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Society for Imaging Science & Technology
7003 Kilworth Lane
Springfield, Virginia 22151

Phone: 703-642-9090
Fax: 703-642-9094

info@imaging.org

Technical Papers Program: Schedule and Contents*

MONDAY JUNE 14, 2010

Workshop 1: Modeling the Interaction of Light, Paper, and Ink Halftones

8:30-12:00 (3.5 hours)

Instructor: Roger D. Hersch (EPFL), assisted by Romain Rossier

Workshop 2: Spectral Color Measurements

13:00-17:00 (4 hours)

Instructor: University of Eastern Finland, Joensuu Color Group

(Jukka Antikainen, Ville Heikkinen, Jouni Hiltunen, Tuija Jetsu, Jussi Kinnunen, and Pertti Silfsten)

Lab 1: Measuring with integrating spheres and bidirectional geometries

Lab 2: Bispectral fluorescence measurements and simulation

Lab 3: Line scanning and LCTF spectral image capturing

19:00 – 21:00

Welcome Reception Sponsored by the City of Joensuu at City Hall

TUESDAY JUNE 15, 2010

Tuesday Keynote

Session Chairs: Jussi Parkkinen and Timo Jääskeläinen, University of Eastern Finland

8:30 – 9:30

8:30 **Cortical Mechanisms of Color Vision,** *Karl R. Gegenfurtner, Justus-Liebig-Universität (Germany)* **1**

The perception of color is a central component of primate vision. Color facilitates object perception and recognition, and plays an important role in scene segmentation and visual memory. Color vision starts with the absorption of light in three different types of light sensitive receptors in the eye, which convert electromagnetic energy into electrical signals, which in turn are transformed into action potentials by a complicated network of cells in the retina. The information is sent to the visual cortex via three independent channels with different chromatic preferences. In the cortex, information from these channels is mixed to enable perception of a large variety of different hues. Furthermore, recent evidence suggests that color analysis and coding cannot be separated from the analysis and coding of other visual attributes such as form and motion. While there are some brain areas that are more sensitive to color than others, color vision emerges through the combined activity of neurons in many different areas.

Colour Vision/Psychophysics

Session Chair: David H. Foster, University of Manchester (UK)

9:30 – 12:40

9:30 **Adding Texture to Color: Quantitative Analysis of Color Emotions,** *Marcel P. Lucassen, Theo Gevers, and Arjan Gijsenij, University of Amsterdam (the Netherlands)*. **5**

What happens to color emotion responses when texture is added to color samples? To quantify this we performed an experiment in which subjects ordered samples (displayed on a computer monitor) along four scales: Warm-Cool, Masculine- Feminine, Hard-Soft and Heavy-Light. Three sample types were used: uniform color, grayscale textures and color textures. Ten subjects arranged 315 samples (105 per sample type) along each of the four scales. After one week, they repeated the full experiment. The effect of adding texture to color samples is that color remains dominant for the Warm-Cool, Heavy-Light and Masculine-Feminine scale (in order of descending dominance), the importance of texture increases in that same order. The Hard-Soft scale is fully dominated by texture. The average intra-observer variability (between the first and second

measurement) was 0.73, 0.66 and 0.65 for the uniform color, grayscale texture and color texture samples, respectively. The average inter-observer variability (between an observer and the other observers) was 0.68, 0.77 and 0.65, respectively. Using some 25,000 observer responses, we derived analytical functions for each sample type and emotion scale (except for the Warm-Cool scale on grayscale textures). These functions predict the group-averaged scale responses from the samples' color and texture parameters. For uniform color samples, the accuracy of our functions is significantly higher (average adjusted R2 = 0.88) than that of functions previously reported. For color texture, the average adjusted R^2=0.80.

9:50 **Testing the Color Harmony for Painting Exhibition,** *Sabrina Lachheb and Philippe Colantoni, C2RMF; and Éric Dinet, Laboratoire Hubert Curien (France)*. **11**
A set of colours aesthetically pleasant are described as in the language of human visual perception. As this encloses a subjective part, a psychophysical experiment carried out to estimate the perception of colour harmony combinations of paintings with the uniform colour of walls which they are hung.

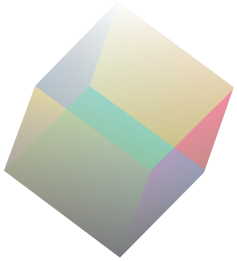
The experiment, that involved 38 observers, was based on colours built upon a specific colour flow. Participants asked to judge the colour harmony of combinations of of 7 selected paintings with backgrounds uniformly in 3 different ranges of colours—achromatic colours, derived from the global average colour of the considered and tones derived from the complementary of the average colour of the considered painting.

Results demonstrate that the best colour harmony is when the average colour of paintings is used to colour background. The experiment presented in this paper shows that the white colour usually used for walls does not optimize the colour harmony.

10:10 – 10:40 Coffee Break

10:40 **Visual Attention Simulation in RGB and HSV Color Spaces,**
Fréderique Robert-Inacio[1,2], Quentin Stainer[2], Rémy Scaramuzzino[2], and Edith Kussener-Combier[1,2]; [1]Institut Matériaux Microélectronique et Nanosciences de Provence and [2]Institute Supérieur de l'Électrique et du Numérique (France). **19**
In computer vision several methods are directly inspired by the human visual system. Visual attention is one of the main abilities a human eye uses to discover a new scene. This ability is based on the focus of attention principle, which enables to look at a particular point. The works presented in this paper describe how to simulate such an ability in computer vision. Color images are resampled according to this principle, in order to considerably decrease the amount of data to be processed. This resampling is done by using a concentric distribution of hexagonal cells instead of the rectangular cell grid generally provided by uniform sensors such as CCD cameras. Such a distribution is derived from the cone distribution on the retina and the result is encoded by using polar coordinates. In this way the information is more and more blurred in an isotropic way, when getting far and far from the focusing point. This resampling method then allows decreasing data number while it globally keeps all the information included in the image. In this way a new scene can be explored by focusing successively at a sequence of focusing points. This allows reproducing the human eye behavior that explores a new scene by saccades. Furthermore the resampled images can be used in order to set up image preprocessing. For example this resampling can be achieved before a preliminary step of segmentation. The resampled image is segmented in order to coarsely determine regions. Afterwards the segmentation step can be refined by combining the segmented resampled image and the original image. A comparison between results obtained in RGB and HSV spaces is also given on a set of images.

11:00 **Online Colour Naming Experiment Using Munsell Colour Samples,** *Dimitris Mylonas and Lindsay MacDonald, London College of Communication (UK)*. **27**
An online colour-naming experiment was designed and developed to determine a broad set of colour words in wide cultural use with their corresponding colour ranges in sRGB and Munsell specifications. The quality of the English dataset was analysed in terms of colour centroids, frequency of names, consistency and response time. The importance of basic colour terms was confirmed while it was also revealed that in free colour naming tasks, the majority of the observers preferred to use non-basic colour terms. The validation of the web-based experimental methodology with previous studies conducted in controlled viewing conditions produced satisfactory results, while a comparison of the 27 most frequent chromatic colour words with a previous web-based experiment showed a remarkable agreement.



11:20 **A Compact Singularity Function to Predict WCS Color Names and Unique Hues,** *Javier Vazquez-Corral[1], Graham D. Finlayson[2], and Maria Vanrell[1]; [1]Universitat Autònoma de Barcelona (Spain) and [2] University of East Anglia (UK)* **33**

Understanding how colour is used by the human vision system is a widely studied research field. The field, though quite advanced, still faces important unanswered questions. One of them is the explanation of the unique hues and the assignment of color names. This problem addresses the fact of different perceptual status for different colors.

Recently, Philipona and O'Regan have proposed a biological model that allows to extract the reflection properties of any surface independently of the lighting conditions. These invariant properties are the basis to compute a singularity index that predicts the asymmetries presented in unique hues and basic color categories psychophysical data, therefore is giving a further step in their explanation.

In this paper we build on their formulation and propose a new singularity index. This new formulation equally accounts for the location of the 4 peaks of the World colour survey and has two main advantages. First, it is a simple elegant numerical measure (the Philipona measurement is a rather cumbersome formula). Second, we develop a colour-based explanation for the measure.

11:40 **Error Estimation of Paired Comparison Tests for Thurstone's Case V,** *Peter Zolliker and Zofia Baranczuk, Swiss Federal Laboratory for Materials Testing and Research (EMPA) (Switzerland).* **39**

Pair comparison methods based on Case V of Thurstone's Law of Comparative Judgment are widely used to derive interval scales for perceptual image quality. A thorough treatment of the involved statistical errors is often neglected, even though this is the base for computing confidence intervals and other statistical tests. In this paper we show, that consequent error estimation through all steps of the data analysis provides a simple and reliable method to compute confidence intervals. Monte Carlo simulations are used to verify the results and to compare the proposed error estimation with other known methods.

12:00 **Chromatic Effects of Metamers of Daylights,** *Sérgio M.C. Nascimento, Paulo E.R. Felgueiras, and João M.M. Linhares, University of Minho (Portugal)* **45**

The relationship between the spectral composition of light sources and the visual appearance of rendered scenes is a matter of practical relevance and assumes today particular significance with the advent of light sources of almost arbitrary spectral distribution, like modern LED based lighting. This relationship has only been studied for specific illuminants, like daylights, and systematic studies with other light sources are necessary. The aim of this work was to address this issue by studying, computationally, some chromatic effects of metamers of daylight illuminants. For each daylight with correlated color temperature (CCT) in the range 25000 K – 4000 K a large set of metamers was generate using the Schmitt's elements approach. The metamers set was parameterized by the absolute spectral difference to the equienergy illuminant E and by the number of non-zero spectral bands. The chromatic effects of the metamers were quantified by the CIE color rendering index CRI and by the CIELAB color gamut generated when rendering the Munsell set. It was found that although CRI decreases with ∂, that is, as the illuminant spectrum becomes spectrally more structured, the largest values for the color gamut could be obtained only for large values of ∂. Furthermore, the relationship between color gamut and number of non-zero bands showed that the largest gamuts were obtained with a small number of spectral bands. Thus, spectrally structured metamers produced low CRI but larger color gamuts, a result suggesting that appropriate spectral tuning may be explored in practical illumination when obtaining large chromatic diversity may be important.

12:20 **Accurate Mapping of Natural Scenes Radiance to Cone Activation Space: A New Image Dataset,** *C. Alejandro Párraga, Ramon Baldrich, and Maria Vanrell, Universitat Autònoma de Barcelona (Spain)* **50**

The characterization of trichromatic cameras is usually done in terms of a device-independent color space, such as the CIE 1931 XYZ space. This is indeed convenient since it allows the testing of results against colorimetric measures. We have characterized our camera to represent human cone activation by mapping the camera sensor's (RGB) responses to human (LMS) through a polynomial transformation, which can be "customized" according to the types of scenes we want to represent. Here we present a method to test the accuracy of the camera measures and a study on how the choice of training reflectances for the polynomial may alter the results.

12:40 – 14:00 Lunch in the Carelia or Aura University Cafeteria

Interactive Paper Session I

14:00 – 16:00

Color Image Processing and Color Analysis

Chromatic Diversity Index — An Approach Based on Natural Scenes, *João Manuel Maciel Linhares, Paulo Daniel Pinto, and Sérgio Miguel Cardoso Nascimento, University of Minho (Portugal)* **58**

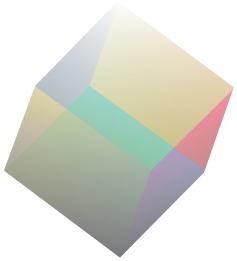
Common descriptors of light quality fail to predict the chromatic diversity produced by the same illuminant in different contexts such as images of natural scenes. The aim of this paper was to introduce a new index, capable of predicting illuminant-induced variations in the chromatic diversity of natural scenes. The spectral reflectance of each pixel of 50 images of natural scenes obtained using a hyperspectral imaging and the spectral reflectance of 1264 Munsell surfaces were converted into the CIELAB color space for each of the 55 illuminants and 5 light sources. The CIELAB volume was estimated by the convex hull method. The number of discernible colors was estimated by segmenting the CIELAB color volume into unitary cubes and by counting the number of non-empty cubes. High correlation was found between the CIELAB volume occupied by the Munsell surfaces, the number of discernible colors and CILEAB color volume of the colors of natural scenes. These results seem to indicate that a new illuminant chromatic diversity index based on natural scenes could be defined using the CIELAB volume of the Munsell surfaces.

