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Proceedings from Gjøvik Color Imaging Symposium 2003

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Contents

Introduction

Gjøvik Color Imaging Symposium was held at Gjøvik University College November 24–25 2003. The first day was devoted to color and quality in digital film and video. Lillehammer University College and Gjøvik University College has been running a joint two year project related to this topic. The project has been funded by Morgenlandet AS over the PROKOM programme. The main idea of the symposium's first day was to bring this project to an end, and to discuss the results of this and related projects.

The second day of the symposium was devoted to multispectral color imaging. Recently, Gjøvik University College received funding from the Norwegian Research Council for a major project in this field. The symposium was planned to serve as a kickoff for that project. The symposium was funded over the two mentioned projects.

Researchers from different locations in Europe contributed to the symposium. All of the presentations were invited, and the authors were encouraged, but not obliged, to contribute with an abstract and the foils used for the presentation for inclusion in these proceedings.

Program

Day 1 (24.11): Color and Quality in Digital Film and Video

Room K102 – A Building

1000–1030: **Managing colors in the production and presentation of digtal video**, Gudmund Stjernvang, Lecturer, Lillehammer University College

1030–1100: **Film scanning and color adjustment: A colorist's perspective**, Egil Ljøstad, Colorist, Norwegian Broadcasting Corporation

1100–1130: **Color adjustment by color space warping**, Jon Y. Hardeberg, Associate Professor, Gjøvik University College

1130–1230: Lunch on your own

Room Eureka 1/3 – E Building

1230–1300: **Practical consequences of the Digital Intermediate (DI) process in feature film and restoration**, John Chr. Rosenlund, Director of Photography, Norway

1300–1320: **Digital cinema commercials – is the quality good enough?** Ivar Farup, Associate Professor, Gjøvik University College

1320–1340: Coffee break

1340–1410: **Monitor calibration and viewing conditions**, Kjell Kolstad, Senior Engineer, Norwegian Broadcasting Corporation/European Broadcasting Union

1410–1450: **ICC color management in the motion picture industry**, Andreas Kraushaar, Researcher, Fogra, Germany

1450–1500: Break

1500–1530: **Media technology education and industry: convergence or divergence?** Jens-Uwe Korten, Dean, Lillehammer University College, and Rune Hjelsvold, Professor, Department head, Gjøvik University College

Day 2 (25.11): Multispectral Color Imaging

Room K105 – A Building

0830–0845: **The Department of Computer Science and Media Technology at Gjøvik University College**, Rune Hjelsvold, Professor, Department Head, Gjøvik University College

0845–0915: **The Norwegian Color Research Laboratory**, Jon Y. Hardeberg, Associate Professor, Gjøvik University College

0915–1015: **Introduction to multispectral color imaging: motivation, spectral dimensionality, and existing systems**, Jon Y. Hardeberg, Associate Professor, Gjøvik University College

1015–1045: Coffee break

1045–1130: **Spectral camera calibration**, Ali Alsam, PhD, University of East Anglia, England

1130–1230: Lunch on your own

1230–1250: **Creating light with arbitrary spectral power distribution**, Ivar Farup, Associate Professor, Gjøvik University College

1250–1330: **Multispectral imaging: acquisition and processing**, Pierre Gouton, Professor, University of Burgundy, France

1330–1350: Coffee break

1350–1430: **Spectral image reproduction using print technology**, Andreas Kraushaar, Researcher, FOGRA, Germany

Managing Colors in the Production and Presentation of Digital Video

Gudmund Stjernvang

Ever since the beginning of the color film era, color adjustment has been a permanent area of difficulties in the production of moving pictures. When the captured shots are edited together, the colors must be harmonized, and this color corrections was done by use of color filters and laboratory chemicals.

The introduction of video technologies changed the methods of work, but color corrections remained a tedious process, requiring expensive equipment for use in profesional environments. The transition from analog to digital video now opens the possibilities for developing methods of video color management, by applying principles similar to those already in use for digital image reproduction on various media. Digital video color management can potentially be implemented using common computer platforms, and equipment which cost a fraction of todays dedicated video editing and color correction equipment. At the same time, the processes can be simplified and made less time-consuming.

In a collaborative research project involving researchers from the neighboring institutions Gjøvik University College(GUC) and Lillehammer University College (LUC), it was decided to investigate further into this interdisciplinary area of research and development. The research project was funded by Morgenlandet AS, a regionally based company which aims for restructuring and innovation, and has a duration of two years (2002-2003). It brings together two scientific communities color science and color management mainly for graphic arts applications at GUC, and video, television, and film production at LUC.

We have identified four different research topics of particular interest

1. Color management in the acquisition of digital video.
2. Color control for editing of digital video.
3. Color characterization of monitors used in the production.
4. Color quality of projective displays used for presentation of digital video.

Film Scanning and Color Adjustment: A Colorist's Perspective

Egil Ljøstad

I think my presentation is done best visually and therefore I will show examples on typical colour correcting work and explain how my approach to get the final result is done.

Colour-correcting experiences from different tape-formats with creative work and rescue operations.

Ways of working in telecine productions. Maybe talk a little about video-to-film productions I have been working on and what to consider for that kind of productions.

Talk about experiences with transfer of archive film-material.

Show examples of ways of making video look like film.

Color Adjustment by Color Space Warping

Jon Y. Hardeberg

Matching the colors of digital pictures that are to be used together is an important problem for many applications, such as image stitching, comparative image analysis, and editing of digital film and video. In particular, for the production of moving pictures, the use of several cameras simultaneously or at different times and under varying lighting conditions results in varying color rendering in the different captured shots. When these shots are edited together, the colors must be harmonized, and this currently requires substantial manual adjustments by skilled professionals.

This paper presents an innovative method for color correction using a technique we call color space warping. The problem definition originated from considering the tasks typically performed by a colorist adjusting colors of video sequences in order to obtain certain effects/moods, and also to match the colors of other sequences. The proposed method could also be applied to other applications such as image stitching and color correction and cast removal of digital still photographs.

While the more commonly known image warping algorithm is based on a set of source/destination pixel locations in the image plane, our color warping algorithm is based on a set of source/destination points in a given color space. This set of color pairs define the warping of the color space, according to the following properties:

- The source color is directly mapped to the destination color.
- Colors close to a given source color end up close to the corresponding destination color.
- Colors that have the same distance to two source colors are influenced equally by the two source/destination pairs.
- Colors are influenced more by closer source colors than by more distant ones.

Promising results have been obtained by a method in which corresponding colors are selected from the two shots to be harmonized. This is done using a color picker tool, either interactively directly in the captured scene, or using a color test target, which have been introduced in the (physical) scene.

Practical Consequences of the Digital Intermediate (DI) Process in Feature Film and Restoration

John Chr. Rosenlund

Digital post-production in feature film represent a paradigm shift from the over 100-year-old analogue lab process to digital colour correction of the film on a computer. In 2001 3 films went through this process, in 2003 the number increased to 60, and in 2007 I expect this number to be 2000 films.

The first film scanner meeting the demand in terms of speed and quality is available at a competitive price 2003/04. This is a turning point for the market enabling economical digital processing of feature films. At IBC 2003 strong signals leads towards a total change in the market of postproduction in feature films from analogue to digital.

The film-production is today where the typewriter was in the late 70´s. when the computer became personal and available for everybody.

The DI process confronts some importance questions regarding technical and artistically quality.

Image and color fidelity

In the computer it is a question of pixels and BIT. To be able to work in the computer with the colour-space and resolution with in the original medium we need to define colour and pixels for the DI process.

Film is analogue and has an enormous amount of information. A healthy exposed negative is close to 6K in pixel resolution and 16Bit colour dept.

The problem is to maintain the image and color fidelity from acquisition to final screening.

We need to calibrate the digital process to the analogue to be able to "WYSIWYG" (What you see is what you get).

Who do we define the "accepted technical image parameters" to be able to say film=film in a Di process.

Digital capture has been part of the world of television and video for more than a decade. The lower spatial, temporal and color resolution of analog video equipment paved the road for a much earlier and easier digital transition. The same has not proved to be the case for film, which is capable of capturing far more detail than current digital camera technologies. Today film can resolve far more detail in terms of spatial resolution, light intensity and temporal changes (high speed photography). Digital video formats such as Digital Betacam, D2, D3, HDCAM and D5, while adequate for TV image reproduction, have too limited a dynamic range or are too reliant on compression to be effective as a high-end replacement for film. They cannot capture image information at high resolution without aggressively compressing the data, which limits their suitability as a high quality digital film master.

Digital Cinema Commercials – is the quality good enough?

Ivar Farup

We describe the partial results of a collaborative research project conducted by researchers at Gjøvik University College and Lillehammer University College. The goal of the project is to develop methods and tools to improve the control of color information in the production and presentation of digital video. The project represents a unique attempt to bring together two scientific communities graphic arts and television/video production on a theme of common interest, namely color. We have investigated the color quality achieved by a system for digital distribution and presentation of cinema commercials. Our results show that the quality bottleneck is the digital projector. Especially in large theaters, the business-type projector does not yield sufficient image quality.

