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Multi-Spectral Scanning for Analogue Film Digitisation: Addressing LED Variability in Spectral Band Selection

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Abstract

The digitisation of analogue film is critical for cultural heritage preservation, as film deteriorates over time due to environmental factors and analogue projectors are becoming obsolete. Conventional RGB scanning methods fail to fully capture the spectral complexity of film, making multispectral imaging (MSI) a feasible alternative. However, MSI faces challenges due to the limited availability of narrow-band LEDs in certain spectral regions and inherent variability in LED emissions. Aiming to minimise colour reproduction errors in film scanning, this study investigates the optimisation of LED spectral band selection and the impact of LED spectra variability. Informed by the optimised bands, multiple market-based LED sets were further evaluated using MSI capture simulations, with the 7-band and 8-band setups achieving good colour accuracy and showing rather low sensitivity to LED spectral variability. A physical multispectral capture of a film photograph demonstrated a good agreement between the capture simulation and the real results.

Motivation

Analogue film collections, which serve as useful records of art, cinema, and historical events, are currently facing the challenges of technological obsolescence and degradation due to chemical instability and inadequate storage conditions (e.g. humidity and temperature variations) [6]. Thus, film scanning is essential for preserving the information contained in these archives.

However, traditional RGB-based scanning methods often fail to capture the full colour depth and spectral properties of film, leading to significant inaccuracies, particularly in cases of film fading or unusual spectral absorption properties [4].

In this context, multispectral imaging (MSI) provides a more effective solution for capturing a broader and more accurate range of spectral information from the film by using multiple spectral bands [10], yet its implementation is challenged by the limited availability and significant variability of LED-based illumination sources. The motivation behind this study is to optimise LED spectral band selection and to identify commercially available LEDs that improve the accuracy of multispectral scanning of film, while accounting for their inherent spectral variability. Furthermore, we seek to determine the minimum number of spectral bands required to achieve reliable colour reproduction, as this helps to considerably simplify the scanning system without compromising spectral accuracy.

Problem

The proposed MSI-based film scanning method relies on LED illumination, which introduces the following issues to be addressed:

1. Spectral Resolution and Absence of Colour Targets – the spectral resolution of a typical LED-based system, combined with the lack of colour targets in film scanning workflows, renders direct spectral reconstruction rather impractical. This requires an alternative approach, such as downsampling the high-resolution colour matching functions (CMFs) and illuminant by integrating their curves over each LED spectral band, as proposed by [10].
2. Spectral Gaps in LED Availability – the market offers limited options for narrow-band LEDs in the 530–590 nm range, leading to gaps in spectral coverage that impact colour reconstruction. To compensate, interference filters must be applied to broadband LEDs [10], increasing the complexity of the system but mitigating this issue.
3. Variability in LED Emissions – the manufacturing process involves the binning of LEDs based on their inherent wavelength shifts, and the emission wavelength can typically vary by ±5 nm [1]. These deviations, in conjunction with the fluctuations caused by temperature and driving current [3, 9], can affect the consistency and accuracy of the imaging process.

Without proper optimisation, these aspects influence the effectiveness of MSI for film scanning and archival preservation. Therefore, we seek to address these challenges by identifying an optimised LED configuration that minimises spectral inconsistencies, and to analyse the influence of spectral shifts on the final colour accuracy.

Approach

Aiming to optimise the colour reproduction accuracy of multispectral scanning of analogue film, the research methodology consists of three main stages: capture simulation, LED spectral band optimisation, and LED variability analysis.

1. Capture Simulation

A hyperspectral dataset of analogue film samples derived from the work of [11] (Figure 1) was used to simulate multispectral imaging with different LED band configurations and served as the reference for colour accuracy evaluation. The dataset is representative of the most notable historical film stocks, with each pixel characterising the transmittance spectrum of one film sample in the 380-730 nm range, at 1 nm intervals. To generate the simulated multispectral bands, we applied the spectral power distributions (SPDs) of the LEDs, normalised and weighted by the sensor's spectral sensitivity curve, to the hyperspectral data, effectively acting as filters. The colour renderings result from the multiplication of the simulated multispectral images by the 1931 colour-matching functions downsampled to the specific spectra of the LED set [10], in order to align their spectral resolutions. These resulting images were then converted to the CIELAB colour space, allowing for ΔE_{00} colour difference comparison to the result obtained from the full hyperspectral data, without downsampling.