Regularized Color Demosaicing via Luminance Approximation, *Johannes Herwig and Josef Pauli, University of Duisburg-Essen (Germany)* **62**

In single-sensor digital imaging a color filter array, that is overlaid onto the image sensor, makes color images possible. Incident light rays become band-limited and each sensor element captures either red, green or blue light. Interpolating the missing two color components for each pixel location is known as demosaicing. This paper proposes to firstly derive an estimated luminance image by low-pass filtering the original mosaiced sensor image. In a second step a deconvolution technique re-sharpenes the blurred luminance approximation, so that it has the same spatial resolution as the original—but bandpassed—sensor image. Using the high-resolution luminance approximation the partial RGB colors from the mosaiced sensor image are transformed into a different color space that is more suitable for color interpolation. The new color space consists of least correlated color data, so that intra-channel interpolation errors have a reduced impact on inter-channel alignment, and therefore result into less prominent interpolation artifacts. Demosaicing is performed on the transformed color data separately for each plane, whereby again the luminance approximation, which encodes the aligned gradient direction of all color channels, regularizes the bilinear interpolation. Finally, the result is remapped into the RGB color space to obtain the demosaiced color image. Additionally, correlated multi-channel anisotropic diffusion is applied onto the demosaiced color image to further reduce interpolation artifacts and enable denoising. The proposed algorithm is evaluated and it is concluded—that although the image formation model could be verified—its performance heavily depends on the quality of the luminance approximation, i.e. the deconvolution method.

Medical Image Colorization Using Learning, *Vladimir Bochko[1], Petri Välisuo[1], Timo M. R. Alho[1], Severi Sutinen[1], Jussi Parkkinen[2], and Jarmo T. Alander[1]; [1]University of Vaasa and [2]University of Eastern Finland (Finland).* **70**

We propose a method for colorization of medical grayscale images using color learning. The colors are learned from a color image and predicted for a grayscale image. Earlier we introduced an efficient algorithm for image colorization which uses a dichromatic reflection model. The colorization algorithm is further developed in this study. First, we improve the algorithm performance by extending its capability to work with the grayscale images the contrast of which is lower than the contrast of the color images. Then, we propose a reliable technique to prevent negative contrast during colorization. In addition, we develop a simple approach for grayscale image colorization by a given RGB value. We give two medical applications of our algorithm: realistic color labeling of skin wounds and colorization of a dental cast models. In the former case we use grayscale images and labeling obtained after support vector classification as input data and for the latter application we use photometric stereo images.



Framework for the Evaluation of Color Prints Using Image Quality Metrics, *Marius Pedersen[1,2], and Seyed Ali Amirshahi[2]; [1]Gjøvik University College (Norway) and [2]Océ Print Logic Technologies S.A. (France)* **75**
Measuring the perceived quality of printed images is important to assess the performance of printers and to evaluate technology advancements. Image quality metrics have been proposed to objectively assess the quality of images, and new metrics are proposed continuously. However, since these metrics require digital inputs, applying these metrics to printed images are not straightforward. In order to accomplish this, the printed reproduction needs to be transformed into a digital copy.

In this paper we propose a framework for applying image quality metrics to printed images, including the transformation to a digital format, image registration, and the application of image quality metrics. The proposed framework introduces less error and is significantly faster than another state of the art framework. Finally, the framework is used to evaluate a set of image quality metrics against subjective data.

Color Reproduction and Color Science

Effect of Colorimetric Attributes on Perceived Blackness of Materials, *Reid Clonts, Renzo Shamey, and David Hinks, North Carolina State University (USA)* **83**
While black is one of the most prevalent industrial colors in the world, the colorimetric attributes of what is considered black vary significantly and the range of subtle hue undertones can be numerous. However, no systematic study can be found in the literature pertaining to the potential role of colorimetric attributes in the perceptual assessment of blackness. We have experimentally determined that the perception of blackness is influenced by hue and chroma using psychophysical assessments of a range of black materials.

In the initial part of this study a series of 2″ × 2″ precision cut glossy Munsell color samples comprising a hue circle with a lightness (L*) of approximately 20.5 and chroma (C*) between 4 and 6 were assessed using thirty color normal observers and a filtered tungsten daylight simulator (D65). Observers were asked to arrange samples in order from most like black to least like black with no time limits in three separate sittings. In the second part of the study 27 over-dyed woolen samples were arranged in 2″× 3″ dimensions. Samples in this set had a lightness range of 14-16 and C* of 0.5-3.5, and were assessed by 25 observers in two sittings in the same manner. The third set of samples comprised 24 precision cut 2″ × 2″ dyed acrylic samples with a L* range of 10.5-12 arranged around the hue circle. Samples were selected such that they comprised three concentric hue circles of eight evenly spaced samples each. The samples were divided into five sets according to chroma: A (C* = 0.12-0.20), B (C* = 0.42-0.57), C (C* = 0.89-0.97), D (C* = 1.58-1.86), and E (C* = 3.34- 3.46). For the assessment of samples in the third set 100 color normal observers were employed that repeated the assessments in three separate sittings with at least 24 hours gap between each sitting. Analysis of the data indicates that, irrespective of chroma, on average samples with hue angles between approximately 200° and 270° were perceived to be the most black, i.e., cyan to bluish-blacks. Blacks with hue angles above 315° or below 45° (reddish-blacks) were considered to be the least black. Chroma and lightness also influenced the perceived blackness but for the majority of samples the effect was less pronounced.

Evaluating the Effect of Noise on 3D LUT-Based Color Transformations, *Zhaohui Wang, Anna Aristova, and Jon Yngve Hardeberg, Gjøvik University College (Norway)* **88**
Image reproduction suffers from several limitations in a color management system. In this paper, we have investigated artifacts resulting from the inherent characteristics of the color transformations by interpolation in three-dimensional look-up tables, and the unavoidable measurement noise of the color measurement done during device profiling. In our experiments, images were manipulated using three interpolation methods, and five levels of random noise. Psychophysical experiments were conducted to evaluate the quality of the reproduced images. Finally the experimental data were collected to analyze the color transformations, and test the performance of two color image difference metrics in this context.

Modeling of Fluorescent Color Mixing by Regression Analysis, *Petri Turunen, Jussi Kinnunen, and Jarkko Mutanen, University of Eastern Finland (Finland)* **94**
Modeling of fluorescent color mixing is studied by applying regression analysis to the measured bispectral data. A sample set was prepared by using three fluorescent paints

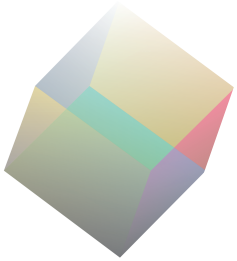
and different mixing combinations. The accuracy of estimations was evaluated by calculating the color difference ΔE in the CIELAB color space and Euclidean distance of spectra. Even though the estimation errors were considerably high, the best results overall was obtained using a sparse training set and of third order terms in regression.

The Influence of Coloured Backgrounds on Mura Detection in TFT-LCDs, *Guo-Feng Wei, M. Ronnier Luo, and Peter A. Rhodes, University of Leeds (UK)* . . **101**
"Mura" is a type of defect caused by irregular luminosity variation in liquid crystal displays. It is currently inspected and graded against neutral grey backgrounds in factories by well-trained human assessors. The aim of this research is to provide more reliable grading results from experts in agreement with ordinary observers watching real complex images on LCDs. This work is a pilot study. Since colour is one of the essential elements of complex images, we initially chose to focus on the influence of uniform coloured backgrounds on Mura detection. Analysis of the results shows that both CIELAB and CIEDE2000 colour-difference formulae are useful tools in establishing just-noticeable difference (JND) criteria for Mura grading tasks. The small correlation coefficients between the predicted and visual results, however, imply better experimental techniques should be applied in the future study. The new experiments will be conducted to take into account the spatial backgrounds.

Experiments in Inkjet Colour Tests for Printmaking, *Carinna Parraman, University of the West of England (UK)* **107**
The motivation for this research is based on how artists mix and print colour by traditional means (painting and printmaking) and how these differ from colour picker tools, slider bars and methods developed for digital printing, and whether it is possible to incorporate both? Artists have been expert at mixing colour for centuries, yet although the artist and designer has access to a wide range of digital imaging tools and technologies, that on first glance, are dedicated to the creation of colour mixtures, the resulting colours are often disappointing. It appears that hardware, software tools and methods for digital printing are not necessarily suited to the specific requirements of the artist. In fact, they are too generalised to obtain a high degree of quality and too inflexible to allow artists to obtain precision and predictability. Based on existing hardware and software, the paper suggests alternative approaches to custom colour ink mixing and printing. Through the development of alternative ink colours specifically mixed for inkjet printing the paper demonstrates specially designed charts for printing and double printing of custom mixed inks.

Estimation of Spectral Bands of Metallic Coatings Assessed by Multi-Angle Spectrophotometers, *Esther Perales[1], José M. Medina[2] , Elísabet Chorro[1], and Francisco Martínez-Verdú[1]; [1]University of Alicante (Spain) and [2]University of Minho (Portugal)* **113**
Using three commercial multi-angle spectrophotometers, we have measured the reflectance spectra over catalogues from the automotive industry that contain metal and interference pigments and involve changes in hue and lightness at certain viewing angles. We have used principal-component analysis to determine the spectral distribution of their constituents in order to compare between the basis functions assessed by each instrument and common measurement geometry and to examine differences between multi-angle spectrophotometers. Our results corroborate that at least a minimum of 8 basis vectors are needed to explain 99.99% of the total variance. Comparisons conclude the existence of differences in those vectors associated with interference pigments. Reconstruction of the original reflectance spectra suggest that those detection geometries close to the specular reflection provide the least accurate results.

Recovering Spectral Data from Digital Prints with an RGB Camera Using Multi-Exposure Method, *Mikko Nuutinen and Pirkko Oittinen, Aalto University School of Science and Technology (Finland).* **120**
The spectral data of a surface can be reconstructed from RGB camera response when reflectance spectrum of the surface and radiance spectrum of the light source are smooth enough. One factor that lowers the reconstruction performance of consumer level cameras is limited dynamic range. Details or intensity levels in low and high luminance regions can not be reliably detected from a single image. With multiple exposures it is possible to capture high dynamic range images. The aim of this study was to apply a multi-exposure method for spectral data reconstruction of prints and find how accuracy it is. Our intended application area is printed image digitization for image quality



calculations. We measured the intensity levels and recovered spectral data of printed samples by taking two images using different exposure times. Based on the results multiexposure method improves the accuracy of spectral data reconstruction of print samples compared to traditional methods and is the preferred choice for printed image digitization process.

Camera-Supervised Monitor Shading Correction for Softproofing Systems, *Johannes Brauers, Julie Klein, Bernhard Hill and Til Aach, RWTH Aachen University (Germany)* **126**
A softproofing system is required to faithfully display color images. As the user relies on an appropriate calibration of the system, a method for the evaluation of the quality of the calibration is required. Such a method has recently been developed and allows a critical side-by-side comparison between the original sample and the reproduced monitor image by placing the original directly in front of the monitor. An internal light source of the softproofing system establishes an almost uniform illumination of the target.

In this paper, we present a method to spatially equalize the brightness of the monitor with respect to an object placed in front of the monitor. The automatic calibration procedure requires minimal user intervention and utilizes a standard RGB camera in combination with a special calibration target. The results show that the camera enables an accurate and uncomplicated homogenization of the monitor with respect to the object in front of the monitor.

New Experiments on Color in Context and Organic-Based Artificial Photoreceptors, *Davide Gadia[1], Gianluigi Lasco[1], Alessandro Rizzi[1], Daniele Marini[1], Maria Rosa Antognazza[2], Stefano Perissinotto[2], and Guglielmo Lanzani[2, 3]; [1]Università degli Studi di Milano, [2]CNST-IIT@POLIMI, and [3]Politecnico di Milano (Italy)* **132**
In recent years, organic semiconductors have been used to develop a new generation of photodetectors; in some cases their outstanding properties, especially in terms of spectral tuning, have been exploited in order to reproduce human cone sensitivities.

To date, however, it is still not clear if the spectral differences between real and artificial cone responses, unavoidable at a certain extent, may lead to real, corresponding differences in the final color perception. As a matter of fact, one should note that perception is the final result of a complex analysis and elaboration made by our visual system at a superior level respect to the color sensation, as detected in the retinal photoreceptors layer. Therefore, aiming at the development of an artificial retina, the way how human perception actually works can not be disregarded.

In this paper, we focus in detail on the role and effect of spatial normalization, when applied to a set of tristimulus values obtained using different integration curves, derived by different organic semiconducting materials.

In a recent work, we proposed an experimental setup to investigate this issue. We used a multispectral rendering of a virtual scene as a simulation of incoming light spectra, and a set of artificial cone sensitivities to obtain different tristimulus values for each combination of integrating curves. Finally, we applied different computational models with and without spatial color computation to partially simulate human perception. A preliminary analysis of the values showed that the application of a spatial color algorithm leads to a normalization of the differences in artificial cones spectral sensitivities.

In this paper we present the results of a new session of experiments, based on the same experimental setup, but using new multispectral test images of real scenes, and a different selection of organic active materials. We analyze the values obtained after the application of the processing methods, trying to define some latex in the selection, among the many available organic semiconductors, of their most effective combination. Moreover, we introduce some hypothesis regarding the effect of different frequency cut points and overlapping areas between the photoresponsivity curves.

