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Repeatability and reproducibility of a hyperspectral camera as a means of measuring color

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ABSTRACT

In this study we evaluate the repeatability and reproducibility of a hyperspectral system as a means of measuring color following the guidelines established in the ASTM E2214-08 standard. The system basically consists of a CCD digital camera, a spectrograph and a linear moving system, which allow sampling the scene both spectrally and spatially with a high resolution. The results highlight the usefulness of such systems to be used in industrial applications.

1. INTRODUCTION

Hyperspectral cameras, which allow measuring the complete spectrum for each pixel of an image, have appeared on the market in recent years (Chang 2009). Their main components are a digital camera, a spectrograph and an objective lens. An additional moving system allows scanning mechanically the complete scene, although sometimes the scan is performed optically. Using such systems, the scene is sampled spectrally but also spatially, creating a 3D cube of data (x, y, λ) with spectral information pixel by pixel. Therefore, the use of these systems can provide significant advantages in the fields of colorimetry and spectrometry, mainly in the characterization of non-uniform materials with complex spatial patterns. In this work we analyze the repeatability and reproducibility of a hyperspectral system following the guidelines specified in the ASTM E2214-08 standard, where the latest multidimensional procedures for characterizing the performance of color-measuring instruments have been established.

2. METHODS

The hyperspectral system analyzed consisted of a 16-bit digital CCD camera (AVT Pike F-210B), a spectrograph (ImSpector V10E), and an objective lens (Cinegon 1.8/16) (Figure 1). As stated before, throughout all the study we followed the guidelines specified in the ASTM E2214-08. It must be taken into account that since color is a multidimensional property of a material, repeatability and reproducibility must be reported in terms of multidimensional standard deviations, and not only using one color difference based metrics. Moreover, another problem usually arises when using color differences: they do not follow a Normal distribution but a curve related to the Chi-squared of F statistical distributions. This standard permits overcoming all these limitations.

To analyze repeatability we performed measurements on a calibrated white plate (BN-R98-SQ10C) and used univariate and multivariate metrics. 50 consecutive readings were taken to account for short-term repeatability, 50 in two consecutive days for medium-term repeatability, and 50 along 5 weeks for long-term repeatability.
To account for reproducibility we used two different sets of samples: 12 glossy ceramic tiles (BCRA CCS-II) and 24 matte patches (CCRC). The multivariate Hotelling and

inter-comparison tests were used to compare the readings of the hyperspectral system with those obtained by a conventional tele-spectracolorimeter (Photo Research PR-655). The reflectance factors from 400 to 700 nm ($\Delta\lambda$=10 nm) and a geometry of D/45 with a SpectraLight III overhead luminaire (Daylight configuration) were used in all measurements. Illuminant D65 and CIE 10º observer were used to compute the color data.

Figure 1. Hypespectral system (camera, spectrograph and lens), illumination system (overhead luminaire) and linear scanning moving system.

3. RESULTS AND DISCUSSION

The results confirmed the good performance of the hyperspectral system in terms of short, medium and long term repeatability. As an example, Table 1 shows some of the metrics used for this purpose. Parameters $\Delta R_{\lambda,2\sigma}$ represents twice the standard deviation of the reflectance at the specified wavelength, ΔE_{00} is the CIEDE2000 color difference and RMSE (%) is the *Root Mean Square Error* (%).

Table 1. Results of short., medium and long term repeatability for some of the metrics proposed by the ASTM E2214-08.

Metrics	Short term	Medium term	Long term
$\Delta \mathbf{R}_{440,2\sigma}$	0.0017	0.0105	0.0223
$\Delta \mathbf{R}_{560,2\sigma}$	0.0011	0.0112	0.0246
$\Delta \mathbf{R}_{650,2\sigma}$	0.0017	0.0146	0.0345
$\Delta \mathbf{E}_{00}$	0.031	0.130	0.399
RMSE (%)	0.1367	0.6631	1.8667

Another issue that should be considered in the analysis of repeatability is the drift shown by the instrument analyzed. This was investigated by studying the 50 consecutive readings obtained in the analysis of short term repeatability for some parameters. Figure 2 shows the L*, a* and b* data of these measurements. As it can be seen the instrument does not seem to be associated with a drift in the results.

In the study of repeatability done by Wyble and Rich (2007a) the repeatability of twelve commercial spectrophotometers was compared. The results found for these authors were similar to those obtained in our study. Therefore it can be concluded that the hyperspectral system shows a precision similar to the majority of instruments used for measuring color.

In the case of reproducibility, the two tests applied reported statistical significant differences between the hyperspectral system and the tele-spectracolorimeter PR-655 at 95% confidence level ($P<0.001$). However, it must be remarked that the statistical tolerance using the methodology proposed by the ASTM E2214-08 is strict as already reported by other authors (Wyble and Rich 2007b), who also found differences among 10 commercial spectrophotometers. Figure 3 shows specific examples of spectral reflectances measured by the hyperspectral system and the PR-655.