Monitor Calibration and Vieweing Conditions

Kjell Kolstad

The human vision has certain properties when perceiving images. Images are received from real life situations or as reproduced images or a combination of both. There are facts to be understood in how we perceive images and mechanisms to be aware of when the human vision is subjectively used for producing images.

Image control requires knowledge on the reproduction technique in question and the understanding of human image perception. There are several issues to be discussed in watching images on a screen. Issues that effect the image variables and the appearance of a scene, a sequence of scenes or a sequence of programs.

ICC Color Management in the Motion Picture Industry

Andreas Kraushaar

Abstract

This paper discusses the implementation of a Colour Management workflow within the post production scenario in the motion picture industry. Beside other image quality aspects like contrast ratio and sharpness the colour reproduction plays a very important role. The main aim is to improve the predictability (reproduceability) and to softproof the cinema screen on class 1 HDTV studio monitors or appropriate projectors. For this purpose, the ICC Colour Management has been implemented in the motion picture environment. Within a labarotory setup display (HDTV and projector) and printer profiles were created. The main purpose is a absolute colorimetrical match between a HDTV-monitor and a projected silde located side by side. While the average delta Es were decreased significantly by the ICC colour management, improvements are still required for dark and yellow colour regions.

Introduction

This paper discusses the implementation of a ICC colour Management workflow within a special part of the post production scenario in the motion picture industry. This industry is driven primarily by high picture quality. Beside other image quality aspects like contrast ratio and sharpness, all kinds of colour decisions are an extremely important component of the post production workflow shown in figure 1.

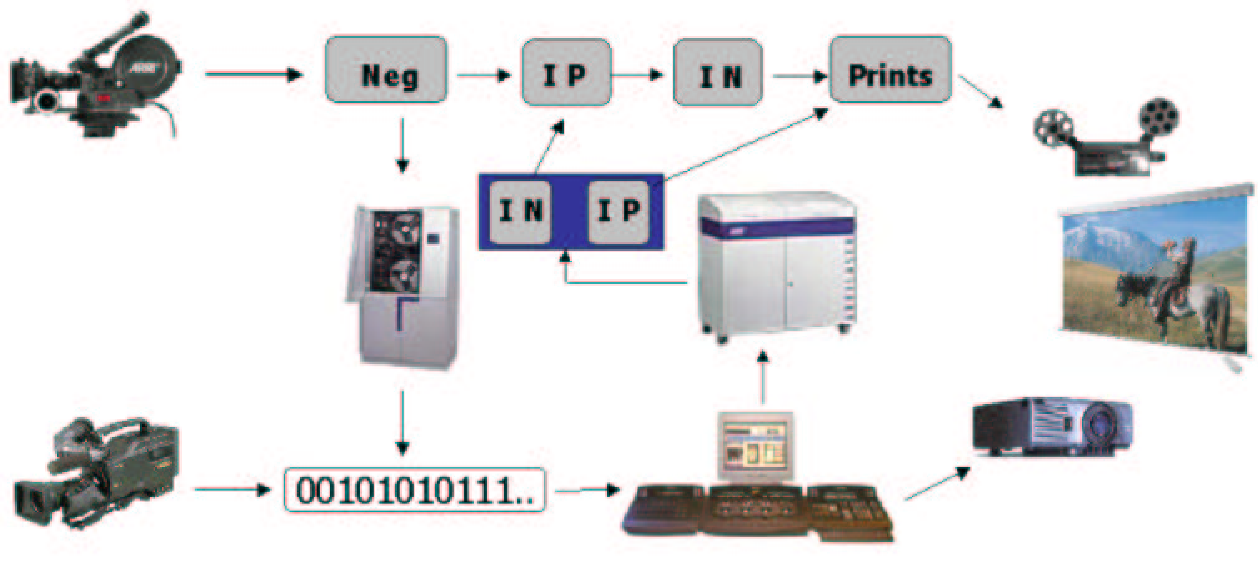

Figure 1: Digital film production workflow.

The field of digital colour reproduction is a playground of several much older industries coming together. Each of these industries has their individual aspects of colour reproduction that have been evolved within the constraints of their particular production workflows. The motion picture industry includes generally the high definition broadcast television, motion pictures as well as computer graphics. There is a great need for appropriate methods of representing, controlling and communicating colour. This paper illustrates how the colour management system was implemented to make the monitor in the post-production simulate the print film projected in the theatre. Fur this purpose the ICC (International Colour Consortium) framework within the latest specification was evaluated. In the past and present a variety of processes were necessary in order to obtain an acceptable colour

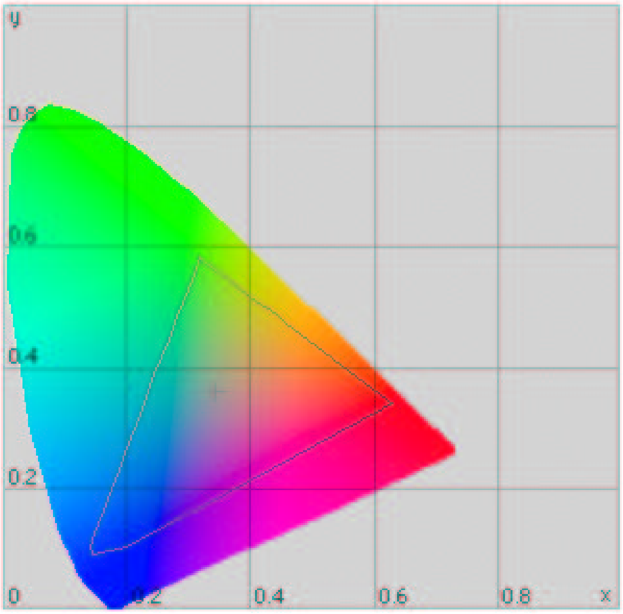

Figure 2: Typical colour chromaticity diagram of a CRT.

match between monitor and film. In everyday work it is very common to apply one dimensional LUT (Look Up Table) iteratively until it looks right. It is very time consuming and costly to output all the images handled and viewed in post production, in order to know what will happen at the end of the chain. The main aim here is to improve the predictability (reproducibility) and to softproof the conventional cinema screen on class one HDTV video studio monitors. In addition, new projectors (DLP) do have a similar imaging performance with respect to colour gamut and contrast ratio. The artist, the producer, as well as the director have to rely on the images displayed on the monitor. They demand a side by side preview nevertheless the later images in the theatre are shown later on.

Theoretically, the colour reproduction system of CRT monitors is a 3-primary (RGB) additive system. Within the assumption of a linear channel behavior and no cross talk, there are several mathematical models (Bodrogi, 2000). These models describe the relationship between the digital frame buffer values driving the colour channel and the phosphor emission of that channel, often in a colorimetrically manner. Due to the specified primaries, e.g. in SMPTE 295, a typical colour chromaticity for CRT displays is easy obtainable and shown in figure 2.

On the other hand, the colour reproduction system of film is a subtractive method with Cyan, Magenta and Yellow dyes. Practically the colour reproduction of the film is more complex because of the non-additive relationship and several other aspects that would exceed the scope of this paper. Hence the computation of a typical print film gamut is more complicated.

Methods

In this work the widely used intermediate stock (Eastman Kodak 5242) and the print stock (Eastman Kodak 2383, Daily Vision film stock) were used. The ARRI Laser film recorder is set up with the system LUT that is designed using the relationship between the 10 Bit code values and status M densities given by the manufacturer. Here several grey patches with neutral 10 Bit code values of R=G=B is interpreted as the status M density provided by Kodak for this material. The reproducibility of the print film is maintained by reaching the appropriate status A densities for the vision film stock. Before illustrating the gamut of the used print film the measurement conditions have to be explained. In contrast to the general measurements in the graphical industry (45/0 or 0/45 for

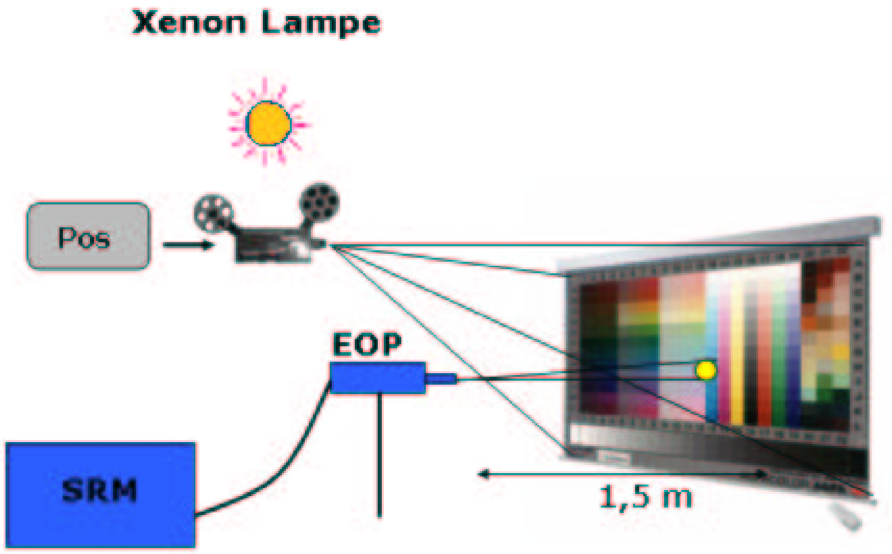

Figure 3: Measurement conditions for cinema colorimetry.

reflective media) here the spectral data was obtained by direct measurement of the stimulus reaching the observer. This is similar with the colorimetric characterization of a CRT monitor with a telespectrometer (PhotoResearch). In this work the projected scene was assumed to be a self-luminating display, a totally new (original) scene.