Estimation of an Individual's Human Cone Fundamentals from Their Color Matching Functions, *Casper F. Andersen, Mediehøjskolen (Denmark), and Graham D. Finlayson, University of East Anglia (UK)*. **138**
Estimating individual cone sensitivities on the basis of their corresponding individual color matching functions is a classic problem of color vision. To solve the problem one has, in effect, to postulate constraints on the shape of the cone sensitivities. For example, Logvinenko applied a linear matching method (originally proposed by Bongard and Smirnov) which excludes all but one primary to which each of the sensitivities of the visual system is supposedly sensitive and, mathematically, if this constraint is met reasonable estimates should result. However, when applied to color matching functions in

general, it turns out that the method estimates middle and especially long wave sensitivity quite poorly. We propose a new method based on linear optimization, in which it is assumed only that the photo-pigment spectral absorptance functions are known a priori. In an iterative scheme, the method works by simultaneously estimating the coefficients of the linear relation between the known individual color matching functions and estimated cone sensitivities and estimating the ocular and macular filtering that multiplied by the absorptances yield the estimated cone sensitivities. The ocular and macular pre-filtration is treated as a single spectral function (i.e. a combined ocular and macular filtration). We are also able to predict the cone sensitivities proposed by Stockman and Sharpe in recent research. The method is tested on a selection of individual 1959 10 degree Color Matching Functions, with the assumption that they have the Stockman and Sharpe 10 degree photo-pigment spectral absorbtance in common. The results for the estimated cone sensitivities look very plausible. Finally we have applied the method to the CIE1964 10 degree observer and get very reasonable result as well.

Digital Reproduction of Small Gamut Objects: A Profiling Procedure Based on Custom Color Targets, *Giorgio Trumpy, Institute of Applied Physics (Italy)* **143**
In this paper the optimization of color accuracy of digital reproductions is approached. Standard color targets currently available on the market, are constituted of colors spread uniformly in the color space, therefore, these targets are usable in any situation, *i.e.* for any chromatic content of the images to be profiled. The usage of standard color targets becomes an issue when the object that has to be reproduced is characterized by a small gamut of colors. In this case the ICC profile that can be obtained with a standard color target may miss to match with sufficient accuracy the dominating color due to two different causes. First, with reference to the colors of the standard target, the software used to create an ICC profile attempts to optimize all colors, including those which are not present in the object. Secondly, the color of the object can be colorimetrically distant from the patches of the target and therefore the interpolation process required results in a low level of precision. Hence the profiling process would work better if the color of the patches of the target were chosen with reference to the palette of the object that has to be reproduced. Here this problem is approached empirically by developing a new profiling procedure. A custom-made color target has been created in order to optimize the color accuracy of the digital reproduction of a small gamut object. Selection of colors has been carried out from a color catalogue, choosing a set with colorimetric values uniformly distributed in the volume of the color space took up by the gamut of the object. Then, the creation of the ICC profile has been carried out referring to the new target. The main results obtained though a comparison between the developed custom profiling procedure and the standard profiling procedure confirmed a higher precision of the new procedure.

Validating Photometric and Colorimetric Consistency of Physically-Based Image Synthesis, *Jakob Bärz, Niklas Henrich, and Stefan Müller, University of Koblenz (Germany)* **148**
The purpose of physically-based image synthesis is to predict the natural appearance of a scenario by simulating the distribution of light using radiometric quantities. A set of spectral measurements on the film plane of the virtual camera is computed to generate a two-dimensional projection of the scene. To guarantee photometric and colorimetric consistency, the measured incident radiance distributions are reproduced exactly on the display device by reconstructing spectra with the same luminance and chromaticity. Although a significant number of predictive rendering systems have been presented in the past, there is still a lack of a comprehensive model incorporating local reflection, light transport, measurement, and reproduction. Furthermore, despite the fact that some of these frameworks have been validated in the last decades, trustworthy reproduction of color and luminance is a challenging field of research. The mathematical model to simulate and reproduce physically-based images while preserving photometric and colorimetric consistency is summarized. As a proof of concept, we integrated the model into a ray tracing system to generate photorealistic images. To validate our approach, a virtual scene and a real model of a well-defined box scenario were built and evaluated by photometric and colorimetric measurements. The scenario included a GretagMacbeth ColorChecker to allow an accurate verification of both luminance and chromaticity values. The illumination was simulated using spectral path tracing and radiometric quantities for the light source and the materials. The projected image was reproduced on a colorimetrically characterized LC device. Our results show that the

1976 CIELAB differences between the measurements of the ColorChecker patches in the real world scene and on the monitor displaying the reproduction of our simulation are well below the Just Noticeable Difference threshold.

Dimensions of Light Source Color Quality, *Peter Bodrogi, Stefan Brückner, and Tran Quoc Khanh, Technische Universität Darmstadt (Germany)* **155**
For the lighting industry, it is important to optimize the colour quality of the lit visual environment by improving the spectral power distributions of novel light sources. In the present work, two colourful still lifes (so-called tabletop arrangements) were built from several real objects. Visual experiments were carried out to scale the different aspects (dimensions) of colour quality (fidelity, harmony, acceptability, visual clarity, brightness and preference) under incandescent, fluorescent as well as RGB LED and white phosphor LED lamps. The visual ranking among these light sources depended on the particular dimension of colour quality. Generally, the incandescent lamp obtained the best ratings. But in the first still life, the colour harmony ratings of the white LED lamp and the colour gamut ratings of the RGB LED lamp exceeded the incandescent lamp's ratings. In the second still life, the brightness ratings of the fluorescent lamp and the harmony ratings of the white retrofit LED lamp exceeded the incandescent lamp's ratings. To optimize a novel lamp for a given application, the most important dimension of that application can be considered.

Colour Reproduction I

Session Chair: Roger D. Hersch, EPFL (Switzerland)
16:00 – 18:20

16:00 **Supporting "Good Enough" Colour Reproduction in Non-Colour Managed Workflow,** *Jutta Willamowski, Frederic Roulland, and David B. Martin, Xerox Research Centre Europe (France)* **160**
In this paper we propose a novel and coherent approach to control and adjust colour reproduction where strict end-to-end colour management cannot be achieved. We first recall the studies and findings that identified the need to reconsider colour management in certain workflows. We then present in detail the Print Mediator system, constituting a first attempt to implement this new approach.

16:20 **Electronic Image Color Conversion between Different Illuminants by Perfect Color-Constancy Actuation in a Color-Vision Model Based on the OSA-UCS System,** *Claudio Oleari, University of Parma (Italy)* **167**
In digital image capturing, the camera signals produced by D65 illuminant, once translated into tristimulus values of the CIE 1931 standard colorimetric observer, are considered appropriate for an accurate rendering. The image likelihood requires that the camera-tristimulus values, for any illuminant other than D65, must be transformed into the corresponding ones produced by the D65 illuminant. Many techniques exist for producing this transformation with different performances. In digital image capturing, this transformation requires color constancy. This research is for a transformation suited to realize perfect color constancy or perfect illuminant discounting (although the perfect color constancy and the perfect illuminant discounting are non-existing for human color vision) by using the color-vision model based on the Optical Society of America-Uniform Color Scales (OSA-UCS) system. This transformation is represented by a matrix obtained by minimizing the Root Mean Square value between the pairs of the uniform scale chromatic responses related to tristimulus values of the 24 color samples of the Macbeth ColorChecker, measured under a pair of different illuminants, one of which is D65. The solution is obtained by a convergent iteration. This transformation is a color conversion, not a simple white conversion. The performance of the result is quantified by a color difference computation.

16:40 **Softproofing System for Accurate Colour Matching and Study of Observer Metamerism,** *Bernhard Hill, RWTH Aachen University (Germany)* **173**
A new design of a softproofing system for accurate colour matching is presented in the first part of this paper. In a cabinet, an LCD display is mounted in the viewing plane and illuminated by fluorescent tubes. This arrangement allows for the direct visual comparison of original surface colours with their displayed reproductions face to face. Test colours are placed in cutouts of a mask on top of the screen for colour matching experiments (colour checker mask) or for calibration purposes. The device provides a

means for very sensitive proofing of the reproduction algorithm and offers the study of the variability between different observers. The reproduction algorithm applied is based on the spectral specification of all the essential components of the system and allows for fast switching between colour matching functions of different observers considered. Experimental results and studies on the reproduction for different observers and observer metamerism problems are presented in the second part of the paper. Colour matching experiments for a white colour under different illuminants have been performed for a number of different persons. The results show very well reproducible shifts of the experimentally matched colours in the chromaticity diagram, if compared with the original colours for the CIE 1931 standard observer. The results differ for the left and right eye matches for most of the observers. Any person exhibits a typical direction of the shifts like a personal characteristic or a "finger print", yet, the directions of shifts in the chromaticity diagram are different for different observers and any direction might appear. All the shifts of all persons form a cloud around the original colour in the chromaticity diagram.

17:00 **Estimation of Backing Influence on Halftone Reflectance,** *Matthias Scheller Lichtenauer[1], Hanno Hoffstadt[2], Andreas Kraushaar[3], Berthold Oberhollenzer[3], and Peter Zolliker[1]; [1] EMPA (Switzerland),[2] GMG GmbH & Co. KG, and [3]Fogra (Germany)* **181**

In the graphic arts industry, there is a need to convert colorimetric readings taken on one backing (usually white) to values that would have been measured with a different backing (usually black). We describe and compare different models for such a conversion. Starting from published models using linear scaling, we developed a new nonlinear model for a strongly scattering substrate. Another new model was derived from the Clapper-Yule model, which includes effects of internal reflectances. All these models are applicable in both the spectral and the tristimulus domain.

For calibration, we used measurements of the bare substrate on both backings. We intentionally make only use of the measured spectral or XYZ values, and do not require knowledge of the nominal CMYK values. This is particularly useful for arbitrary patches measured with a stand-alone measurement device. The test data sets consisted of a large set of test prints, originating from digital or conventional printing processes, and covering typical ranges of mass per area. Both new models outperformed linear regression models and the spectral versions always yielded better results than their corresponding versions in tristimulus space.

17:20 **Psychovisual Assessment of Tone-Mapping Operators for Global Appearance and Colour Reproduction,** *Céline Villa and Raphaël Labayrade, Université de Lyon (France)* **189**

To identify people's preference, psychovisual tests are carried out in virtual environment. Images of scenes used for psychovisual tests are natively High Dynamic Range (HDR) images. However, in order to allow a Low Dynamic Range (LDR) display device to project HDR pictures, their dynamic range must be compressed with a tone-mapping operator (TMO). Thus, before tests are carried out, selection of the most suitable TMO, perceptually speaking, is required to present images faithfully, depending on the aim of the application.

In this paper, three different experimental protocols are proposed for assessing the applications of a display device used for psychovisual tests and selecting the most suitable TMO from six candidates. An additional goal is to give a first idea of the applications that can be addressed by this device. Two subjective experiments were conducted and are presented in the paper. The first one is divided in two steps. The results of three different protocols (two protocols in the first test and the third in the second test) for the identification of the preferred TMO for five different scenes are compared and LDR image defects noticed by observers are highlighted in the paper.

17:40 **The Compositional Markovian Reflectance Model of Halftone Prints on Diffusing Substrate,** *Xiao-xia Wan, Zhen Liu, and Bao-zhen Xing, Wuhan University (China)* **197**

In the development of the technology of halftone imaging there has been significant interest in physically modeling the halftone microstructure. An important aspect of the microstructure is the scattering of light within the paper upon which the halftone image is printed. And the scattering of light within paper is the key factors which affect the color reproduction. A new spectral reflection prediction model was proposed in this paper that modified the classical Williams- Clapper model using markov chains, By

considering the fact that the incident light entered into a given medium surface and exited from another medium, such as entered from colorant patch and exited from paper sheet. And the complex multiple reflection-transmission process occurring between different layers was described by Markov chain. Considering the transverse scatting influence of light propagated in the paper sheet, we introduced experience probability theory, then we calculated four fundamental transfer matrixes under different situation; finally, a new spectral reflectance model of halftone images based on the optical dot gain was established.

18:00 **Ink-Dependent *n*-Factors for the Yule-Nielsen Modified Spectral Neugebauer Model,** *Romain Rossier and Roger D. Hersch, Ecole Polytechnique Fédérale de Lausanne (Switzerland)*. **202**
Different inks may have different mechanical and/or optical properties. Existing Yule-Nielsen modified Neugebauer spectral prediction models assume however that the inks forming a color halftone behave similarly, i.e. that a single *n*-factor can model the lateral propagation of light within the paper as well as non-uniformities of the ink dot thickness profiles. However, if the inks have very different optical or mechanical properties, each ink may be separately modeled with its specific *n*-factor. In order to predict the reflection spectrum of such color halftones, we extend the ink spreading enhanced Yule-Nielsen modified spectral Neugebauer (EYNSN) model by calculating for each halftone an optimal *n*-factor as an average of the ink specific *n*-factors weighted by a parabolic function of the ink surface coverages. We compare the prediction accuracies of the standard EYNSN model where each halftone is predicted by making use of one global *n*-factor with the predictions accuracies of the extended EYNSN model where each halftone is predicted with its corresponding optimal *n*-factor derived from the individual ink-specific *n*-factors. For inks having very different optical and/or mechanical properties, we observe an improvement of the prediction accuracies.