***Figure 1**. RGB rendering under D65 of the target hyperspectral cube of analogue film spectra*

2. LED Spectral Band Optimisation

In order to improve upon the results obtained in the capture simulation, we sought to identify the optimal LED bands that would help minimise the average colour difference between the multispectral capture and the reference.

To achieve this, we optimised the positions of the band centres within the restricted range of 420-680 nm – on the one hand, to avoid local minima, as bands at both ends (380-420 nm and 680-730 nm) tended to converge ineffectively and were not properly optimised, and, on the other hand, because most sensors have a rather poor performance in the 400-420 nm range. Starting from equally spaced bands, we employed MATLAB's *fmincon* optimisation function [7] to find the wavelengths that constitute the ideal spectral peaks for each set of 6, 7 and 8 LEDs. We experimented with both the interior-point algorithm and sequential quadratic programming (SQP), and we settled on the interior-point algorithm as it performed better in terms of minimising the colour reproduction error (ΔE00). This algorithm is well-suited for large-scale, constrained optimisation problems and iteratively adjusts the band positions to find the optimal solution [2].

3. LED Variability Analysis

To assess the impact of LED emission variability, we generated approximated SPD curves based on each LED's datasheet – in terms of peak wavelength, FWHM, variation interval and spectral curve skewness (Figure 2) – and modelled the potential wavelength shifts that were subsequently used in capture simulations. For example, if a band's variation range is set to ±5 nm, the wavelength is shifted sequentially from -5 nm to +5 nm in 1 nm increments. This stepwise variation ensures that all potential wavelength shifts within the range are evaluated, as well as all possible combinations of these wavelength shifts for the different LEDs of one set, thus creating a multidimensional grid of shift values. It is important to mention that for the bands where interference filters are combined with broadband LEDs, no variation is applied, and the SPD remains fixed. This simulation examined how the real-world behaviour and spectral drifts of commercial LEDs affect the colour accuracy of an MSI-based film scanning system.

Results

1. Band Optimisation

The spectral band optimisation process yielded the following ideal spectral peaks:

- 6 optimal centres: 436, 475, 520, 563, 606, 646 (nm)
- 7 optimal centres: 435, 471, 515, 547, 583, 626, 648 (nm)
- 8 optimal centres: 435, 467, 508, 538, 571, 607, 637, 672 (nm)

Based on these ideal band sets obtained from the optimisation, we selected commercially available LEDs from distributors such as Mouser Electronics and DigiKey, in order to match the optimal peak values as closely as possible. In the cases where suitable narrow-band LEDs were not available, we combined interference filters (having a FWHM of 20-25 nm) with broadband LEDs, particularly in the 530-580 nm range.

No. of LEDs	Mean ΔE_{00} Ideal set	Max ΔE_{00} Ideal set	Mean ΔE_{00} Real set	Max ΔE_{00} Real set
6	0.55	1.59	1.42	3.62
7	0.46	1.03	0.86	3.15
8	0.30	1.00	0.84	2.46

***Table 1**. ΔE_{00} capture errors for the ideal (obtained through mathematical optimisation) and real (commercially available) LED band sets*

We tested multiple configurations and identified LED setups that significantly reduced colour reconstruction errors – as we can see in Table 1, the 7-band ("Real") market LED set has a maximum ΔE_{00} just above the acceptability threshold of 3 advised by [5], while the 8-band set remains within the recommended limit.

Furthermore, from the performance comparison between the commercial sets of 6, 7 and 8 LEDs with peaks close to the optimal bands (with the SPDs plotted in Figure 2), we can say that spectral placement had a greater impact on accuracy than merely increasing the number of spectral bands, considering the significant reduction in mean error from 6 to 7 bands vs. from 7 to 8 bands (Table 1) and the capture error maps in Figure 3.