For laboratory work a mobile film projector (ARRI LocPro) was colorimetrically characterized. This had the advantage of a film transport frame by frame without destroying the film base as well as using a common Xenon lamp . Peak luminance of the film has to be gathered from the digital code value of R=G=B=1024. Note that this code value is about 800 after applying the recorder LUT. Figure 4 illustrates the resulting colour gamut and figure 5 shows both gamuts simultaneously.

These two different kinds of display have 3 dimensional gamuts which exceed film in some areas and fail to match it in others.

In principle, the XYZ tristimulus space should be able to represent any colour stimulus presented on a theatrical projection screen unambiguously (Giorgianni, 1998). CIELAB was designed furthermore as a uniform colour space for average-surround reflection colorimetry at a stable adaptation condition. Unsurprisingly, it does not model human visual performance well in dark-surround theatre conditions. The absence of a white reference in natural scenes greatly complicates the application of colour science to the production of motion pictures. It is necessary to devise a method for determining an adopted white luminance and chromaticity. Some authors obtain the white point by taking the brightest colour (Yaguschi, 1984). However most cinematic presentations occur at an average luminous scene level between 5 and 15 cd/m^2. During the viewing process the luminous discrepancy depends on the viewing angle on the retina and the time history of the darkest and brightest colours presented on the screen. In post production, the colour shift shown in figure 4 has been known as a nature of film recording. Thus, in colour matching process of CRT to film the following factors become more important than anything else: Handle gamut mapping (white point drift), Minimal change to the workflow, No introduction of artifacts trough computation Introduction of a quality control system.

As Bartleson says: The object of a colour television cannot be simply to reproduce the colorimetric values of objects (Bartleson, 1968). The main aspect in this work is to match the appearance between the monitor and the theatre!

As a first step, display profiles were built and tested out by the use of the above mentioned

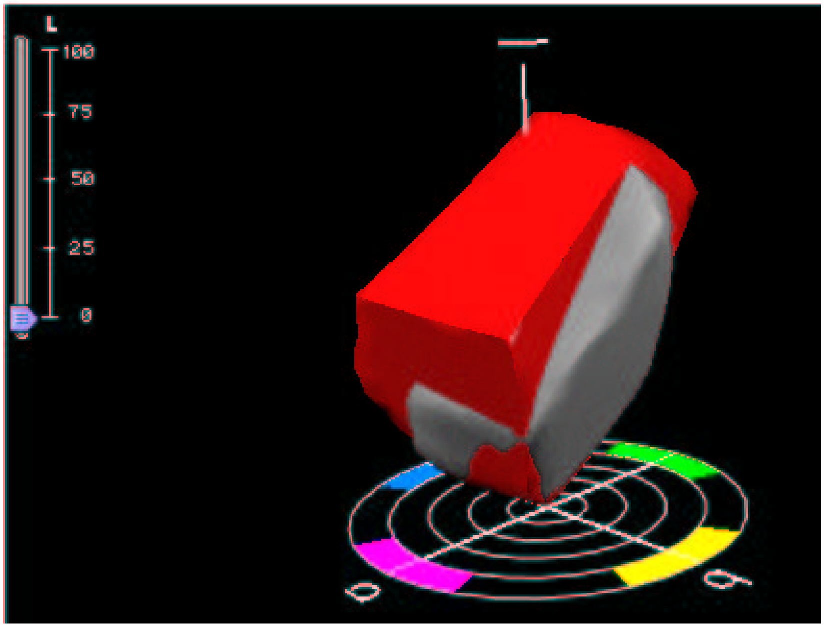

Figure 4: Both, LocPro and monitor colour gamut.

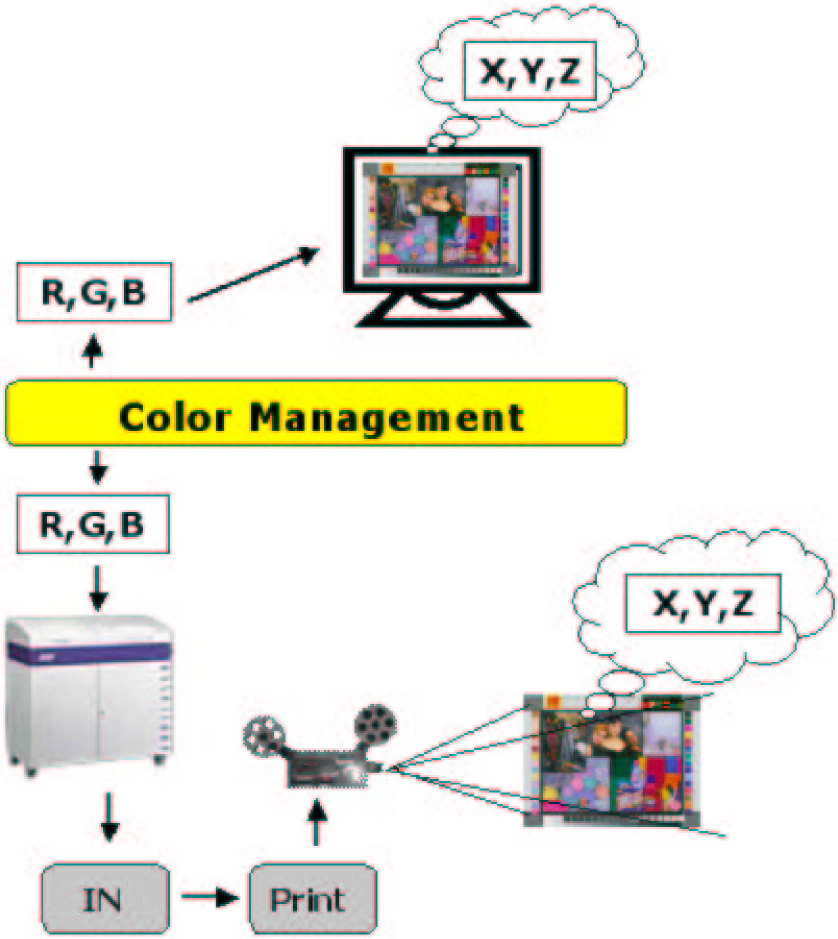

Figure 5: Colour management scenario.

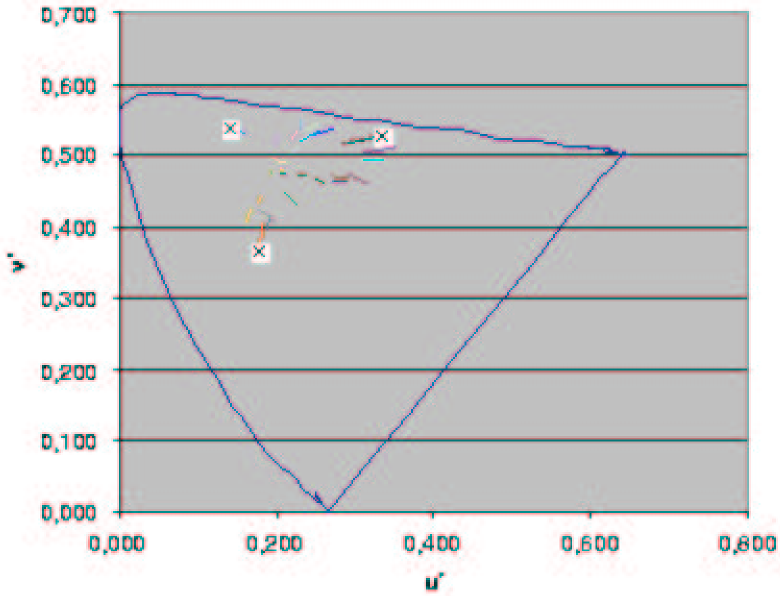

Figure 6: Differences between the monitor and the projection.