20:00 – 22:00
Conference Reception at the Home of the Polar Bears

WEDNESDAY JUNE 16, 2010

Wednesday Keynote

Session Chairs: Theo Gevers, University of Amsterdam, and
Alain Trémeau, Université Jean Monnet
8:30 – 9:30

8:30 **Object-Colour Space Revisited,** *Alexander D. Logvinenko, Glasgow Caledonian University (UK)*. **207**
Colorimetry can predict which lights will look alike. Such lights are called metameric. Two lights are known to be metameric if they have the same tri-stimulus values. Using the tri-stimulus values as the Cartesian coordinates one can represent light colours as points in a 3D space (referred to as the colorimetric space). All the light colours make a tri-dimensional manifold which can be represented as a circular cone in the colorimetric space. Furthermore, colorimetry can also predict which reflecting objects illuminated by the same light will look alike: those which reflect metameric lights. All the object colours can be represented as a closed solid inscribed in the light colour cone provided the illumination is fixed. However, when there are multiple illuminants the reflected light metamerism does not guarantee that the reflecting objects will look identical (referred to as the colour equivalence). In this paper three axioms are presented that allow the derivation of colour equivalence from metamerism. The colour of a reflecting object under various illuminations is shown to be specified by six numbers (referred to as its six-stimulus values). Using the six-stimulus values one can represent the colours of all the reflecting objects illuminated by various illuminants as a cone in the 6D space over the 5D ball.

Colour Image and Video Processing

Session Chair: Faouzi Alaya Cheikh, Gjøvik University College (Norway)

9:30 – 12:40

9:30 **Extending SURF to the Color Domain,** *David Gossow, Peter Decker, and Dietrich Paulus, University of Koblenz-Landau (Germany)* **215**

Automatic extraction of local features from images plays an important role in many computer vision tasks. During the last years, much focus has been put on making the features invariant to geometric transformations such as a rotation and scaling of the image. Recently, some work has been published concerning the integration of color information into the detection and description step of SIFT. In various evaluations, it has been shown that including color information can increase distinctiveness and invariance to photometric transformations caused by illumination changes. In this paper we build on the results from these approaches and apply them to the SURF descriptor, which is advantageous compared to SIFT in terms of speed, making it a perfect candidate for online applications, for example in the field of robotics. Our results show significant improvements concerning the repeatability and destinctiveness of SURF for 3D objects under varying illumination directions.

In contrast to many other evaluations we also determine the accuracy of the orientation assignment and include this into our comparisons.

9:50 **Evaluation Perceptual Color Edge Detection Algorithms,** *Aurora Sáez, Carmen Serrano, and Begoña Acha, University of Seville (Spain)*. **222**

Although several colour edge detectors have been proposed, all of them utilized colour Euclidean distances in the colour space to measure colour differences. In this paper a set of colour edge detection algorithms based on colour visual perception is proposed. These algorithms are a combination of vector edge detector, in uniform colour spaces and using perceptual colour difference equations. A comparative study has been performed. To evaluate the detectors performance a set of synthetics images is generated and various measures are used. It can be concluded that detectors based on CIEDE2000 colour difference equation are better regarding the correlation with colour visual perception.

10:10 **Color Edge Saliency Boosting Using Natural Image Statistics,** *David Rojas Vigo, Joost van de Weijer, and Theo Gevers, Universitat Autonoma de Barcelona (Spain)*. **228**

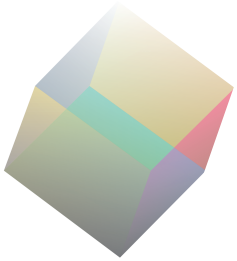
State of the art methods for image matching, content-based retrieval and recognition use local features. Most of these still exploit only the luminance information for detection. The color saliency boosting algorithm has provided an efficient method to exploit the saliency of color edges based on information theory. However, during the design of this algorithm, some issues were not addressed in depth: (1) The method has ignored the underlying distribution of derivatives in natural images. (2) The dependence of information content in color-boosted edges on its spatial derivatives has not been quantitatively established. (3) To evaluate luminance and color contributions to saliency of edges, a parameter gradually balancing both contributions is required.

We introduce a novel algorithm, based on the principles of independent component analysis, which models the first order derivatives of color natural images by a generalized Gaussian distribution. Furthermore, using this probability model we show that for images with a Laplacian distribution, which is a particular case of generalized Gaussian distribution, the magnitudes of color-boosted edges reflect their corresponding information content. In order to evaluate the impact of color edge saliency in real world applications, we introduce an extension of the Laplacian-of-Gaussian detector to color, and the performance for image matching is evaluated. Our experiments show that our approach provides more discriminative regions in comparison with the original detector.

10:30 – 11:00 Coffee Break

11:00 **Unsupervised Hierarchical Spatio-Colorimetric Classification for Color Image Segmentation,** *Cindy Torres and Alain Clément, Université d'Angers (France)* . . . **235**

A new unsupervised vectorial segmentation method developed for color images is presented. Both spatial and color information have been used during the classification process of the pixels. To overcome the problem of memory space associated with multidimensional histograms analysis and avoid a color requantization, this method is



based on a multidimensional compact histogram and an original compact spatial neighborhood probability matrix. The multidimensional compact histogram allows a drastic reduction of memory space necessary for coding color histograms without any data loss. Leaning upon the compact histogram, a spatial neighborhood probability matrix has been computed. It contains all non-negative probabilities of spatial connectivity between pixel colors and allows a spatial distance inside a variable size neighborhood to be defined. In an unsupervised histogram analysis classification process, two phases are classically distinguished: (i) a learning process during which histogram modes are identified and (ii) a second step called the decision step in which a full partition of the colorimetric space is carried out according the previously defined classes. In a standard colorimetric approach, in the second step, a colorimetric distance like Euclidean or Mahalanobis is used. We introduced here a spatio-colorimetric distance taking into account the information of pixel neighborhood colors. This distance is defined as a weighed mixture between a colorimetric distance and the spatial distance calculated from the spatial neighborhood probability matrix. The vectorial classification method is based on previously presented principles, achieving a hierarchical analysis of the color histogram using a 3D-connected components labelling.

11:20 **Color Image Super Resolution: A Two-Step Approach Based on Geometric Grouplets,** *Aldo Maalouf and Mohamed-Chaker Larabi, University of Poitiers (France)* **240**
In this work, a two-step technique for constructing a super-resolution (SR) image from a single multi-valued low-resolution (LR) input image is proposed. The problem of SR is treated from the perspective of image geometry-oriented interpolation. The first step consists of computing the image geometry of the LR image by using the grouplet transform. Having well represented the geometry of each color channel in the LR image, we propose a grouplet-based structure tensor whose role is to couple the geometrical information of the different image color components. In a second step, a functional is defined on the multispectral geometry defined by this structure tensor. The minimization of this functional insures the synthesize of the SR image. The proposed super-resolution algorithm outperforms the state-of-the-art methods in terms of visual quality of the interpolated image.

11:40 **Colour Fractal Analysis for Video Quality Assessment,** *Mihai Ivanovici, Transylvania University (Romania), and Nöel Richard and Christine Fernandez-Maloigne, University of Poitiers (France)* **247**
Fractal dimension and lacunarity are two fractal measures widely used for image analysis, segmentation and indexation. In this paper, we show how these two fractal features are able to capture several aspects that characterize the degradation of the video signal, based on the fact that the quality perceived is directly proportional to the fractal complexity of an image. Thus, we demonstrate that the fractal dimension and lacunarity can be used to objectively assess the quality of the video signal and how they can be used as metrics for the user-perceived video quality degradation for an MPEG-4 streaming application.

Unfortunately, all the existing approaches are defined only for binary and grey-scale images. Based on the probabilistic algorithm for the estimation of the fractal dimension and computation of lacunarity, we propose a colour approach that makes possible the analysis of the complexity in the RGB colour space of any colour image. We discuss our experimental results and then draw the conclusions.

12:00 **Local Perceptual Weighting in JPEG2000 for Color Images,** *Jaime Moreno, Xavier Otazu, and Maria Vanrell, Universitat Autònoma de Barcelona (Spain)* . . . **255**
The aim of this work is to explain how to apply perceptual concepts to define a perceptual pre-quantizer and to improve JPEG2000 compressor. The approach consists in quantizing wavelet transform coefficients using some of the human visual system behavior properties. Noise is fatal to image compression performance, because it can be both annoying for the observer and consumes excessive bandwidth when the imagery is transmitted. Perceptual pre-quantization reduces unperceivable details and thus improve both visual impression and transmission properties. The comparison between JPEG2000 without and with perceptual pre-quantization shows that the latter is not favorable in PSNR, but the recovered image is more compressed at the same or even better visual quality measured with a weighted PSNR. Perceptual criteria were taken from the CIWaM (Chromatic Induction Wavelet Model).

12:20 **Denoising of Multispectral Images via Nonlocal Groupwise Spectrum-PCA,** *Aram Danielyan, Alessandro Foi, Vladimir Katkovnik, and Karen Egiazarian, Tampere University of Technology (Finland)* **261**
We propose a new algorithm for multispectral image denoising. The algorithm is based on the state-of-the-art Block Matching 3-D filter. For each "reference" 3-D block of multispectral data (sub-array of pixels from spatial and spectral locations) we find similar 3-D blocks using block matching and group them together to form a set of 4-D groups of pixels in spatial (2-D), spectral (1-D) and "temporal matched" (1-D) directions. Each of these groups is transformed using 4-D separable transforms formed by a fixed 2-D transform in spatial coordinates, a fixed 1-D transform in "temporal" coordinate, and 1-D PCA transform in spectral coordinates. Denoising is performed by shrinking these 4-D spectral components, applying an inverse 4-D transform to obtain estimates for all 4-D blocks and aggregating all estimates together. The effectiveness of the proposed approach is demonstrated on the denoising of real images captured with multispectral camera.

12:40 – 14:00 Lunch in the Carelia or Aura University Cafeteria

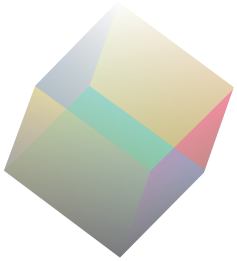
Interactive Paper Session II

14.00 – 16.00

Color Image Processing and Color Analysis

Perceptually Adapted Color-Texture Image Segmentation Algorithm Based on K-Dimensional Multi-Step Region Growing, *Irene Fondón, Carmen Serrano, and Begoña Acha, University of Seville (Spain)* **267**
This paper presents a new approach for the segmentation of color-textured images, which is based on a novel, perceptually adapted K-means algorithm and a multidimensional multistep region growing technique. The method consists of several steps. Perceptually adapted K-means clustering algorithm is performed to determine the N reference colors of the desired region. Texture features are computed using the energy of some low order statistical moments Then, an N-dimensional multi-step region growing procedure controlled by texture is performed with the automatically extracted seeds by computing, for each new pixel in the image, its perceptual distance to the reference colors, that is, computing the CIEDE 2000 color distance in the L*a*b* color space to the colors that compound the multicolored texture, rather than Euclidean distance in a non-uniform color space. The method has an adaptive structure due to the growth tolerance parameter that changes with a step size that depends on the mean of the variance for each reference color of the actual grown region. Contrast is also introduced to decide which value of this tolerance parameter is taken, choosing the one that provides the region with the highest mean contrast in relation to the background. Using these tools, a set of 80 natural images is considered. To validate the segmentation results obtained, a comparison with state-of-the-art color-texture based algorithms has been completed. The proposed technique outperformed the published ones achieving a Recall value of 0.757 and a Precision value of 0.812.

Imaging of Cosmetics Foundation Distribution by a Spectral Difference Enhancement Filter, *Ken Nishino[1], Mutsuko Nakamura[2], Masayuki Matsumoto[2], Osamu Tanno[2], and Shigeki Nakauchi[1]; [1]Toyohashi University of Technology and [2]Kanebo Cosmetics Inc. (Japan)* **275**
The light reflected from an object contains a range of information about its physical and chemical properties. Changes in the physical properties of an object can sometimes be evident as barely detectable changes of the spectra. However conventional color sensors (e.g. human color vision or typical RGB camera) are not able to detect most of spectral differences because the spectrum information is mapped into three-dimensional RGB signal. This article proposes a method for designing an optical filter which optically performs discriminant analysis of incoming spectrum to enhance object's spectral difference. First, spectral transmittance of the filter is theoretically determined by minimizing the misclassification of two selected target colors by discriminant analysis. In this study, spectral datasets of human facial colors in the presence and absence of cosmetics foundation were used as these targets. A real optical filter was developed by vacuum deposition technology according to the theoretical design, and was applied to the detection of the presence of a cosmetics foundation on the human face. In the first experiment, a digital camera equipped with the developed filter was



used to detect foundation on face. The result confirmed a clear enhancement of spectral difference between facial colors with/without foundation (misclassification rate for these two sets was 4.1%), which were difficult to discriminate by naked eyes. As the second experiment, a calibration curve between the discriminant score calculated from filtered image and the amount of applied cosmetics foundation was experimentally obtained and high estimation accuracy was established (decision coefficients were about 0.9). Finally, the optical filter was applied to visualize the spatial foundation distributions of a realistic made-up skin condition. Visualized foundation map clearly indicated the unevenness of foundation distribution even though the skin color looked uniform. Results confirm that the proposed filter can achieve to visualize the foundation distribution without any destructive inspection.