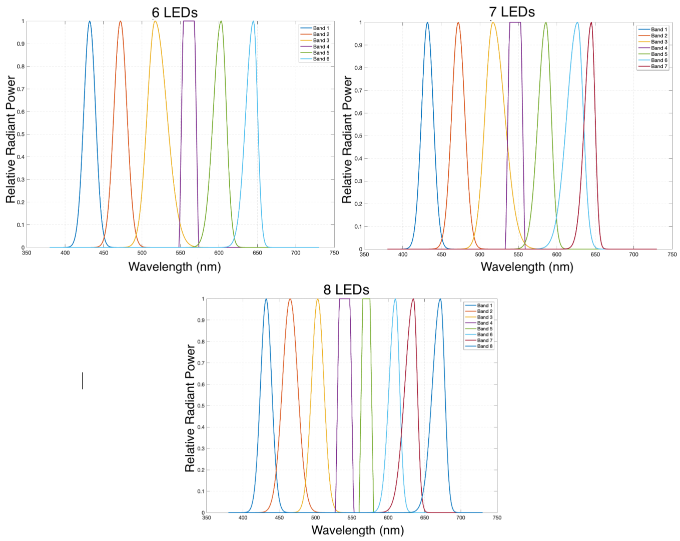

***Figure 2**. Spectral power distributions of the commercial band sets used in capture simulations: (a – top left) 6-LED set, (b – top right) 7-LED set, (c – bottom) 8-LED set*

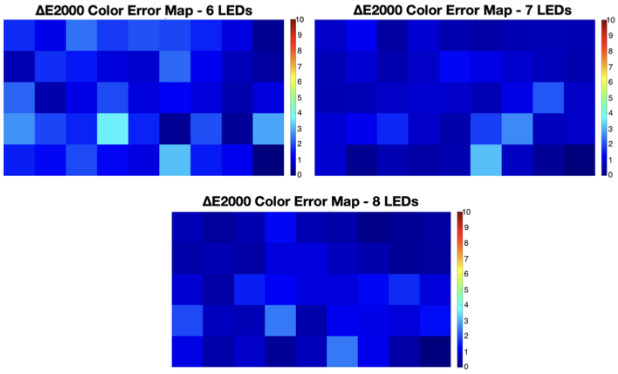

***Figure 3**. ΔE_{00} error maps (scale 1-10) of the simulated captures with commercial LEDs: (a – top left) 6-LED set, (b – top right) 7-LED set, (c – bottom) 8-LED set*

2. LED Spectral Variability Simulation

By analysing the distribution of ΔE_{00} values resulting from all the simulated spectral variation configurations, we can determine the configurations with the lowest errors and assess whether the potential spectral fluctuations of a given LED set are below the acceptable colour error threshold of $\Delta E_{00} = 3$. The results are reported in Table 2, where we can observe a strong improvement for the 7-LED set, namely from 84% (6-LED set) to over 98% (7-LED set) of the variation cases leading to a colour reproduction error below the threshold. However, the improvement from 7 to 8 LEDs is not as substantial, considering that the increase of 1 percentage point requires not only one additional LED, but also an interference filter. This renders the 7-LED setup as an option that offers the best balance between accuracy and system complexity.

No. of LEDs	No. of shift combinations	Percentage of $\Delta E00 \leq 3$
6	419,265	84.03%
7	5,226,837	98.28%
8	14,674,275	99.19%

***Table 2**. LED variability analysis results*

The histograms of the ΔE_{00} values corresponding to the simulated captures when spectral variation is applied (Figure 4) also demonstrate a significant reduction in the range of error values for the sets of 7 and 8 LEDs, even in the case of spectral fluctuations: a more substantial shrinkage from [0.5, 6] for the 6-LED set to [0.5, 4.5] for the 7-LED set, followed by a smaller reduction to [0, 4] for the 8-LED set, with all distributions mostly right-skewed.

Although the above results represent a validation of the optimisation process and of the chosen LED sets, we consider it important to verify the results through actual captures in the future. Additionally, a discussion can be conducted regarding the further refinement of the 6-band set, as well as whether the 7-band set would be a suitable practical choice, considering the improved cost and time efficiency compared to an 8-LED system.