telespectrometer. Beyond this, cinema profiles were established by the means of RGB printer profiles. Here the basICColour tools (print3c) have to be tested. In this evaluation step the ARRI LocPro was used to emulate the cinema screen. This mobile film projector is very popular for the purpose of fast observing film material. With this setup, theatre screen and monitor were arranged in the following manner: The monitor was placed one meter beside the cinema screen in a darkened room. For a first (absolute colorimtric) comparison the aspect ratio and the absolute luminance (about 80 cd/m^2) were quite similar. Now a surround light was placed behind this construction because several years of usage has led to a universal acceptance by production and technical personnel. It serves as a helping point for adapting colour temperature. The luminance level of the neutral surround at about 2 cd/m^2 is similar to practical situations. In contrast, monitor is set up with a colour temperature of 6500 K regarding the SMPTE specification and LocPro projection was set up with a colour temperature of about 5300K. This laboratory scenario hardly attains comparable viewing conditions but lets the artist valuate the image picture by picture or scene by scene. Afterwards profile modification were done by means of changing the gradation, the white scaling and the gamut mapping strategies were tested. During this trial and error process subjective judgments were conducted to compare both images. Results This environment suitably ensures that important colour appearance effects (Abney effect, Bezold-Brueke shift, Hunt effect, Bartleson-Brenamann effect, rod intrusion) have mainly to be neglected. Cinema projection (35mm release prints) readily span a whiteto-black ratio of 1900:1 (at ARRI cinema Munich, 1999). In contrast, ARRI LocPro involves a whiteto-black ratio of 500:1 and the SONY HDTV monitor of about 250:1 (ANSI), respectively. So, there were only a few discrepancies for the laboratory construction. The colour management tools for cinema projection must encompass an accurate and controllable work over the entire tone scale, including the deep shadows and some yellow regions. Thereupon subjective judgments were carried out in a non-professional way so only colorimetric values are available. Figure 6 shows the differences between the monitor and the projection in the u,v diagram, while table 1 illustrates several results of some colour difference formulas.

Conclusion

In conclusion, it has been shown that the average delta Es were decreased significantly by the ICC colour management, improvements are still required for images containing gradients in the higlight region. Beyond this, it was recognized that colour management for cinema hardly assures a absolute colorimetrical match because of differences in the pertinent color gamuts and different gamut mapping strategies. Furthermore, a method was established to judge a monitor display and the cinema projection side by side. An important issue is the time between colour timing the scenes in front of the monitor and the viewing (later) in the theatre. It is well known that human vision is very restricted when matching two colours successively. For this purpose a relative colorimetrical transformation has to be prefered but the artist, the producer, as well as the director want a simultaneously demonstration, where an absolute colorimetric transformation is necessary. In spite of all the quantitative data presented on the quality of the profiles and transformations, it is mandatory that the colour match, or lack thereof, is verified visually. Unfortunately, the results from this test cannot be quantified, but it is suffice to say that the colour timers were suitably impressed. Additional work has to be done in future in the field of gamut mapping from the monitor gamut (D65) to the film gamut (5300 K) as well as the adopting for new electronic cinema display devices.

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Introduction to Multispectral Color Imaging: Motivation, Spectral Dimensionality, and Existing Systems

Jon Y. Hardeberg

Conventional color imaging science and technology is based on the paradigm that three variables are sufficient to characterize a color. However, in particular, due to the effect of metamerism, three color channels are often insufficient for high quality imaging e.g., for museums and digital archives. In this course the general requirements for digital image capture and reproduction are addressed. We start with an introduction to 3-color imaging and limitations to the current systems. Metamerism in image capture and reproduction systems are explained. Current digital color image capture systems are then described in terms of the achievable tolerances of several important system characteristics. Several practical systems for multispectral image capture and delivery will then be described, along with their strengths and weaknesses.

Attendees of the tutorial will be able to:

- Understand the basics of color science.
- Realize the limitations of conventional color imaging, and how increasing the number of color channels to more than three can resolve these limitations.
- Decide between 3-color and multispectral approaches.
- Understand the issues and tradeoffs involved in the design and practical realization of a color image acquisition system.
- Learn methods to evaluate the performance of multispectral acquisition systems.
- Know where to find more information about this subject, equipment, and tools.

Creating Light with Arbitrary Spectral Power Distribution

Ivar Farup

The spectral integrator at the University of Oslo consists of a lamp whose light is dispersed into a spectrum by means of a prism. Using a transmissive LCD display controlled by a computer, certain fractions of the light in different parts of the spectrum is masked out. The remaining spectrum is integrated and the resulting colored light projected onto a dispersing plate. Attached to the computer is also a spectroradiometer measuring the projected light, thereby making the spectral integrator a closed-loop system. One main challenge is the generation of stimuli of arbitrary given spectral power distributions. We have solved this by means of a computational calibration routine: Vertical lines of pixels within the spectral window of the LCD display are opened successively and the resulting spectral power distribution on the dispersing plate measured. A similar procedure for the horizontal lines gives, under certain assumptions, the contribution from each opened pixel. Hereby, light of any spectral power distribution can be generated by means of a fast iterative heuristic search algorithm. The apparatus is convenient for research within the fields of color vision, color appearance modeling, multispectral color imaging, and spectral characterization of devices ranging from digital cameras to solar cell panels.

Multispectral Imaging: Acquisition and Processing

Pierre Gouton

A Multispectral imaging system acquires images of the same scene simultaneously in many contiguous spectral bands over a given spectral range. By adding wavelength to the image as a third dimension, the spectrum of any pixel in the scene can be calculated [1].

I – Multispectral system with Rotating wheel fitted with optical filters

The first multispectral camera system we use is a low cost device. It is designed to be flexible and portable (figure 7). It is composed of a single monochrome IR CCD camera: Jai CVM50 IR, a standard photographic lens, a set of nine interference filters and a personal computer. The filters wavelength varies from 400 to 1100 nm to cover all the range of the camera sensor. The average Full-Width-at-Half-Maximum (FWHM) bandwidth is approximately 65 nm, each one overlapping the immediate neighbors. A wheel fitted with nine holes houses the nine filters (numbered 1 to 9). The wheel is located in front of the camera/lens system. It is motorized to rotate and all is piloted by software. Multispectral images are captured during each revolution and transferred to the computer. The image acquisition in this system is completely computer controlled. We can choose the number of spectral bands (1-9), the number of multispectral data sets to acquire, the time between each dataset and for extending the dynamic range of the camera, we also control the exposure time for each spectral band according to each filter transmittance under a fixed gain and aperture. A multi-spectral image is thus acquired by positioning successively each of the nine filters in front of the camera; this image is composed of nine shots. Each of them can be considered as a narrow-band image having a wavelength band equal to that one of the filter. Our optical system is composed of a standard lens and a set of nine interference filters, all with the same thickness. Interference filters combine many thin-film layers of dielectric materials having different refractive indices to produce constructive and destructive interference in the transmitted light. In this way, filters are designed to transmit only in a specific waveband, function of the filter bandpass. This system is working [2], and we test it actually for different spectral reflectance reconstruction methods. Also we test it for agriculture of precision in separating onions from weeds.

II – Multispectral system with Liquid Crystal Tunable Filter

A second Multispectral imaging system is actually under developing (figure 8). It is based on The VariSpec liquid crystal tunable filter. The VariSpec LCTF uses electronically-controlled liquid crystal elements to select a transmitted wavelength range, while blocking all others. the colour of the light it transmits is electronically-controllable through an RS-232 interface enabling the filter to respond to signals and synchronization pulses generated by computers. This filter is combined with a large band camera: Jai CV-M2. which is a digital monochrome camera using 1600x1200 CCD. It features frame delay readout and single or dual video output of either 10 bit and the wavelength range of the CCD is from 300nm to 900nm. All functions of this camera are also controlled via RS232C. In simple terms, an LCTF is something like a filter wheel. But being electronic; therefore, it is ideal for automation and acquisition requiring fastness. Being continuously tunable, a wider range of colours is tus available.

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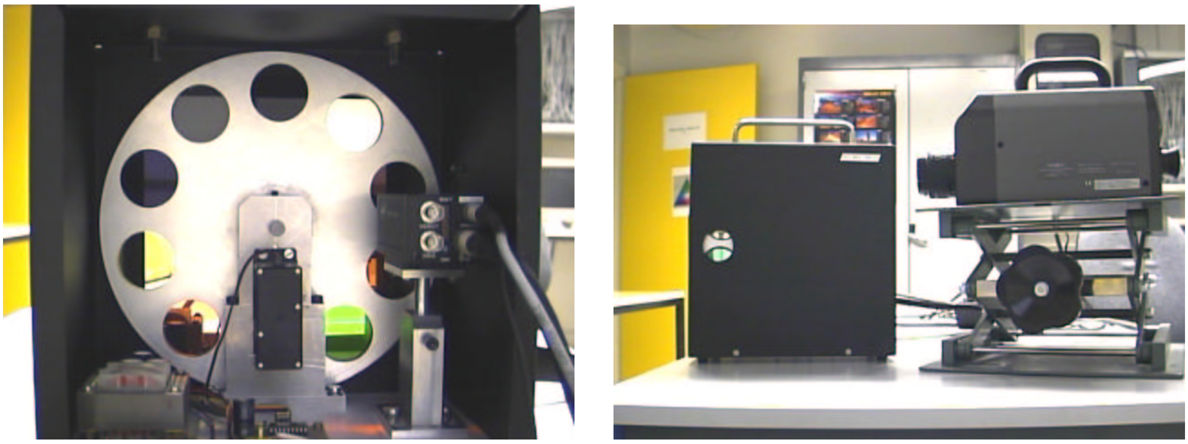


Figure 7: Multispectral camera based on rotating wheel with optical filters.