Color Enhancement of Multispectral Images for Effective Visualization, *Noriaki Hashimoto, Yuri Murakami, Masahiro Yamaguchi, Takashi Obi, and Nagaaki Ohyama, Tokyo Institute of Technology (Japan)* **282**
The color enhancement of multispectral images is a useful tool to visualize their spectral features. Previously, a color enhancement method which enhances the feature of specified spectral band without changing the average color distribution was proposed. However, the enhanced feature is sometimes unapparent or invisible, when the wavelength range of the specified band is visually insignificant. In this paper, we propose a modified method for more effective visualization capability in the color enhancement for multispectral images. In the proposed method, a user specifies both the spectral band for extracting the spectral feature and the color to be visualized, respectively. Then, the spectral feature in the multispectral image is enhanced by arbitrary color. The proposed method of the color enhancement was experimentally applied to multispectral images, such as a human skin image and microscopic images of pathological tissue specimen. As a result, we verified that the proposed method can effectively visualize the spectral features.

Tracking Categorical Surface Colour Across Illuminant Changes in Natural Scenes, *Kinjiro Amano and David H. Foster, University of Manchester (UK)* **289**
How well can categorical colour perception be maintained in natural environments with varying illuminants? To address this question, a colour naming experiment was performed with colour-monitor images of natural scenes simulated under two different daylights of correlated colour temperature 6500 K and 25000 K. Images were obtained from a set of hyperspectral data to enable the accurate control of illuminant and reflectance spectra. Each scene contained a spherical test surface whose digitally manipulated spectral reflectance coincided with that of a sample drawn randomly from approximately 430 Munsell reflectances grouped into eight colour categories, namely, red, green, blue, yellow, pink, purple, brown, and orange. Observers had to name the colour of the test surface in each image, presented for 1 s, by pressing one of nine computer keys corresponding to the eight categorical colour names and a neutral category. Focal colours were estimated from the peaks of the smoothed distributions of observers' naming responses in the CIE 1976 (u', v') chromaticity diagram. The effect of the illuminant change was quantified by a focal colour constancy index, with values 0 and 1 corresponding to no constancy and perfect constancy. Average levels of focal colour constancy were close to those from traditional measures of colour constancy, but with variation across categories and surface lightness. For blue and purple surfaces levels approached 0.9. For many surface colours, colour naming seems to be robust under illuminant changes and may help to anchor non-categorical judgements of arbitrary surface colours in natural scenes.

Convex Objects Recognition and Classification Using Spectral and Morphological Descriptors, *Steven Le Moan[1,3], Alamin Mansouri[1], Tadeusz Sliwa[1], Madaín Pérez Patricio[2], Yvon Voisin[1], and Jon Y. Hardeberg[3]; [1]Le2i – Université de Bourgogne (France), [2]Instituto Tecnológico de Tuxtla Gutiérrez (Mexico), and [3]Gjøvik University College (Norway)* **293**
In this paper, a new approach for the recognition and classification of convex objects in color images is presented. It is based on a collaboration between color quantization, mathamatical, morphology and reflectance estimation from RGB data. This yeilds a robust algorithm regarding the conditions of illumination, the color sensor used for acquisition, as well as the shape /overlapping ambiguities among the objects. One singularity of this work is the use of mathmatical morphology in two distinct topologies: first in the entire, for segmentation purposes, then locally, to enhance the classification

of each object. A resolution reduction is used to alleviate the effect of local disturbances such as noise or natural impurities on the objects. The method's efficiency and usefulness are illustrated on the particular task of cofee beans sorting.

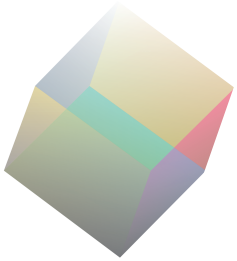
Hyperspectral Imaging of Face for Tongue Region Extraction, *Satoshi Yamamoto, Norimichi Tsumura, Toshiya Nakaguchi, Takao Namiki, Yuji Kasahara, Katsutoshi Terasawa, and Yoichi Miyake, Chiba University (Japan)*. **300**
In this article, we propose a hyperspectral imaging system and automatic hyperspectral image processing method to extract the uncoated area of the tongue for the clinical inspection of Kampo medicine (Japanese traditional herbal medicine). The automatic processing methods were built based on the analysis of nine taken hyperspectral image. The effectiveness of the method was confirmed by applying to other eight hyperspectral images.

Combining Color Descriptors for Improved Codebook Model-Based Image Retrieval, *Aitor Alvarez Gila[1,2,3], Guanqun Cao[1,2,3], Sheikh Faridul Hasan[1,2,4], and Yu Hu[1,4]; [1]University of Granada, (Spain), [2]University of Saint-Etienne (France), [3]Gjøvik University College, (Norway), and [4]University of Eastern Finland, Joensuu (Finland)*. **306**
In this paper we present the design of an image Content-Based Indexing and Retrieval (CBIR) system which, based upon existing implementations of a number of well-known color descriptors, makes use of the bag-of-words or codebook model in order to construct a robust approach to the retrieval of images from a database in a query-by-example context. A new object image database was constructed specifically for this task, in an attempt to challenge the invariance properties of the system under controlled conditions of illumination, point of view and scale. The system permits the combined use of up to two of the different color descriptors considered. The experiments run over a subset of the image database show an improvement of the obtained results under some of the tested combinations, as well as the effect of the variation of the employed codebook size.

A Multi Color Space Approach for Texture Classification: Experiments with Outex, Vistex and Barktex Image Databases, *Alice Porebski[1,2], Nicolas Vandenbroucke[1,2], and Ludovic Macaire[2]; [1]École d' Ingenénieurs du Pas du Calais and [2]Université Lille 1 (France)* **314**
The color of pixels can be represented in different color spaces which respect different properties. Many authors have compared the classification performances reached by these color spaces in order to determine the one which would be the well suited to color texture analysis. However, the synthesis of these works shows that the choice of the color space depends on the considered texture images. Moreover, the prior determination of a color space which is well suited to the considered class discrimination is not easy. That is why we propose to consider a multi color space approach designed for color texture classification. It consists in selecting, among a set of color texture features extracted from images coded in different color spaces, those which are the most discriminating for the considered color textures. In this paper, we experimentally study the contribution of this multi color space with three well-known benchmark databases, namely Outex, Vistex and Barktex. Comparison and discussion are then carried out.

Optimal Palette Extraction as Part of Scanned Graphics Vectorization, *Vinciane Lacroix and Mahamadou Idrissa, Royal Military Academy (Belgium)* . . . **320**
The proposed scanned graphics palette extraction process starts with the extraction of colors of uniform regions, then the colors of local features. In order to enhance the discrimination of unsaturated colors, the image is converted into L*a*b* space and the CMC color difference is used together with the Euclidean distance. After the palette extraction, a regularization process modifies the color of a pixel in order to make it coherent with its neighborhood, thus reducing the number of connected components, hence providing one step further to vectorization. Results are shown on scanned maps and on some scanned graphics.

Groundtruth Data for Multispectral Bidirectional Texture Functions, *Martin Rump, Ralf Sarlette, and Reinhard Klein, Universität Bonn (Germany)* **326**
In this paper we present a method for the acquisition of multispectral Bidirectional Texture Functions (BTFs) for the color-correct reproduction of complex materials in virtual scenes with arbitrary illumination. We explain our acquisition setup in detail as well as its careful calibration. The main purpose of the described setup is to provide accurate



groundtruth data to verify future methods for simplified multispectral BTF measurements as well as techniques for efficient compression and rendering of multispectral BTF data. We show the accuracy of data obtained with our setup by comparing rendered images to photographs of real scenes. We also verify our datasets using reference measurements obtained with a spectrometer.

Color Texture Classification Across Illumination Changes, *Mozhdeh Seifi, Xiaohu Song, Damien Muselet, and Alain Trémeau, Université Jean Monnet (France)* **332**
Color has been shown to be a very important clue in the context of texture classification. However, since color is not stable across illumination changes, color invariant descriptors are required when the illumination is not controlled. In this paper, we propose to characterize color textures by analyzing the rank correlation between pixels located in the neighborhood from each other. Thus, considering one distance and one direction in the image space, we obtain a correlation measure which i) is related to the colors of the pixels, ii) is not sensitive to illumination changes, and iii) represents the spatial interactions between different color components of neighbored pixels. Furthermore, we show how this measure can be very fast extracted from cooccurrence matrices. The discriminative power of this descriptor is assessed on a public color texture database.

Recognition of Objects Represented in Different Color Spaces, *Marcin Grzegorzek, Alexandra Wolyniec, Frank Schmitt, and Dietrich Paulus, University of Koblenz-Landau (Germany)* **338**
In this article we present a statistical framework for automatic classification and localization of 3D objects in 2D images. The new functionality of the framework allows us to use objects represented in different color spaces including gray level, RGB, and Lab formats. First, the objects are preprocessed and described by local wavelet features. Second, statistical modeling of these features under the assumption of their normal distribution is performed in a supervised way. The resulting probability density functions are determined by the maximum likelihood estimation. The density functions describe a particular object class from a particular training viewpoint. In the recognition phase, local feature vectors are computed from an image with an unknown object in an unknown pose. Those features are then evaluated against the trained density functions which yields the classes and the poses of objects found in the scene. Experiments performed for more than 40.000 images with real heterogeneous backgrounds have delivered very good classification and localization rates for all investigated object representations. Moreover, they brought us to interesting conclusions considering the general performance of statistical recognition systems for different image representations.

Estimating Melatonin Suppression and Photosynthesis Activity in Real-World Scenes from Computer Generated Images, *David Geisler-Moroder and Arne Dür, University of Innsbruck (Austria)* **346**
In lighting design and architectural illumination planning simulations of luminance and illuminance distributions within scenes are performed using rendering tools such as RADIANCE. In this paper we focus on the evaluation by two action spectra other than the luminous efficiency function — the circadian action function describing the melatonin suppression and the photosynthesis action function. We show how indices that are derived from these action spectra can be calculated from spectrally rendered images of a real-world scene. For both action spectra we derive approximations based on the CIE color matching functions that allow estimations of the corresponding index from RGB rendered images. We evaluate the differences between the spectral results and the RGB approximations for an office room with three different types of illumination.

Color Semantics for Image Indexing, *Martin Solli and Reiner Lenz, Linköping University (Sweden)* **353**
We propose a color-based image descriptor that can be used for image indexing based on high-level semantic concepts. The descriptor is based on Kobayashi's Color Image Scale, which is a system that includes 130 basic colors combined in 1170 three-color combinations. Each combination is labeled with one of 180 high-level semantic concepts, like "elegant", "romantic", "provocative", etc. Moreover, words are located in a two-dimensional semantic space, and arranged into groups based on perceived similarity. From a modified approach for statistical analysis of images, involving transformations of ordinary RGB-histograms, a semantic image descriptor is derived, containing semantic information about both color combinations and single colors in the

image. We show how the descriptor can be translated into different levels of semantic information, and used in indexing of multi-colored images. Intended applications are, for instance, image labeling and retrieval.