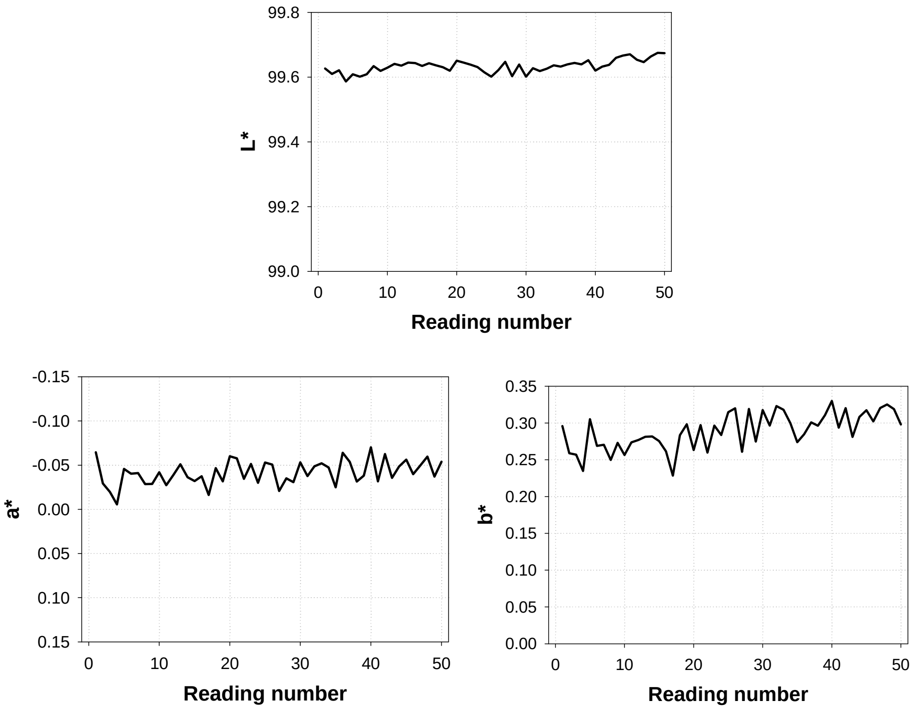

Figure 2. L, a* and b* vs. measurement number for the hyperspectral camera. The 50 consecutive readings obtained in the short-term analysis are considered.*

Table 2. Results of reproducibility in terms of mean color differences and RMSE (%)between the measurements provided by the hyperspectral and PR-655 tele-spectracolorimeter..

Set of samples (number)	ΔE_{00}	RMSE (%)
CCRC (24)	1.181	6.5422
BCRA (12)	4.339	23.0598

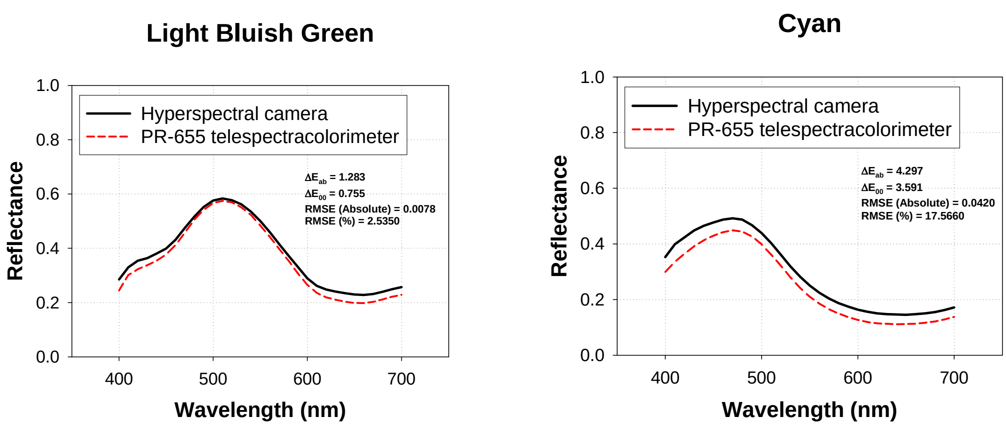

Figure 3. Spectral reflectances measured by the hyperspectral camera as well as the PR-655 tele-spectracolorimeter for the Light bluish green sample of the CCRC chart and the Cyan tile of the BCRA collection.

However, and taking into account the obtained results, it was concluded that the reproducibility was acceptable for matte CCRC samples while that corresponding to the glossy BCRA tiles was much lower. This might be explained by the gloss of the last set of samples and the geometry used (D/45), which could contribute to a higher variability among the results, i. e. the positioning of the sample with respect to the light source as well as the instrument would be more critical. Furthermore, one must have into account that geometrically speaking, both instruments do not actually have identical configurations, what can reinforce the former explanation and justify the larger differences found for the BCRA tiles. Hyperspectral cameras, allow measuring the complete spectrum for each pixel of an image, but this is done by measuring only one line on the scene. Later on, an additional mechanical moving system allows linearly scanning the desired part of the sample that is aimed to be analyzed. On the contrary, the PR-655 does not need the scanning system. It already has a viewing field of 1 degree. Having these differences in mind, the gloss could affect in a different way both instruments and for this reason worse results with the BCRA would be found.

On the other hand, non-uniformities of the illumination on the sample measured could also play an important role in the results. Even the overhead luminaire is designed to be perfectly uniform and incorporates a diffuser placed below the light bulbs, it does not provide a perfect uniform field of illumination.

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4. CONCLUSIONS

In conclusion, it could be established that the hyperspectral system provided very good results in terms of repeatability and acceptable data in terms of reproducibility. Therefore, these systems are reliable and could be used in the industry providing advantages in the field of colorimetry and spectrometry, mainly in the characterization and identification of non-uniform materials with complex spatial patterns with a high spatial and spectral resolution.

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