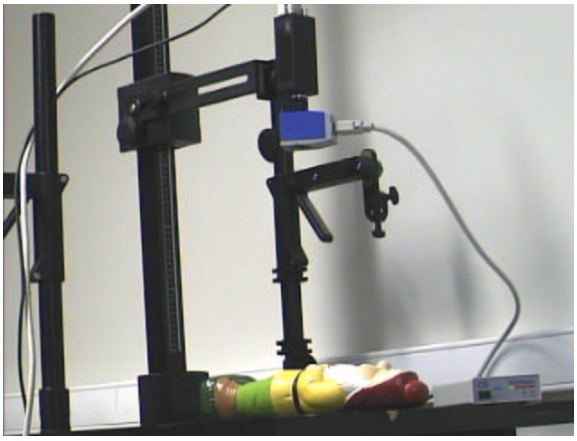


Figure 8: Multispectral camera based on Liquid Crystal Tunable Filter.

[2] A. Mansouri, J Y. Hardeberg, F. S. Marzani, P. Gouton, Optical calibration by deblurring channel images in a multispectral imaging system, In *Proceedings of VIIP2003*, Benalmadena, Spain, (1) 210-215, 2003.

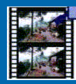
Appendix: Foils from selected presentations

1. Gudmund Sternvang: Managing colors in the production and presentation of digital video
2. Jon Y. Hardeberg: Color adjustment by color space warping
3. Ivar Farup: Digital cinema commercials – is the quality good enough?
4. Andreas Kraushaar: ICC color management in the motion picture industry
5. Jon Y. Hardeberg: Introduction to multispectral color imaging: motivation, spectral dimensionality, and existing systems
6. Ali Alsam: Spectral camera calibration
7. Ivar Farup: Creating light with arbitrary spectral power distribution
8. Pierre Gouton: Multispectral imaging: acquisition and processing
9. Andreas Kraushaar: Spectral image reproduction using print technology

Color management
What is that?

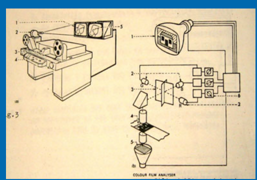
Color management

- In aquisition:
- Film:
- filters or different filmtypes
- Video:
- whitebalance or filters



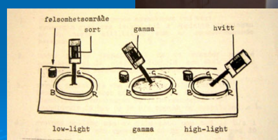
Color management

- History:
- Postproduction film
- Laboratory ,filters, chemicals



Color management

- Postproduction video:
- Film in television
- Neg. directly to tape
- Video to video



Color management

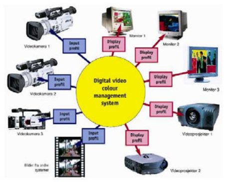
- Live production
- Subjective evaluation of colors

Color management

- Monitors (or displays)
- CRT or LCD

Color management
What is that?

- Auto white balance
- Auto white balance during editing
- Auto profiling of monitors (ICC)



Color management

- The collaborative research project brought together two communities:
- The color management for graphics art at Gjøvik University College and video and television production at Lillehammer University College who identified 4 topics of particular interest:
- 1. Color management in the aquisition of digital video
- 2. Color control for editing of digital video
- 3. Color caracterization of monitor used in the production of digital video
- 4. Color quality of projective displays for presentation of digital video

colorlab.no Gjøvik Color Imaging Symposium, November 24-25, 2003, Gjøvik, Norway

Color Adjustment by Color Space Warping

Jon Y. Hardeberg

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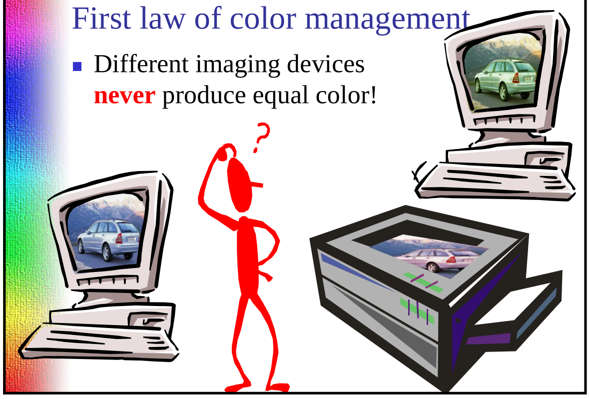
Outline

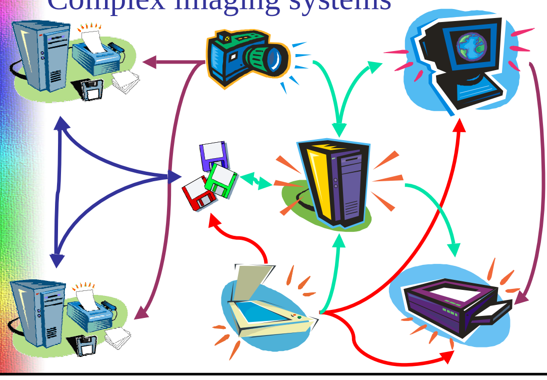
- Introduction
  - Color management principles
- Color management for film and video
  - R&D topics
- Color adjustment for digital video editing
  - Existing solutions
- Color adjustment by color space warping
  - Algorithm, implementation, and results
- Conclusions and perspectives

First law of color management

- Different imaging devices **never** produce equal color!

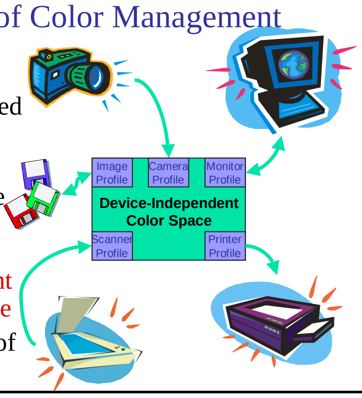


Complex imaging systems

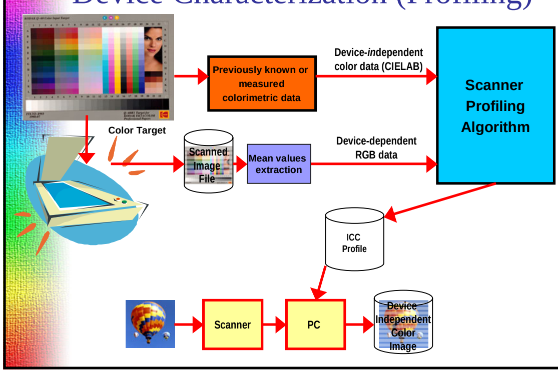


Principle of Color Management

- Imaging devices characterized by Profiles
- Image interchange through Device-Independent Color Space
- Esperanto of colors



Device Characterization (Profiling)



Color Management

- International Color Consortium (ICC) established in 1993
  - http://www.color.org
  - ”ICC Profiles”
- Established standard in Graphic Arts
  - Still issues…

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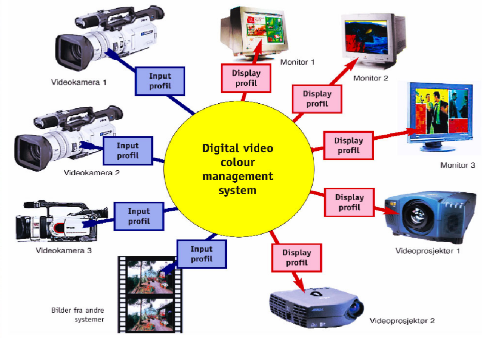
Color management for film and video



Color management for film and video

- Case study – making of *The Iron Giant*
  - (Ramamurthy et al, 1999, SMPTE-J)
  - Significant savings in time, material, and labor

Color management for film and video

- Problem areas – R&D topics:
  - Real-time processing requirements
  - Seamless integration of computer-generated and natural scenes
  - Varying viewing conditions
    - Color Appearance Modeling
  - Stability of devices
  - And more…

Characterization of monitors

- In video production, typically several monitors are used simultaneously
  - Huge color differences, even after calibration
- Could a color-managed PC monitor replace analog reference monitors used in video production?

Two monitors with the same input signal

Soft-proofing

- Do the colors of the viewing media used in the production phase correspond to those of the final target media, e.g. cinema theater projection or television?
- If not, can we simulate it?
  - Soft-proofing cinema screen on reference monitors (Kraushaar, 2002, CIC+IARIGAI)
  - Soft-proofing conventional cinema on electronic projection systems
  - Soft-proofing reference video monitors on PC monitors used for DV editing

Characterization of videoprojectors

- More and more used devices
  - Working their way into cinema environment
- Joint project with SINTEF, Trondheim
  - (Seime and Hardeberg, 2002, CIC, JSID)
  - LCD and DLP technologies
- Problem areas:
  - Colorimetric shift in primaries
  - Non-uniformity
  - Low stability
  - Dependency on viewing conditions

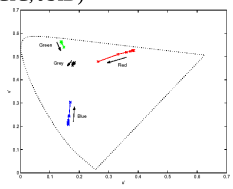


Figure 7: Changes in the colour coordinates of the primary colours and grey due to different driving levels for the DLP projector. The arrows indicate the direction of change with decreasing driving level.