Color Reproduction and Color Science

Prediction and Visualization of Fat and Fatty Acid Content of Beef Using Near-Infrared Multispectral Imaging, *Ken-ichi Kobayashi[1], Yasunori Matsui[2], Yosuke Maebuchi[1], Ken Nishino[1], Toshihiro Toyota[1], and Shigeki Nakauchi[1]; [1]Toyohashi University of Technology and [2]Mie Prefecture Livestock Research Institute (Japan).* **359**

The beef quality grade is greatly affected by visible fat content. Especially, in Japanese black (Wagyu) cattle, high fat content is typically valued highly. In this paper, we describe the feasibility of beef evaluation by visualizing fat characteristics using near-infrared (NIR) multispectral imaging. An intact raw beef cut from Wagyu cattle was used as an evaluation target. The content of fat and fatty acid, such as the total saturated fatty acid (SFA) content, the total unsaturated fatty acid (UFA) content, myristic acid (C14:0) , palmitic acid (C16:0), stearic acid (C18:0), myristoleic acid (C14:1), palmitoleic acid (C16:1), oleic acid (C18:1), and linoleic acid (C18:2) were estimated and visualized. The total SFA content was calculated as the sum of myristic acid, palmitic acid, and stearic acid. Also, the total UFA content was calculated as the sum of myristoleic acid, palmitoleic acid, oleic acid, and linoleic acid. Reference values for the fat content and fatty acid composition were determined by conventional physical and chemical methods. The fatty acid composition was determined from the extracted lipids by Folch's method, by gas chromatography (GC) using its methyl ester. The fat content was determined by using the Gerhardt SOXTHERM. The NIR multispectral images of the sample were acquired by using the SPECIM Spectral Camera SWIR. It works in the wavelength range of 970-2500 nm with 6.3 nm of bandwidth at 320 pixels resolution in spatial domain. The absorbance spectra of each pixel calculated from pixel intensity of subject and reference white standard was used for constructing the prediction model. In total, 33 samples from various parts of the 2 head of Wagyu cattle were measured. Calibrations were performed by a partial least squares (PLS) regression using mean extracted spectra from each individual sample, limited wavelength range from 1000 to 2300 nm. The coefficients of determination (R^2) were between 0.68 and 0.87. The ranks by evaluation index (EI) were "B (high accuracy)" and "C (slightly high)." The ratios of the standard error of prediction to the standard deviation (RPD) were between 1.74 and 2.74. These results indicate a sufficient feasibility of the prediction except for myristoleic acid content. The visualizations, which show the spatial distribution of fatty acid content, were performed by applying the model to predict the content of each pixel.

Evaluation of the Repeatability and Reproducibility Levels for Color Measurement Obtained by Digital Imaging Capture Devices, *Elísabet Chorro[1], Meritxell Vilaseca[2], Jorge A. Herrera[2], Esther Perales[1], Francisco Miguel Martínez-Verdú[1], and Jaume Pujol[2]; [1]University of Alicante and [2]Technical University of Catalonia (Spain)* **366**

Conventional and multi-spectral digital imaging capture devices can be used for colorimetric measurements. However, a preliminary study of their repeatability and reproducibility is very advisable if they want to be used for this purpose. In this work, a methodology to study the repeatability and reproducibility of such systems is proposed and two digital imaging capture devices working as spectroradiometers with three and seven filters, respectively, are analyzed with respect to a reference tele-spectracolorimeter. The results of the statistical test show that both have good levels of repeatability, although not the same conclusion is reached regarding the reproducibility, due to some systematic errors.

Perceptual Reproduction of Wide-Dynamic-Range Scene Based on Local Adaptation of the Human Visual System, *Toshihiro Toyota[1], Hiroki Yokomakura[1], Koichi Kaneko[2], Akira Usui[2], and Shigeki Nakauchi[1]; [1]Toyohashi University of Technology and [2]Yamaha Corporation (Japan)* **372**

Dynamic-range of luminance under standard visual environment, for example among luminance for stars of night sky and for sunlight reaches up to 160 [dB]. Although our visual system can give stable perception against such environment, conventional electronic imaging devices such as digital cameras cannot be able to capture these scenes without lack of information because of the restriction of their dynamic-range. Dynamic-ranges of such conventional electronic imaging devices are only 60 [dB] and lack of

dynamic-range yields lacks of information as under exposure or over exposure. Limitation of dynamic-range is crucial problem for wide-dynamic-range image capturing as vehicle video systems, security cameras and so on. Several methods for such problem were proposed in recent studies. For example, the method for using a series of images with different shutter speed is known as 'multiple exposure' can achieve the wide-dynamic-range imaging using pseudo expansion of dynamic-range using conventional electronic imaging device. Recently, this method was implemented as a hardware system combined with a CMOS image sensor to achieve 160 [dB] dynamic-range. The problems for lack of dynamic-range are not only for imaging device but also for image reproduction medium such as displays. Luminance corrections are required to compress the luminance range to fit with image reproduction device's one. This process is known as 'tone mapping' which corresponds to compression of the dynamic-range for multiple exposure image to that of image reproduction devices. Tone mapping method by effective luminance remapping is need to perform the WYSIWYG image reproduction. This study aims to propose the tone mapping method to achieve the natural contrast reproduction characteristics and to apply it to video sequences. Proposed tone mapping hypothesized that the local luminance adaption to average luminance around each pixel plays an important role to reproduce the spatially-localized contrast with keeping the global luminance variation by simulating the local adaptation mechanisms for the human visual system. In proposed tone mapping, smoothing by a Bilateral filter was applied to suppress the pseudo edges by halo to calculate the luminance of around pixels for each pixel. Additionally, multi-resolution representation for spatial frequency was introduced to save the calculation cost. Also, a series of subjective evaluation experiment were performed to investigate the dependency of each parameter for reproduced image quality and the dynamic-range dependencies of the proposed tone mapping. Result showed that proposed tone mapping gave highest quality composed image compare to conventional tone mapping or conventional wide-dynamic-range imaging device.

Gamut Mapping for Motion Picture, *Jürgen Stauder, Corinne Porée, Patrick Morvan, and Laurent Blondé, Thomson Corporate Research (France)*. **380**
New technologies in capturing and displaying images with extended color gamut and new standards for wide color gamut color encoding enable a new market of extended-color-gamut content (cinema, television, video on demand, games, electronic documents). This paper addresses the scenario of introducing extended-color-gamut motion picture production, postproduction and distribution. One technical issue is the management and compatibility of different color gamuts. Manual (high-end) and automatic (consumer) color conversion tools are needed. For this purpose, we analyze in this paper different gamut mapping algorithms for motion picture type content. A psycho-physical evaluation framework is developed that is based on motion-picture related quality criteria aiming the preservation of the artistic intent and the optimal use of destination color gamut. We notably focus on gamut mapping algorithms that analyze geometrically both the source and the destination color gamut. A new method for automatic detection of the cusp of a color gamut is developed and used for cusp to cusp gamut mapping. The evaluation of several gamut mapping algorithms shows that best results are obtained for cusp to cusp mapping. According to the motion picture evaluation framework, the cusp to cusp gamut mapping algorithm performs significantly better, notably for night scenes and animated content.

Recovering Normal Vectors and Albedo Under Uncontrolled Illumination with an RGB Digital Camera, *Clara Plata, Juan Luis Nieves, Eva Valero, Javier Hernández-Andrés, and Javier Romero, Universidad de Granada (Spain)* **387**
This paper proposes a spatio-spectral imaging device to simulate and acquire color images under different geometries of illumination. The method allows image analysis and synthesis, even for rough-textured surfaces, under different directions of the incident illumination. In addition the use of the albedo instead of directly the RGB information helps to avoid any shadows or highlights that might falsify results. For accurate color reproduction under uncontrolled illumination conditions an RGB digital camera is used in combination with a 4-source-based photometric stereo algorithm to estimate the normals at each image point and the albedo of the surfaces at each pixel. The experimental results show good colorimetric accuracy in the color reproduction of artificial texture objects.

Colour Science

Session Chair: Alessandro Rizzi, Università Degli Studi di Milano (Italy)

16:00 – 17:40

16:00 **On Curvature of Color Spaces and Its Implications,** *Toko Kohei and Jinhui Chao, Chuo University (Japan), and Reiner Lenz, Linköping University (Sweden)* **393**

In this paper we discuss the role of curvature in the context of color spaces. Curvature is a differential geometric property of color spaces that has attracted less attention than other properties like the metric or geodesics. In this paper we argue that the curvature of a color space is important since curvature properties are essential in the construction of color coordinate systems. Only color spaces with negative or zero curvature everywhere allow the construction of Munsell-like coordinates with geodesics, shortest paths between two colors, that never intersect. In differential geometry such coordinate systems are known as Riemann coordinates and they are generalizations of the well-known polar coordinates.

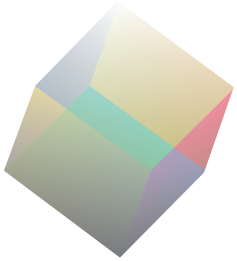
We investigate the properties of two measurement sets of just-noticeable-difference (jnd) ellipses and color coordinate systems constructed from them. We illustrate the role of curvature by investigating Riemann normal coordinates in CIELUV and CIELAB spaces. An algorithsm is also shown to build multi-patch Riemann coordinates for spaces with the positive curvature.

16:20 **Colour and Appearance Analysis of Fruit and Vegetable Soup Using a Digital Colour Imaging System,** *Gerard van Dalen, Faisal Osman, and Aat Don, Unilever Research and Development (the Netherlands)* **399**

Within Food R&D scientists, chefs and engineers aim to develop natural fruit and vegetable based soups with optimal flavour, texture, appearance and health benefits whilst maintaining product safety. The colour and appearance has a major influence on the perceived quality (e.g. nutrition and freshness). This paper describes a method for the determination of the colour of soups containing vegetable particles. Digital images were made under controlled lighting using a DigiEye imaging system. It allows documenting the appearance by making colorimetrically accurate images which are suitable for the measurement of colour uniformity, size and shape. The uniformity of the light under diffuse and directional illumination was investigated using different targets and soup samples. For accurate colour analysis the images have to be corrected for non-uniform illumination and the colour has to be measured at a fixed location outside the centre of the lighting cabinet. Directional illumination (angled light with additional mirrors) was used to introduce gloss resulting in images matching the actual appearance of soups and vegetable particles very closely. Imaging glossy soups under diffuse illumination resulted in dull images with dark spots. No significant difference was found between the colours of soups analysed under diffuse or directional illumination. Under directional illumination a better repeatability was observed. Additionally, for 36 different soups, the measured results from the DigiEye system were compared to two different colorimeters (0°/45° and diffuse/0° geometry). Linear relations were found between the CIE Lab values measured by the DigiEye system and those measured by two different colorimeters. Best correlations were obtained between DigiEye and 0°/45° colorimeter (r2=0.980-0.996). The short term precision of the DigiEye system is somewhat better than those of the colorimeter.

16:40 **Angular Variations of Color in Turbid Media—The Influence of Bulk Scattering on Goniochromism in Paper,** *Magnus Neuman[1], Per Edström[1], Mattias Andersson[1], Ludovic Coppel[1,2], and Ole Norberg[1]; [1]Mid Sweden University and [2]Inneventia AB (Sweden)* **407**

The angular variations of color of a set of paper samples are experimentally assessed using goniophotometric measurements. The corresponding simulations are done using a radiative transfer based simulation tool, thus considering only the contribution of bulk scattering to the reflectance. It is seen that measurements and simulations agree and display the same characteristics, with the lightness increasing and the chroma decreasing as the observation polar angle increases. The decrease in chroma is larger the more dye the paper contains. Based on previous results about anisotropic reflectance from turbid media these findings are explained. The relative reflectance in large polar angles of wavelengths with strong absorption is higher than that of wavelengths with low absorption. This leads to a loss of chroma and color information in these angles. The increase in lightness is a result of the anisotropy affecting all wavelengths equally, which is the case for transmitting media and obliquely incident illumination. The only



case with no color variations of this kind is when a non-absorbing, non-transmitting medium is illuminated diffusely. The measured and simulated color differences are clearly large, and it is an open issue how angle resolved color should be handled in standard color calculations.

17:00 **A Color Matching Experiment Using Two Displays: Design Considerations and Pilot Test Results,** *Abhijit Sarkar[1,2], Laurent Blondé[1], Patrick Le Callet[2], Florent Autrusseau[2], Patrick Morvan[1], and Jürgen Stauder[1]; [1]Technicolor Research and [2]IRCCyN-IVC (France)* **414**

Various recent studies have shown that observer variability can be a significant issue in modern display colorimetry, since narrow-band primaries are often used to achieve wider color gamuts. As far as industrial applications are concerned, past works on various aspects of observer variability and metamerism have mostly focused on cross-media color matching, an application context that is different from color matching on two displays, both in terms of human visual performance and the application requirements. In this paper, we report a set of three preliminary color matching experiments using a studio Cathode Ray Tube (CRT) display with broadband primaries, and a modern wide-color gamut Liquid Crystal Display (LCD) with narrow-band primaries, with and without surround. Two principal goals of these pilot tests are to validate the experimental protocol, and to obtain a first set of metameric data of display color matches under different viewing conditions. In this paper, various experimental design considerations leading to the current test setup are discussed, and the results from the pilot tests are presented. We confirm the validity of our test setup, and show that the average color matches predicted by the 1964 CIE 10° standard observer, although acceptable as average matches, can often be significantly and unacceptably different from individual observer color matches. The mean, maximum and the 90th percentile values of the standard observer-predicted color difference of individual observer color matches were 1.4, 3.3 and 2.6 ΔE^*_{00} respectively.