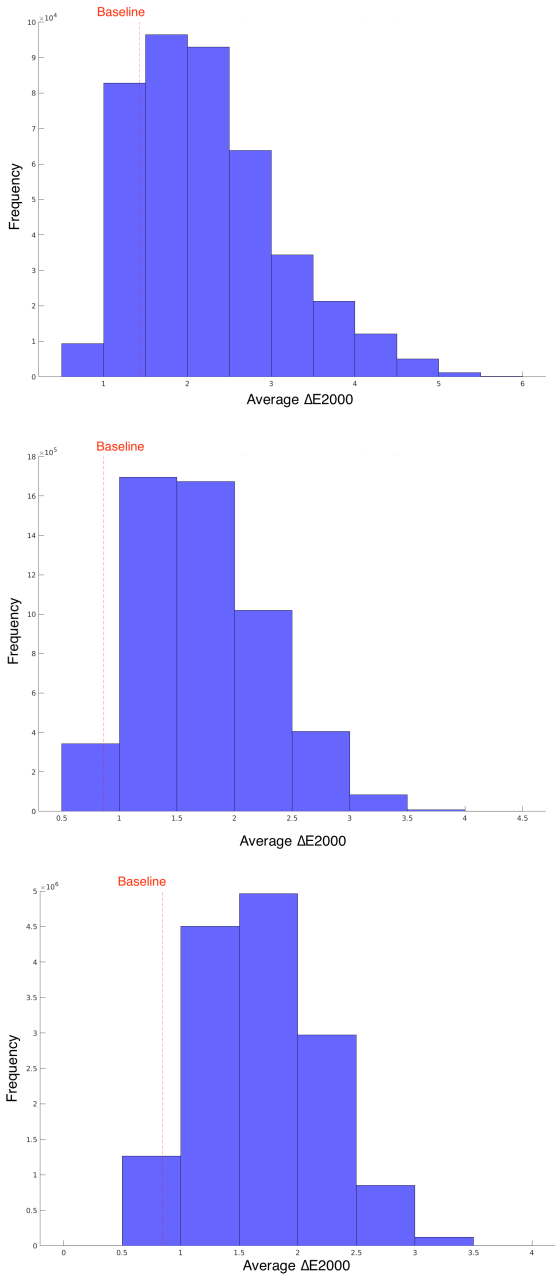

***Figure 4**. Distribution of the average ΔE_{00} values for all the possible shift combinations for (a) 6 LEDs, (b) 7 LEDs and (c) 8 LEDs; "Baseline" represents the error value when no shift is applied.*

3. Simulation Validation

To verify the reliability of the proposed multispectral capture simulation (described in the *Approach* section), we proceeded to evaluate the difference between the results of the simulation method and the results of an actual multispectral capture. Using the system described in [10] (integration sphere with multiple LEDs and a QHYCCD QHY600 Photographic Monochrome Camera with a SONY IMX455 CMOS sensor), we scanned a film photograph [8] (Fujifilm F-64D) depicting a portrait and a set of control patches (Figure 5). Considering that the band optimisation demonstrated a good performance for the optimal set of 7 bands, we selected 7 out of the already-existing LEDs of the multispectral system.

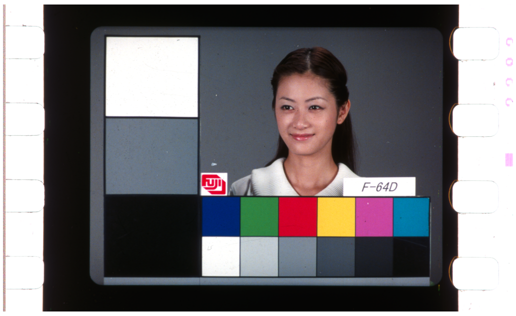

***Figure 5**. Reference film frame used in the multispectral capture*

Separately, using an overhead projector, we projected this frame onto a Spectralon white reference, and measured each control patch using a Konika Minolta CS-3000HDR spectroradiometer. The resulting spectral radiance data was then divided by the white target without the film (two averaged measurements of the projector's halogen light falling onto the Spectralon), thus obtaining the transmittance values. Subsequently, as described in the "Approach" section, we simulated a multispectral capture based on the patch transmittances and the SPDs of the LEDs mounted inside the multispectral scanning sphere [10] (Figure 6), weighted by the sensor's spectral sensitivity curve. This enabled us to compute the colour difference between the control patches of the simulated rendering and those of the physical capture.

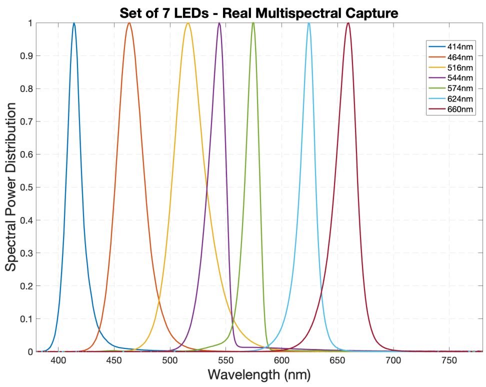

***Figure 6**. Spectral power distribution of the LEDs used by the multispectral scanning system*

The results of this comparison are reported in Table 3 and can be visualised in Figure 7. With an average ΔE_{00} of 1.63 and maximum ΔE_{00} of 3.06 (very close to the aforementioned threshold of 3), we can consider the simulation acceptable in terms of colour reproduction. Furthermore, in Figures 7a and 7b, we can observe that the two sets of patches appear to be very similar, perhaps with slightly lower lightness and saturation values in the case of the simulated colour patches.