Characterization of film scanners

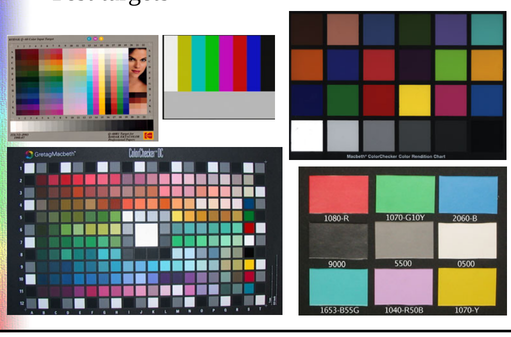
- Relationship between device-dependent and device-independent representations
  - (Noriega et al, 2001, AIC+CIC)
- Problem areas:
  - Densitometry or colorimetry?
  - Negative film
  - Dynamic range

Characterization of video cameras

- Using a test target in the scene to be captured
  - (Benedikt et al, 1998, SMPTE-J)
- Problems:
  - Colorimetric or spectral characterization models
  - Temporal changes in lighting conditions
  - White balance
    - Automatic or manual
    - Computational color constancy
  - Choice of test target

Characterization of video cameras

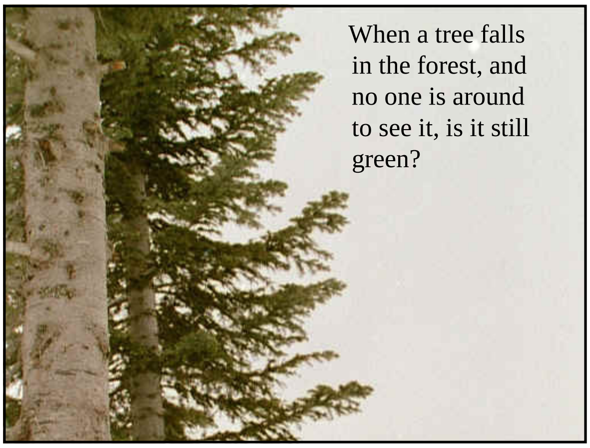
- Test targets



Video quality

- Highly relevant question:
  - Can the quality of digital cinema production and projection match conventional technology?
- How do we define quality?
  - Color, spatial resolution, brightness, flicker, sharpness, pixelization, pleasantness, naturalness, …
- Quality is what the customer wants!
  - Who is the customer?
  - The film enthousiast, the casual moviegoer, the film maker, the film maker, the advertiser, the color scientist, …

(Pettitt and Walker, 2001, CIC)



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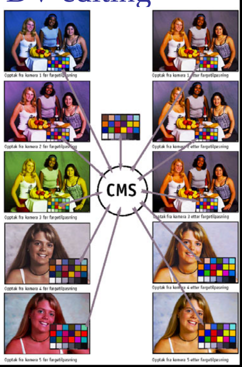
Color adjustment for DV editing

- Can footage from different sources and conditions be brought to a common color standard?
  - Want to create an illusion of continuity
  - Different camera, different lighting conditions
- By a professional colorist: **YES**
- In a color managed environment: **YES**
- For consumer/prosumer DV editing purposes: **???**



Telecine processing

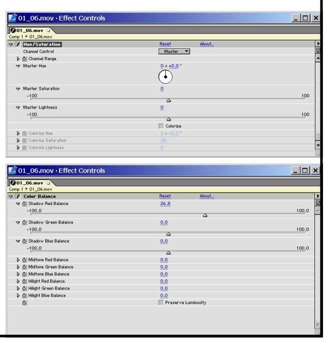
- Telecine devices for converting cinema film to video suitable for broadcast television
  - Expensive equipment
    - E.g. Davinci 8:8:8 Renaissance
  - Advanced color adjustment possibilities with dedicated UI devices such as trackballs and thumb wheels
  - Operated by colorists

- *"The colorist has full control over all aspects of how the image is going to look … in the absence of any color science whatsoever"*

(Lempp and Noriega, 2002)

Consumer/prosumer DV editing suites

- Adobe Premiere
- Adobe After Effects
  - Relatively simple color adjustment possibilities
  - No color management support

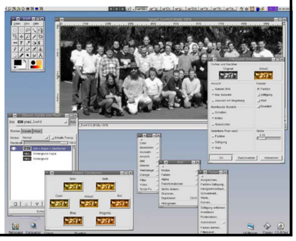


State-of-the art *image* editing software

- Adobe Photoshop
  - Advanced color adjustment possibilities
    - "Variations"
    - "Curves"
    - "Levels"
    - +++
  - Support for color management (v6.0++)

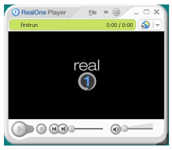
State-of-the art *image* editing software

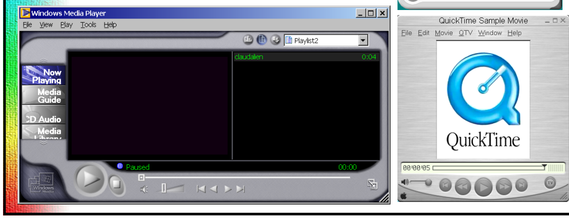
- The GIMP
  - Open-source ”Photoshop-clone” for Linux
  - ”Filterpack” plugin offers extensive color adjustment possibilities with a”color darkroom-like” user interface
  - Still lacks in intuitiveness and fine-tuning possibilities
  - No color management (?)



Multimedia player software

- No color management:
  - RealOne Player
  - QuickTime Player
  - Windows Media Player





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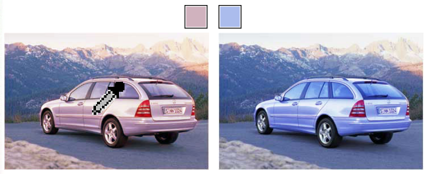
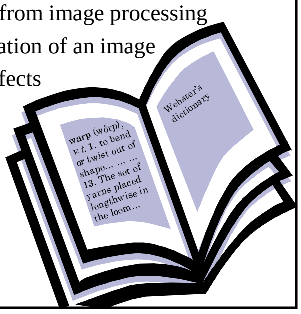
Color adjustment by color space warping

- Warping of color space based on selected corresponding colors
  - Source/destination color pairs
  - Either directly from the scene, or from test target



About warping

- Image warping
  - Technique known from image processing
  - Geometric deformation of an image
  - To create visual effects
  - Building block of morphing



Color space warping

- Extension from convensional 2D image warping to three color dimensions
- Desired properties of the color space warping algorithm
  - Source color directly mapped to destination color
  - Colors close to a source color end up close to the corresponding destination color
  - Colors having the same distance to two source colors are equally influenced by the two color pairs
  - Colors are influenced more by closer source colors

Color space warping

- The change in color corresponds to a weighted sum of the contribution of all source/destination color pairs

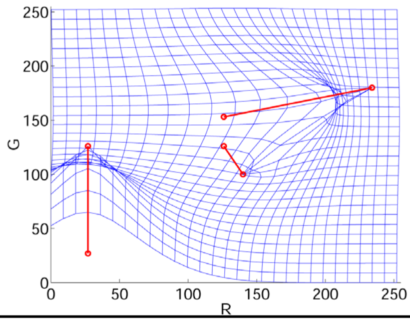
$$\mathbf{C}_O = \mathbf{C}_I + \sum_{k=0}^{N-1} w_1(k) w_2(k) \left(\mathbf{C}_D(k) - \mathbf{C}_S(k)\right),$$

$$w_1(k) = \begin{cases} \frac{1/d(k)}{\sum_{n=0}^{N-1} 1/d(n)}, & \text{if} \min d(k) > 0, \\ \delta(k, k_{\min}), & \text{if} \min d(k) = 0, \end{cases}$$

$$w_2(k) = e^{\frac{-d^2(k)}{2\sigma^2}}$$

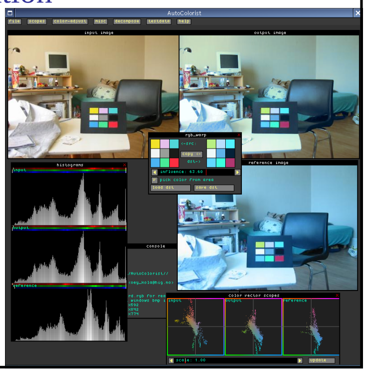
Color space warping

- Illustration in 2D



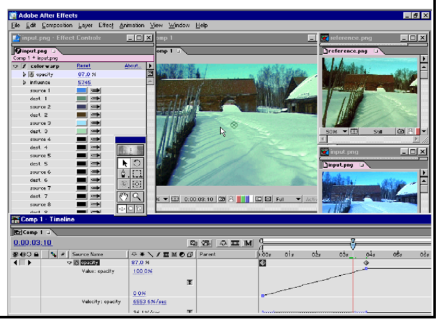
Implementation

- Øyvind Kolås' student project 2002
- AutoColorist
- Research framework application



Implementation

- Plugin to Adobe After Effects



Experimental results

- Picking three color pairs from the scene
  - Barn roof, snow in sun, snow in shadow
- Improved results possible by choosing more colors

Source Destination Result

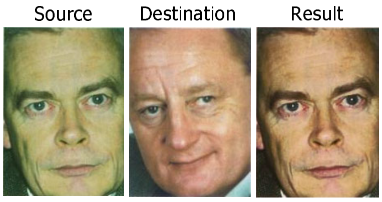
Experimental results

- Picking nine color pairs from the target
- Improved results possible by choosing colors also from the scene

Source Destination Result

Experimental results

- Picking two color pairs from the scene
  - Light skin, skin in shadow



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Conclusions and perspectives

- Video Color Management
  - Promising concept
  - Interdiciplinarity
  - Many more aspects need to be investigated
  - Standards!