17:20 **Evaluation of Performance of Twelve Color-Difference Formulae Using Two NCSU Experimental Datasets,** *Renzo Shamey[1], David Hinks[1], Manuel Melgosa[2], M. Ronnier Luo[3], Guihua Cui[3], Rafael Huertas[2], Lina Cárdenas[1], and Seung Geol Lee[1]; [1]North Carolina State University (USA), [2]University of Granada (Spain), and [3]University of Leeds (UK)* **423**

We previously reported the performance of four color difference equations around the CIE 1978 blue color center (NCSU-B1) using various statistical measures. In this study we employed the standardized residual sum of squares (STRESS) index to test the performance of twelve color-difference formulae using two experimental NCSU datasets. The first dataset (NCSU-B1) included 66 sample pairs around the CIE 1978 blue color center and the second dataset (NCSU- 2) contained 69 sample pairs around 13 color centers. In the first dataset 26 observers made a total of 5148 assessments of sample pairs with small color differences (ΔE^*_{ab}<5) while the second dataset involved 20,700 assessments by 100 observers from four different geographical regions of the world (25 in each region). Each pair in both sets was assessed by each color normal observer in three separate sittings on separate days and the average of assessments was calculated. For the samples in the first dataset a custom AATCC standard gray scale was employed to assess the magnitude of difference between colored samples. A third-degree polynomial equation was used to convert gray scale ratings to visual differences (ΔV). In the second study a novel perceptually linear gray scale was developed and a linear function was used to obtain visual differences. Based on the analysis of STRESS index results the DIN99d equation gave the best results for both datasets, and the CIELAB equation the worst.

19:30 – 22:00
Conference Banquet at Teatteri Ravintola

THURSDAY JUNE 17, 2010

Thursday Keynote

Session Chairs: Theo Gevers, University of Amsterdam, and
Alain Trémeau, Université Jean Monnet
8:30 – 9:30

8:30 **Color by Numbers—Quantifying the Quality of Color Reproduction,**
Jon Y. Hardeberg, Gjøvik University College (Norway) **429**
Quantifying the perceptual difference between original and reproduced (and inevitably modified) color images is currently a key research challenge in the field of color imaging. Such information can be extremely valuable for instance in the development of new equipment and algorithms for color reproduction.

While in many research areas it is common practice to obtain quantitative quality information by the use of perceptual tests, in which the judgments of several human observers are being collected and carefully analyzed statistically, this approach has serious limitations for practical use, in particular because of the time consumption.

Motivated by this, and aided by the ever increasing available knowledge about the mechanisms of the human visual system, the quest for perceptual color image quality metrics that can adequately predict human quality judgments of complex images, has been on for several decades. However, unfortunately, the Holy Grail is yet to be found.

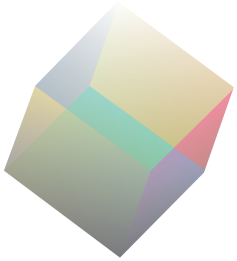
The current paper outlines the state of the art of this field, including benchmarking of existing metrics, presents recent research, and proposes promising areas for further work. Aspects that are covered in particular include new models and metrics for color image quality, and new frameworks for using the metrics to improve color image representation and reproduction algorithms.

Colour Reproduction II

Session Chair: Jon Y. Hardeberg, Gjøvik University College (Norway)
9:30 – 12:20

9:30 **RGBE vs Modified TIFF for Encoding High Dynamic Range,** *Jakkarin Singnoo and Graham D. Finlayson, University of East Anglia (UK)* **431**
High Dynamic Range (HDR) imaging has become more widespread in consumer imaging in the past few years, due to the emergence of methods for the recovering HDR radiance maps from multiple photographs. In the domain of HDR encoding, the RGBE radiance format (.hdr) is one of the most widely used. However, conventional image editing applications do not always support this encoding and those that do take considerable time to read or write HDR images (compared with more conventional formats) and this hinders workflow productivity. In this paper we propose a simple, fast, and practical framework to extend the conventional 12 and 16-bit/channel integer TIFF gamma-encoded image format for storing such a wide dynamic range. We consider the potential of our framework for the tone-mapping application both by measuring the ΔE S-CIELAB color difference between original and encoded image, and by conducting a psychophysical experiment to evaluate the perceptual image quality of the proposed framework and compare it with an RGBE radiance encoding. The preliminary results show that our encoding frameworks work well for all images of a 65 image dataset, and give equivalent results compared to RGBE radiance formats, while both consuming much less computational cost and removing the need for a separate image coding format. The results suggest that our method, used in the normal tone mapping workflow, is a good candidate for HDR encoding and could easily be integrated with the existing TIFF image library.

9:50 **Saliency Models as Gamut-Mapping Artifact Detectors,** *Guanqun Cao[1], Marius Pedersen[1,2], and Zofia Baranczuk[3]; [1]Gjøvik University College (Norway), [2]Óce Print Logic Technologies S.A. (France), and [3]Swiss Federal Laboratory for Materials Testing and Research EMPA (Switzerland)* **437**
When an image is reproduced with a device different artificats can occur. These artifacts, if dectectable by observers, will reduce the quality of the image. If these artifacts occur in salient regions (regions of interest) or or if the artifacts introduce salient regions regions they contribute to reduce the quality of the reproduction. In this paper we



propose a novel method for the detection of artifacts based on saliency models. The method is evaluated against a set of gamut mapped images containing the artifacts, which have have been marked by a group of group experts. The results have shown that the proposed metrics are promising to detect the artifacts through the reproduction.

10:10 – 10:40 Coffee Break

10:40 **Spectral Image Prediction of Color Halftone Prints Based on Neugebauer Modified Spectral Reflection Image Model,** *Masayuki Ukishima[1,2], Yoshinori Suzuki[1], Norimichi Tsumura[1], Toshiya Nakaguchi[1], Martti Mäkinen[2], Shinichi Inoue[3], and Jussi Parkkinen[2]; [1]Chiba University (Japan), [2]University of Eastern Finland (Finland), and [3]Mitsubishi Paper Mills Ltd. (Japan)* **444**
As the spectral prediction model for color halftone prints using the microscopic measurement, the conventional spectral reflection image (SRIM) is extended by introducing the concept of the conventional spectral Neugebaur Model, and a new production model, the Neugebauer modifies spectral reflection image model (NMSRIM), is proposed. Compared to the SRIM, the NMSRIM abstracts the spatio-spectral transmittance distribution of ink layer using the the limited number of base color functions and the spatial position function for each base color in order to efficiently predict the reflectance of color halftone prints from a small number of measurements. The NMSRIM separately analyzes the mechanical dot gain and the optical dot gain. The NSRIM can predict can predict not only the spectral reflectance but also the microscopic spatial distribution of reflectance. The spatial distribution of reflection of reflectance is related to the appearance of halftone prints. The methods to obtain the parameters of NMSRIM are also proposed. Several parameters are obtained by measurements and the others are obtained by computational estimations. To evaluate the validity of the NMSRIM, the spatio-spectral distrbution of reflectance printed with two inks, cyan and magenta (testing data) is predicted from the measurements of the halftones printed with one ink, the unprinted paper, and the solid prints of ink which are the cyan, magenta and blue (training data), where the blue corresponds to the combination of cyan and magenta inks. The spectral prediction accuracy was significant since the average and maximum values ΔE_{94} in all samples were 0.66 and 1.30, respectively. We also obtained the interesting results according to the spatial data.

11:00 **RAW Image Files: The Way to HDR Image From a Single Exposure,** *Massimo Fierro, Tae-Hyoung Lee, and Yeong-Ho Ha, Kyungpook National University (Korea)* **452**
HDR image formation and display has been an argument of extreme interest even when digital cameras were not yet consumer products. While recent research in both fields has seen very interesting works, none is really revolutionary, since what goes on behind the scene has been left basically unchanged. In the image formation field in particular, a lot of energy has been spent so to solve the problems that arise when taking multiple exposures: illumination change, camera shake and in-scene movement. In this paper we approach HDR image formation from a different perspective, which tries to solve in one move all the mentioned problems. More specifically, we propose a method that is able to estimate missing exposures for HDR image formation starting from only one under-exposed shot. Estimation is done through artificial neural networks: the development of a mathematical model is a highly desirable, but time consuming task. The results are are very interesting, although not perfect, and suggest that further research might lead to a suitable solution.

11:20 **Simplified Gamut Boundary Representation Using Mesh Decimation,** *Arne Magnus Bakke and Ivar Farup, Gjøvik University College (Norway)* **459**
Gamut boundary determination is an important step in device characterisation and colour gamut mapping. Many different algorithms for the determination of colour gamuts are proposed in the literature. They vary in accuracy, computational efficiency, and complexity of the resulting triangulated gamut surface. Recently, an algorithm called uniform segment visualization (USV) was developed. The gamut surfaces produced by the USV algorithm is more accurate than the ones produced by the the segment maxima algorithm, while at the same time, they are significantly simpler than the ones produced by the somewhat more accurate modified convex hull. In this paper, we propose a new method. First, an accurate gamut boundary is computed using the modified convex hull. The resulting surface is then simplified using an established mesh decimation technique. This results in surfaces that are significantly more accurate than the ones produced by the USV algorithm at a comparable complexity.

11:40 **Cubical Gamut Mapping Colour Constancy,** *Milan Mosny and Brian Funt, Simon Fraser University (Canada)* **466**
A new color constancy algorithm called Cubical Gamut Mapping (CGM) is introduced. CGM is computationally very simple, yet performs better than many currently known algorithms in terms of median illumination estimation error. Moreover, it can be tuned to minimize the maximum error. Being able to reduce the maximum error, possibly at the expense of increased median error, is an advantage over many published color constancy algorithms, which may perform quite well in terms of median illumination-estimation error, but have very poor worst-case performance. CGM is based on principles similar to existing gamut mapping algorithms; however, it represents the gamut of image chromaticities as a simple cube characterized by the image's maximum and minimum rgb chromaticities rather than their more complicated convex hull. It also uses the maximal RGBs as an additional source of information about the illuminant. The estimate of the scene illuminant is obtained by linearly mapping the chromaticity of the maximum RGB, minimum rgb and maximum rgb values. The algorithm is trained off-line on a set of synthetically generated images. Linear programming techniques for optimizing the mapping both in terms of the sum of errors and in terms of the maximum error are used. CGM uses a very simple image pre-processing stage that does not require image segmentation. For each pixel in the image, the pixels in the N-by-N surrounding block are averaged. The pixels for which at least one of the neighbouring pixels in the N-by-N surrounding block differs from the average by more than a given threshold are removed. This pre-processing not only improves CGM, but also improves the performance of other published algorithms such as max RGB and Grey World.

12:00 **Wide-gamut Image Capture,** *Charles Poynton, Simon Fraser University (Canada)* **471**
Colour gamut refers to the range of colours that can be reproduced by an imaging system. The definition of gamut is quite clear for displays and for hard-copy printing. Colour image science experts disagree, however, on the definition—or even applicability of the concept—of gamut for cameras. I disagree that there is any meaningful concept of "capture gamut." In this note, I review trichromacy and metamerism and discuss various gamuts. I conclude that although metamerism is a phenomenon of what I call "31-space," gamut lives in 3-space. With suitable colour signal processing, a 3-channel camera is capable of acquiring wide gamut images.

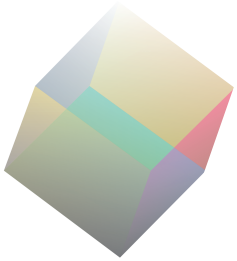
12:20 – 13:40 Lunch in the Carelia or Aura University Cafeteria

Colour Difference Equations

Session Chair: Rafael Huertas, University of Granada (Spain)
13:40 – 15:20

13:40 **Improving Color-Difference Formulas Using Visual Data,** *Ingmar Lissner and Philipp Urban, Technische Universität Darmstadt (Germany* **483**
We propose a method to improve existing color-difference formulas with additional visual data from color discrimination experiments. Color-difference formulas are treated as mean functions of Gaussian processes, and the visual data are considered as observations of these processes. Gaussian process regression is applied to predict unknown color differences. The method was evaluated with a combination of the CIEDE2000 color-difference formula and the RIT-DuPont dataset. The standardized residual sum of squares (STRESS) index between visual and computed color differences was determined for several sets of visual data. The results show a STRESS index of 6.94 (CIEDE2000: 19.47) for the RIT-DuPont dataset. The prediction performance on other visual data (BFD, Leeds, Witt) is not significantly different from CIEDE2000 at a 95% confidence level.

14:00 **Analysis of the Difference of Gaussians Model in Image Difference Metrics,** *Sebastien Akli Ajagamelle[1,3], Marius Pedersen[2,3], and Gabriele Simone[3]; [1]Grenoble Institute of Technology and [2]Océ Print Logic Technologies (France), and [3] Gjøvik University College (Norway)* **489**
The goal of this work is to present and review two new image difference metrics, named S_{DOG} -CIELAB and S_{DOG} -DEE. These metrics are along the same lines as the standard S-CIELAB metric (Zhang and Wandell, 1997), modified to include a pyramidal subsampling, the Difference of Gaussians receptivefield model (DOG) (Tadmor and



Tolhurst, 2000), and the ΔE_E color-difference formula (Oleari et al., 2009). The DOG model and the ΔE_E formula have been shown to improve respectively contrast measures and image quality metrics (Simone et al., 2009). Extensive testing using 29 state-of-the-art metrics and six image databases has been performed. Although this new approach is promising, we only find weak evidence of effectiveness. Analysis of the results indicates that the metrics show fairly good correlations over particular test images, yet they do not outperform the most common objective quality measures.