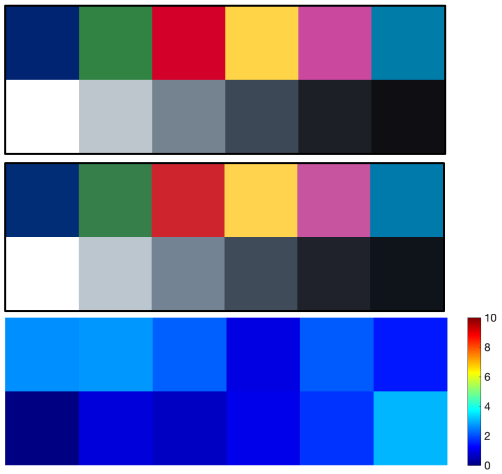

***Figure 7**. RGB renderings from the (a) physical and (b) simulated MS captures of the control patches and (c) ΔE_{00} between the two*

Comparison	Mean ΔE_{00}	Median ΔE_{00}	Max ΔE_{00}
Simulated vs Real Capture	1.63	1.61	3.06

***Table 3**. ΔE_{00} statistics for the simulated vs. actual multispectral capture renderings.*

Nevertheless, we should take into account that these errors may not be ascribed completely to the simulation approach, but can also be related to differences in measuring setup characteristics: light projection directly onto the sensor in the MS capture vs. onto the Spectralon support in the TSR capture, differences in sensor type and measurement geometry. As a result, a possible direction of future work would be to acquire a hyperspectral scan of the film sample – using a similar illumination geometry as in the multispectral capture – and to use it as a reference for further validating the capture simulation method.

Conclusions

In conclusion, the spectral band optimisation for multispectral capture of analogue film has proven effective in enhancing colour reproduction accuracy. Specifically, the optimal 8-band configuration consistently yields the lowest colour reproduction error (ΔE_{00}), remaining within the recommended acceptability threshold. However, the 7-band LED set proves to be a more viable option in terms of cost and system complexity, at a comparable accuracy level, making it well-suited for real-world implementation. The variation simulations assessed the impact of market-available LED spectral shifts on colorimetric performance, showing that 84% of the possible shifts in the set of 6 bands had average ΔE_{00} errors less than 3, with a strong improvement for the sets of 7 LEDs (98%) and 8 LEDs (99%). A physical multispectral capture was acquired in order to verify the proposed simulation method, and the mean colour difference (ΔE_{00} = 1.63) and maximum (ΔE_{00} = 3.06) confirm that the approach is acceptably accurate; this validation can be further extended by using a hyperspectral scan as a reference. Future work is necessary for assessing the performance of the proposed LED-based analogue film digitisation system, including experimental validation through actual MSI captures using the proposed LED and interference filter setups.

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Author Biography

Mihaela Elizabeta Balica is currently pursuing a master's degree in Computational Colour and Spectral Imaging. After working as a full-stack software developer, she redirected her focus to explore the intersection of technology and art. Her ongoing master's dissertation investigates methods for reconstructing the historical appearance of paintings using analogue photographic records.

Giorgio Trumpy is currently Associate Professor in Colour Imaging at the Norwegian University of Science and Technology and founding member of Scan2Screeen GmbH (Swiss company for film digitization). Imaging Scientist with experience in bridging the gap between art and science. Fields of expertise span from optics to spectroscopy, from colorimetry to image processing, from heritage conservation to visual arts. Previously worked at the Institute of Applied Physics in Florence on non-invasive analyses of paintings with fiber optic reflectance spectroscopy and hyper-spectral reflectance imaging (2006-2010). PhD project at the University of Basel (2010-2013), devising an optical setup for the detection and restoration of dust and scratches on photographs and motion-picture films. Postdoc fellow at National Gallery of Art in Washington DC (2014-2016), designing spectral imaging methodologies for works of art. Research scientist at the University of Zurich (2016-2022) conducting scientific analyses of historical film colours and designing an innovative archival film scanner.