Conclusions and perspectives

- Color space warping algorithm for color correction and matching of shots
  - Promising results
  - More extensive experimental results needed
  - Testing and validation by video professionals
  - Overcome a few limitations in the plugin interface
  - Application to other task such as profiling

Wrap-up

- Color management for digital video
- Color correction by warping in color space

- Literature:
  - Proc. IARIGAI Conf. 2002
- E-Mail:
  - jon.hardeberg@hig.no, jon@hardeberg.com
- Web:
  - http://www.hig.no, http://color.hardeberg.com, http://www.colorlab.no
- **Questions?**

- Acknowledgments:
  - Øyvind Kolås (the one who has been doing the hard work)
  - Ivar Farup and Gudmund Stjernvang (coauthors)
  - Egil Ljøstad (valuable feedback from a professional Colorist in the Norwegian Broadcasting Corporation)
  - Morgenlandet AS (money!)

Digital Cinema Commercials – is the Quality Good Enough?

Jon Y. Hardeberg*, Ivar Farup*, and Gudmund Stjernvang[†]
*Gjøvik University College, P.O. Box 191, N-2802 Gjøvik, Norway
[†]Lillehammer University College, N-2626 Lillehammer, Norway

24th November 2003

Outline of the Presentation

- Background
  - The project
  - The introduction of digital cinema commercials in Norway
- Technical solution
- Quality analysis
  - Visual tests
    - ∗ Question form
    - ∗ Paired comparison
  - Measurements
  - Interviews
- Conclusion

Background: The Project

- Lillehammer Univerisity College:
  - Television
  - Video
  - Film
- Gjøvik University College:
  - Media technology
  - Computer science
  - Colour science and technology
  - Graphic arts/image quality
- Joint project funded by Morgenlandet through the Prokom programme:
  1. Colour management in the acquisition of digital video
  2. Colour control for editing digital video
  3. Colour characterisation of monitors
  4. Colour characterisation of video projectors

Background: Digital Cinema Commercials in Norway

- Until 2002, cinema commercials were distributed on 35 mm film. Local commercials used photographic slides
- In 2002, CAPA (the distributor of commercials) decided to switch to digital projection of commercials
- Movie theatres without equipment for digital commercials are "on their own"
- To our knowledge, Norway is the first country to introduce this at such a big scale
- Voiced concern about the quality – decided to investigate this as part of the collaborative project

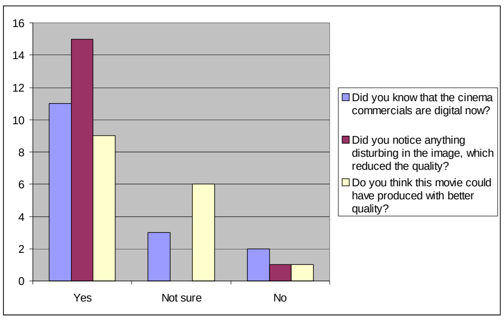
Technical Solution

- Most commercials are shot using digital eqipment such as DigiBeta or DV cameras
- Material on 35 mm film is digitised using telecine equipment
- Compressed to 15 Mbit/s MPEG-2
- Distributed to movie theatres by satellite
- Playlists are managed for each individual movie presentation
- Two main types of projectors:
  - High-resolution digital cinema projectors using 3-chip DLP technology
  - Conventional business-type projectors using LCD technology
- Big differences in price, spatial resolution, and brightness

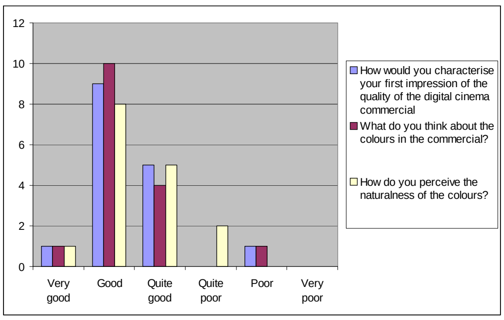
Visual Tests

- Difficult to obtain material both on 35 mm film and digital footage
- Investigate whether the digital equipment is used to its full potential
- Created DV quality test movie containing
  - Cuts from real commercials
  - Sequences from challenging test movies created by the Norwegian Broadcasting Corporation
- 16 observers in a movie theater watched original DV version on using a "business-type" projector

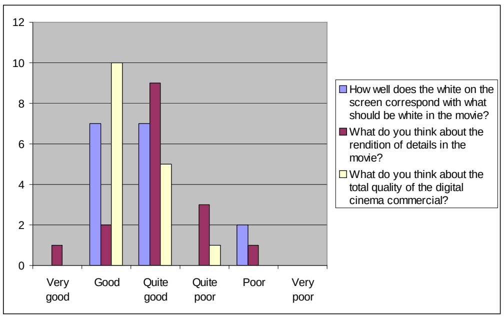
Visual Tests: Results (1)



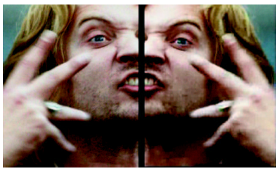
Visual Tests: Results (2)



Visual Tests: Results (3)

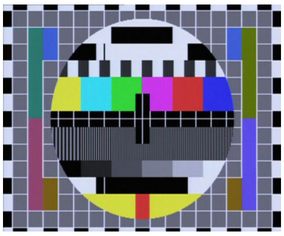


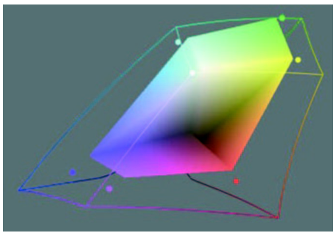
Paired Comparison Blind Test



- Test movie compressed to MPEG-2
  - 25 MBit/s (original DV)
  - 15 MBit/s (CAPA)
  - 2 MBit/s
- The three versions of the test movie were shown simultaneously side by side
- All combinations tested
- The panel had to choose between left or right
- Statistical analysis:
  - No significant difference between DV and CAPA versions
  - Significant difference between both DV and CAPA versus 2 Mbit/s version

Measurements





- Standard test image from the test videos shown on calibrated reference video monitor
- 12 colours were measured for both original DV and CAPA version
  - Average colour difference: $7.9\Delta E^*_{ab}$
  - Maximum colour difference: $16.6\Delta E^*_{ab}$ for blue

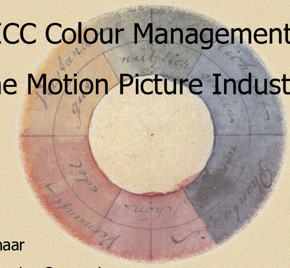
Interviews and Overall Analysis

- Interview with the management of several movie theaters:
  - Those using high-quality DLP generally satisfied
  - Those using “business-type” projectors generally not satisfied

Conclusion

- Limited scope:
  - Investigating ditital media only
  - “Business-type” projectors only
- The MPEG-2 introduces degradations relative to DV which are not visible on “business-type” projectors
- The projector seems to be the main “quality bottleneck”
- Ideas for future work:
  - Comparison of different types of projectors
  - Comparison of 35 mm film and DV

FOGRA



"ICC Colour Management in the Motion Picture Industry"

Andreas Kraushaar
Gjøvik Color Imaging Symposium
Nov. 24th, 2003

Agenda

FOGRA

- Who or What is FOGRA?
- Film Production Workflow
- Colour Management System
- Laboratory Setup
- Where to go in the Future?

Who or What is FOGRA?