14:20 **Evaluating Color Difference Formulae by Riemannian Metric,** *Dibakar Raj Pant[1,2] and [1]Ivar Farup; [1]Gjøvik University College (Norway) and [2]University Jean Monnet (France)* **497**

For precision color matching, visual sensitivity to small color difference is an essential factor. Small color differences can be measured by the just noticeable difference (JND) ellipses. The points on the ellipse represent colours that are just noticably different from the colour of the centre point. Mathematically, such an ellipse can be described by a positive definite quadratic differential form, which is also known as the Riemannian metric. In this paper, we propose a method which makes use of the Riemannian metric and Jacobean transformations to transform JND ellipses between different colour spaces. As an example, we compute the JND ellipses of the CIELAB and CIELUV color difference formulae in the xy chromaticity diagram. We also propose a measure for comparing the similarity of a pair of ellipses and use that measure to compare the CIELAB and CIELUV ellipses to two previously established experimental sets of ellipses. The proposed measure takes into account the size, shape and orientation. The technique works by calculating the ratio of the area of the intersection and the area of the union of a pair of ellipses. The method developed can in principle be applied for comparing the performance of any color difference formula and experimentally obtained sets of colour discrimination ellipses.

14:40 **Checking Recent Colour-Difference Formulas with a Dataset of Metallic Samples and Just Noticeable Colour-Difference Assessments,** *Rafael Huertas[1], Alain Tremeau[2], Manuel Melgosa[1], Luis Gomez-Robledo[1], Guihua Cui[3], and M. Ronnier Luo[3]; [1]Universidad de Granada, (Spain),[2]Université Jean Monnet (France), and [3]University of Leeds (UK)* **504**

Several colour-difference formulas have been proposed since the last recommendation of CIEDE2000 by the "Commission Internationale de L'Eclairage" (CIE) in 2001. Some of them have been tested using the same dataset used to fit them. Thus, it is of great interest to check the performance of these formulas with new experimental datasets. On the other hand, some previous studies show that many colour-difference formulas perform quite badly in the very small colour difference range of 0 to 1 CIELAB units. This paper pursues these two goals. The colour-difference formulas DIN99d, OSA-GP, OSA-GP Euclidean (OSA-GPE), CAM02-SCD and CAM02-UCS are tested with a new experimental dataset, which has been carried out in the Laboratoire Hubert Curien of Saint Etienne (France) in two different modes, physical metallic samples and virtual samples displayed in a LCD monitor. This new dataset is composed by 390 colour pairs arranged around 16 colour centres with colour differences in the range 0.14 to 2.14 CIELAB units, with an average value of 0.80. In this work only just noticeable differences have been considered from this dataset. The results show a bad performance of all studied colour-difference formulas for just noticeable colour differences, in agreement with previous studies. Further research must be conducted to fit colour-difference formulae to this important range of colour differences.

15:00 **Comparison of Colour Difference Methods for Natural Images,** *Henri Kivinen, Mikko Nuutinen, and Pirkko Oittinen, Aalto University School of Science and Technology (Finland)* **510**

Perceptual colour difference in simple colour patches has been extensively studied in the history of colour science. However, these methods are not assumed to be applicable for predicting the perceived colour difference in complex colour patches such as digital images of complex scene. In this work existing metrics that predict the perceived colour difference in digital images of complex scene are studied and compared. Performance evaluation was based on the correlations between values of the metrics and results of subjective tests that were done as a pair comparison, in which fifteen test participants evaluated the subjective colour differences in digital images.

The test image set consisted of eight images each having four versions of distortion generated by applying different ICC profiles. According to results, none of the

metrics were able to predict the perceived colour difference in every test image. The results of iCAM metric had the highest average correlation for all images. However, the scatter of the judgements was very high for two of the images, and if these were excluded from the comparison the Hue-angle was the best performing metric. It was also noteworthy that the performance of the CIELAB colour difference metric was relatively high.

15:20 – 15:50 Coffee Break

Multispectral Colour Science MCS'10

Session Chair: Juan Luis Nieves, University of Granada (Spain)

15:50 – 18:30

15:50 **Spatial and Spectral Analysis and Modeling of Transversal Chromatic Aberrations and Their Compensation,** *Julie Klein, Johannes Brauers, and Til Aach, RWTH Aachen University (Germany)* **516**

The wavelength-dependency of the refraction indices in optical systems involves chromatic aberrations: one object point is not projected on exactly one image point on the sensor plane, but dispersed depending on its wavelengths in a rainbow-like manner due to the wavelength-dependency. These distortions have already been analyzed for the three broadband color planes red, green and blue of an RGB camera for example. As far as the authors know, no analysis was performed yet for more than three narrow wavelength bands and each color plane was considered separately so far.

In this paper, we describe the measurement of chromatic aberrations for multiple narrowband color channels and extend the models from the literature to characterize these distortions. We then link the parameters obtained for all color channels in order to include the wavelength-dependency into the models of the distortions. This leads to a more general model for the chromatic aberrations, calculating the distortions as a function of the wavelength and the image position. We then compensate the chromatic aberrations using these models and finally estimate their accuracy.

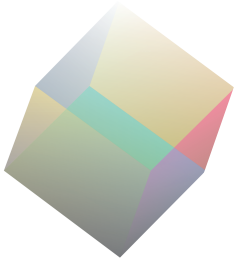
16:10 **Noise Analysis of a Multispectral Image Acquisition System,** *Noriyuki Shimano, Kinki University (Japan)* **523**

Prior knowledge of the noise present in a color acquisition device is very important for the recovery of spectral reflectance of an object being imaged, since recovery performance is greatly influenced by the noise.

In the previous paper (IEEE Trans. Image Process. 1848 (2006), the author proposed a new model to estimate noise variance of an image acquisition system by assuming the noise variance in each channel is equal and showed this model is very useful to accurately recover a reflectance of an imaged object. This paper describes extended model for the estimation of the covariance matrix the noise present in an image acquisition system without assumption. It is demonstrated that the proposal overfits noise covariance matrix to learning samples and that recovery performance for the test samples is poor with the previous model. However this overfitting means the estimates are correctly performed using the model. The new model is effective in analyzing the present in an image acquisition system.

16:30 **Effective Illumination Control for an Active Spectral Imaging System,** *Takahiko Horiuchi, Hirokazu Kakinuma, and Shoji Tominaga, Chiba University (Japan).* **529**

A high-speed spectral imaging system using an active spectral illumination has a big potential in the spectral color imaging field. However, it has been difficult to produce an accurate target illuminant because the basis illuminants are not ideal narrow-band spectra. Therefore, we need a mechanism of appropriate adjustments for emitting the desired illuminants from the light source. This paper proposes a control method for producing an arbitrary target illuminant precisely from the active spectral light source by combining the light source with a measurement device. We construct two types of illuminant control systems. The first system uses a high-speed monochrome camera as the measurement device. In this system, we determine the desired sequence of the camera outputs in advance. Then we adjust the light source system for generating the target camera outputs by a feedback control. The second system uses a spectroradiometer as the measurement device. In this system, the target is the spectral-power distribution determined by multiplying the surface-spectral reflectance to the illuminant. The system



adjusts the light source for producing the optimum illuminant with the target spectrum by the feedback control. We consider two applications of the illuminant control system to (1) accurate generation of a target illuminant and (2) estimation of surface-spectral reflectances without knowing the camera spectral sensitivity function.

16:50 **Multiresolution-Based Pansharpening in Spectral Color Images,**
Oili Kohonen, University of Eastern Finland (Finland) **535**
This work examines the spectrum preserving properties of a multi-resolution analysis-based intensity modulation (MRAIM) when used for increasing the spatial resolution of spectral color images. The MRAIM algorithm is originally designed to fuse high-resolution panchromatic images with low-resolution spectral images in order to get high-resolution spectral images for remote sensing applications. Instead of panchromatic images, for which the MRAIM algorithm has originally been designed for, the MRAIM algorithm is implemented to use information from both grayscale and RGB color images. In order to utilize the information of the three channels included in RGB images, two different models are derived and examined. In addition, two kind of scaling factors are used for compensating possible differences between the images acquired at different resolution levels. The resulting high resolution spectral images are compared to the real acquired high resolution spectral images with respect to both maximum and average RMS errors and ΔE^*_{ab} color differences under CIE illuminants D_{65}, A, F8 and F11. The used images are acquired by NuanceFX spectral imaging system, which allows the measuring of both spectral and RGB images at different resolution levels at identical geometry.

17:10 **Enhancing Spectral Color Images by RGB-Based Sharpening,**
Oili Kohonen, University of Eastern Finland (Finland) **541**
This work examines a possibility to enhance the spatial resolution of spectral color images by using RGB color images. NuanceFX spectral imaging system, which allows the measuring of both spectral and RGB color images at different resolution levels using the identical geometry, is used for acquiring the images needed. The used enhancing process is based on the correspondence between spectra of a low spatial resolution spectral image, LR_{SPE}, and RGB-triplets of a high spatial resolution RGB image, HR_{RGB}, both globally and locally. In a global approach, an estimated spectrum corresponding to index number i is defined as the average of all the spectra mapping into that index number, whereas in a local approach an estimated spectrum is defined as a spectrum of the closest mother pixel with the same index number. In the cases where the index number of pixel to be estimated equals to zero, the missing spectrum is estimated based on its neighborhood. The estimated high resolution spectral images, EHR_{SPE}, are evaluated by comparing them to the real, measured high resolution spectral images, HR_{SPE}, with respect to RMS erors and ΔE^*_{ab} color differences under four different CIE illuminants, D_{65}, A, F8 and F11.

17:30 **Spectral Variability of Light-Emitting Diodes with Angle,** *Óscar Martínez, Hewlett-Packard España; and Meritxell Vilaseca, Carles Pizarro, Èdgar Ferrer, Monserrat Arjona, and Jaume Pujol, Technical University of Catalonia (Spain)* . . . **547**
Multispectral systems allow the spectral characterization of the scene through several acquisition channels with different spectral features. The spectral sampling can be done by using transmittance filters and a white light source or illuminating the scene using light sources with different spectral emission characteristics. Light-emitting diodes based light sources have started to be used in multispectral systems, mainly to develop low-cost devices for the industry. In this study we analyze the spectral power distribution and color variability of white and single color light-emitting diodes relative to the viewing angle, and highlight some aspects that must be taken into account if these light sources want to be used in a multispectral system.

17:50 **Fast Non-Iterative PCA Computation for Spectral Image Analysis Using GPU,**
Jukka Antikainen, Markku Hauta-Kasari, Timo Jääskeläinen, and Jussi Parkkinen, University of Eastern Finland (Finland) **554**
In this study, we implement a fast non-iterative Principal Component Analysis computation for spectral image analysis by utilizing Graphical Processing Unit GPU. PCA inner product computation efficiency between Central Processing Unit CPU and GPU was examined. Performance was tested by using spectral images with different dimensions and different PCA inner product image counts. It will be shown that the GPU implementation provides about seven times faster PCA computation than the optimized CPU

version. Difference to the commonly used scientific analysis software Matlab is even higher. When spectral image analysis is needed to make in real-time, CPU does not offer the necessary performance for larger spectral images. Therefore, powerful GPU implementation is needed.

18:10 **Surface Reflectance Models Based on Characteristic Functions,**
Oh-Seol Kwon, Holly E. Gerhard, and Laurence T. Maloney, New York University (USA) **560**
Surface reflectance functions (SRFs) and spectral power distributions (SPDs) of illuminants are typically modeled as elements in an N-dimensional linear function subspaces. Each SRF and SPD is represented by an N-vector and the mapping between SRF and SPD functions and an N-dimensional vector assigns N-dimensional "color" codes representing surface and light information. The N basis functions are chosen so that SRFs and SPDs can be accurately reconstructed from their N-dimensional vector codes. Typical rendering applications assume that the resulting mapping is an isomorphism where vector operations of addition, scalar multiplication and component-wise multiplication on the N-vectors can be used to model physical operations such as superposition of lights, light-surface interactions and inter-reflection. When N is small, this implicit isomorphism can fail even though individual SPDs and SRFs can still be accurately reconstructed by the codes. The vector operations do not mirror the physical. However, if the choice of basis functions is restricted to characteristic functions (that take on only the values 0 and 1) then the resulting map between SPDs/SRFs and N-vectors is an isomorphism that preserves the physical operations needed in rendering. The restriction to bases composed of characteristic functions can only reduce the goodness of fit of the linear function subspace to actual surfaces and lights. We will investigate how to select characteristic function bases of any dimension N (number of basis functions) and evaluate how accurately a large set of Munsell color chips can approximated as a function of dimension.