with F illuminant	D65 + F
	P15 illuminant	P15
	P15 illuminant with F illuminant	P15 + F
	Illuminant F	F
	D65 illuminant, P15 illuminant, and F illuminant	D65 + P15 + F

also important to consider lighting conditions with a low variance for consistency. Finally, we analyzed the best scenario that includes DLP lighting to establish best practices, as DLP lighting is often unavoidable in many applications.

The FPP setup for 3D reconstruction was calibrated using the technique proposed by Vargas et al.[21,22] to ensure accurate and reliable measurements. At 60 fps, we extracted phase information from the deformed fringe patterns using a 3-step phase-shifting algorithm with gray coding for phase unwrapping. To capture the texture image, uniform illumination was provided by the DLP projector, allowing accurate color and texture details of the skin. In scenarios with ambient illumination, a black image was projected to prevent the DLP from contributing to the illumination.

3. RESULTS

The color accuracy varied significantly across the 15 lighting configurations, as shown by the color differences (ΔE_{00}) for all 23 patches. The DLP, as the sole light source, resulted in high color differences. However, when combined with another light source, such as the D65 and P15, although not as much with the F, lower color differences were observed. This inconsistency highlights the complex relationship between different light-source characteristics and their impact on color accuracy. The P15 illuminant, with its narrow-band phosphor emission and moderate color temperature, complements the DLP's spectrum, improving overall color balance and reducing the ΔE_{00} values to more acceptable levels. In contrast, the F illuminant's broader spectral output at a lower color temperature appears to be less compatible with the DLP, likely due to the mismatched spectral outputs of the F illuminant's warm light and the DLP's cooler tones, resulting in uncorrected color differences.

Table 2 indicates that the use of two light sources generally results in lower color differences. However, adding a third light source does not always improve the color accuracy, as demonstrated by the lower color differences when two light sources are used without the DLP. DLP projectors are important for color imaging, but their spectral output must be balanced with other light sources. The combination of D65 and P15 suggests that a mix of moderate and cooler temperatures in lighting can produce a more neutral white balance and lower color differences. However, introducing a third light source with a warmer color temperature, such as the F illuminant, can increase the color differences, as evidenced by the higher average ΔE_{00} values. Therefore, using a third light source may complicate the color correction process rather than improve the color fidelity.

4. CONCLUSION

This research highlights the limitations of relying solely on Digital Light Processing (DLP) technology for precise color reproduction in the field of 3D imaging. The findings of this study indicate that a hybrid approach, which involves integrating DLP with the P15 illuminant, can greatly enhance color accuracy, particularly in the representation of skin tones. These results have significant implications for various applications, such as medical image analysis and optical metrology, that require accurate color reproduction. Future research could

Table 2: Mean and standard deviation values for the ΔE_{00} color differences from the 23 patches under the 15 lighting settings.

Lighting setup	**Mean**	**Standard deviation**
DLP	29.8154	8.7091
DLP + D65	21.8828	6.3518
DLP + P15	19.6937	6.1804
DLP + F	27.7143	7.4409
DLP + D65 + P15	22.1755	6.9020
DLP + D65 + F	30.2178	7.4658
DLP + P15 + F	26.6764	7.0491
DLP + D65 + P15 + F	28.1274	7.4231
D65	23.1549	8.0162
D65 + P15	16.4839	7.2055
D65 + F	20.4929	7.4768
P15	18.9729	8.0980
P15 + F	17.4033	8.6622
F	19.6691	7.7014
D65 + P15 + F	28.5148	8.1915

focus on enhancing color-correction algorithms for mixed lighting conditions and investigating other effective combinations of illuminants. Overall, the study suggests that a comprehensive approach that incorporates DLP with additional light sources can achieve optimal results in color correction.

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REFERENCES

[1] Barrios, E., Pineda, J., Romero, L. A., Millán, M. S., and Marrugo, A. G., "Skin color correction via convolutional neural networks in 3d fringe projection profilometry," *Proc. SPIE* **11804**, 40–45 (2021).

[2] Marrugo, A. G., Gao, F., and Zhang, S., "State-of-the-art active optical techniques for three-dimensional surface metrology: a review," *JOSA A* **37**(9), B60–B77 (2020).

[3] Jiang, H., Lin, Z., Li, Y., Yan, Y., Zhou, Z., Chen, E., Yan, Q., and Guo, T., "Projection optical engine design based on tri-color leds and digital light processing technology," *Applied Optics* **60**(23), 6971–6977 (2021).

[4] Tanaka, S., Kakinuma, A., Kamijo, N., Takahashi, H., and Tsumura, N., "Auto white balance method using a pigmentation separation technique for human skin color," *Optical Review* **24**(1), 17–26 (2017).

[5] Hanlon, K. L., Wei, G., Correa-Selm, L., and Grichnik, J. M., "Dermoscopy and skin imaging light sources: a comparison and review of spectral power distribution and color consistency," *Journal of Biomedical Optics* **27**(8), 080902–080902 (2022).

[6] Xiao, K., Yates, J. M., Zardawi, F., Sueeprasan, S., Liao, N., Gill, L., Li, C., and Wuerger, S., "Characterising the variations in ethnic skin colours: a new calibrated data base for human skin," *Skin Research and Technology* **23**(1), 21–29 (2017).

[7] Corbalan-Fuertes, M., Garcia-Verela, M. S. M., and Yzuel, M. J., "Color measurement in standard cielab coordinates using a 3ccd camera: correction for the influence of the light source," *Optical Engineering* **39**(6), 1470–1476 (2000).

[8] Fairchild, M. D., [*Color appearance models*], John Wiley & Sons (2013).

[9] Gijsenij, A., Gevers, T., and Van De Weijer, J., "Computational color constancy: Survey and experiments," *IEEE transactions on image processing* **20**(9), 2475–2489 (2011).

[10] Yang, J., Cai, M., and Zhou, Z., "Evolving convolution neural network by optimal regularization random vector functional link for computational color constancy," *Optical Engineering* **61**(10), 103102–103102 (2022).

[11] Xu, J. and Zhang, S., "Status, challenges, and future perspectives of fringe projection profilometry," *Optics and Lasers in Engineering* **135**, 106193 (2020).

[12] Pineda, J., Vargas, R., Romero, L. A., Marrugo, J., Meneses, J., and Marrugo, A. G., "Robust automated reading of the skin prick test via 3d imaging and parametric surface fitting," *PloS one* **14**(10), e0223623 (2019).

[13] Voisin, S., Page, D. L., Foufou, S., Truchetet, F., and Abidi, M. A., "Color influence on accuracy of 3d scanners based on structured light," *Proc. SPIE* **6070**, 72–80 (2006).

[14] Takiwaki, H., Overgaard, L., and Serup, J., "Comparison of narrow-band reflectance spectrophotometric and tristimulus colorimetric measurements of skin color: Twenty-three anatomical sites evaluated by the dermaspectrometer® and the chroma meter cr-200®," *Skin Pharmacology and Physiology* **7**(4), 217–225 (1994).

[15] Matias, A. R., Ferreira, M., Costa, P., and Neto, P., "Skin colour, skin redness and melanin biometric measurements: comparison study between antera® 3d, mexameter® and colorimeter®," *Skin Research and Technology* **21**(3), 346–362 (2015).

[16] Tedla, S., Wang, Y., Patel, M., and Brown, M. S., "Analyzing color imaging failure on consumer-grade cameras," *JOSA A* **39**(6), B21–B27 (2022).

[17] Roa, R., Huertas, R., López-Álvarez, M. A., Gómez-Robledo, L., and Melgosa, M., "A comparison between illuminants and light-source simulators," *Optica Pura y Aplicada* **41**(3), 291–300 (2008).

[18] Cooksey, C. C., Allen, D. W., and Tsai, B. K., "Reference data set of human skin reflectance," *J. Res. Nat. Inst. Standards Technol.* **122**, 1–5 (2017).

[19] McCamy, C. S., Marcus, H., Davidson, J. G., et al., "A color-rendition chart," *J. App. Photog. Eng* **2**(3), 95–99 (1976).

[20] Sharma, G., Wu, W., and Dalal, E. N., "The ciede2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations," *Color Research and Application* **30**(1), 21–30 (2005).

[21] Vargas, R., Marrugo, A. G., Zhang, S., and Romero, L. A., "Hybrid calibration procedure for fringe projection profilometry based on stereo vision and polynomial fitting," *Applied Optics* **59**(13), D163–D169 (2020).

[22] Vargas, R., Romero, L. A., Zhang, S., and Marrugo, A. G., "Pixel-wise rational model for a structured light system," *Optics Letters* **48**(10), 2712–2715 (2023).