FOGRA

The FOGRA: Graphic Technology Research Association

- Founded in 1951
- is a registered association with about 600 members (about half are graphic arts companies, ranging from prepress to binders, and the other half are suppliers
- operates its own institute in Munich (30 experts)
- Advice and reports based on Research and development
- Knowledge transfer (publications, lectures, seminars, symposia)
- Committee work (standards, ISO)
- Applications for funds, Membership dues, Commercial activities

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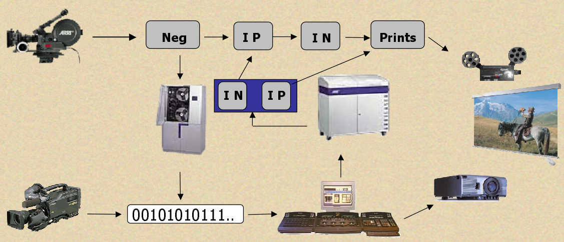
Today's Film Production Workflow:

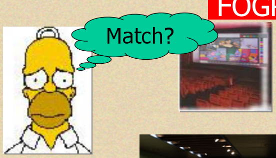
FOGRA



Final Goal

FOGRA

t1



t2

But...

You have to prove!

Side-by-Side

---

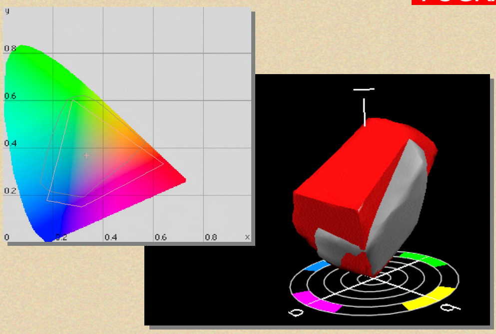
present cumbersome Situation:

FOGRA

- Apply one dimensional LUT's (Look Up Table) until it looks right.
- Many standards (SDTV, HDTV, data formats).
- CRT and film have 3 dimensional gamuts which exceed each other in some areas and fail to match in others.

Monitor ⟷ Film

FOGRA



Colour Management System

FOGRA

"... appropriate methods of representing, controlling, and communicating colour."

Goals: Consistent side by side match

➡ • Laboratory setup
- Colorimetrical measurements
- Colour encoding
- ICC implementation

Typical Preview Screen

FOGRA

ARRI, Munich

Laboratory Setup for Screen Simulation

FOGRA

ARRI LocPro

✓ Frame by frame film transport

✓ Xenon light source

Colorimetrical Measurement Method

FOGRA

- Visual match of self luminous displays
- Emissive colour measurement
- Yxy measurements ⇨ Lab
- Photoresearch telespectroradiometer
- LMT – 3 color filter
- Short measuring time (neccessary)

Colour Encoding

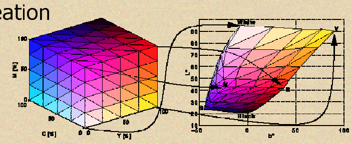
FOGRA

1.

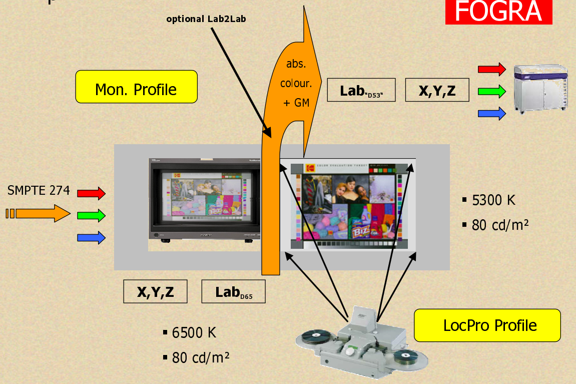
x	y	L		X	Y	Z
				x*(Y/y)	Y=(Y*100)/ k* Lmax	z*(Y/y)

2. Profile creation

- Argyll CMS
- color solutions

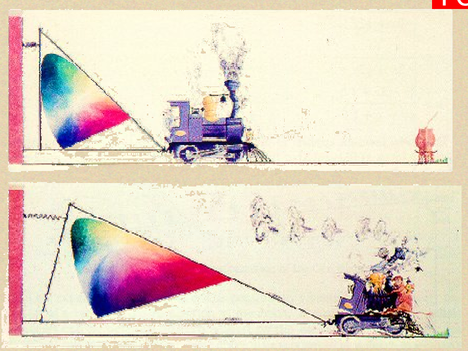


Implementation



Where to go in the Future?

- Improve metrology (fastness, reliability, noise)
- Enhanced Gamut Mapping strategies for absolute colorimetric transformation
- Develop compact models based on great data basis (shot calibration by the customer)



colorlab.no
The Norwegian Color Research Laboratory

Introduction to Multispectral Color Imaging

Motivation, spectral dimensionality, and existing systems (and maybe a little system characterization)

Jon Y. Hardeberg,
The Norwegian Color Research Laboratory,
Gjøvik University College

Gjøvik Color Imaging Symposium 2003

Background

- Based on a 4-hr tutorial/short course
  - Together with Francisco Imai
  - Given at the PICS03 conference in Rochester, NY
- Attendees of *that* tutorial should be able to:
  - Understand the basics of color science
  - Realize the limitations of conventional color imaging, and how increasing the number of color channels to more than three can resolve these limitations
  - Decide between 3-color and multispectral approaches
  - Understand the issues and tradeoffs involved in the design and practical realization of a multispectral color image acquisition system
  - Learn methods to evaluate the performance of multispectral acquisition systems.
  - Know where to find more information about this subject, equipment, and tools

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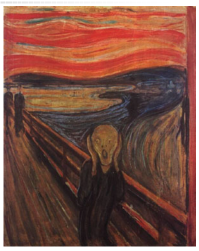
Outline

- Introduction
  - Color and metamerism
  - Why multispectral?
- Spectral dimensionality
  - Principal Component Analysis
- Multispectral color image acquisition systems
  - Principles and examples
- Spectral characterization
  - Theory and practice
- Conclusions and outlooks

What *is* Color?

What *is* Color?

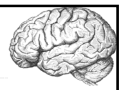
"**Color** consists of the characteristics of **light** other than spatial and temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the **visual sensations** which arise from the stimulation of the retina of the eye." [OSA 1940]

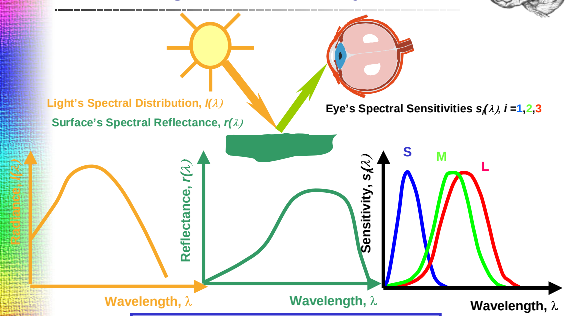


- Color is a sensation
  - Interaction between physical world and our senses

Psychophysics

Color: Light, surface, eye +

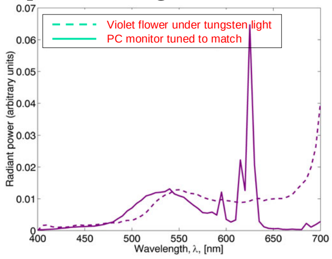


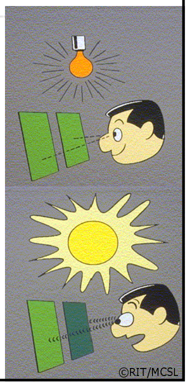


$$c_i = \int_{\lambda_{min}}^{\lambda_{max}} l(\lambda) r(\lambda) s_i(\lambda) d\lambda, \quad i = 1, 2, 3$$

Metamerism

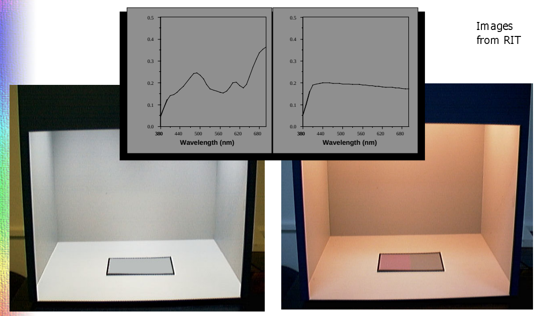
- Metamers: Different light spectra having the same color





Metamerism: A curse and a blessing!

Metamerism

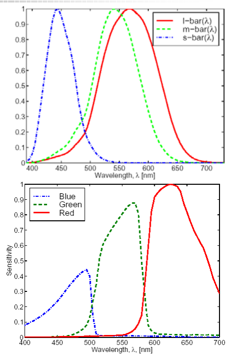


Images from RIT

Daylight illuminant **Incandescent illuminant**

Metamerism

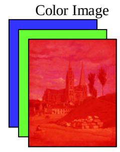
- Not only visual metamerism
- Camera metamerism
  - Different spectral reflectances gives same RGB triplet
- Camera sensitivity ≠ visual sensitivity
  - ➔ Camera metamerism ≠ visual metamerism
    - ➔ Camera confounds what humans discriminate



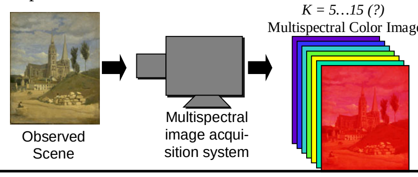
Multispectral color imaging

- My definition:
  - Imaging based on spectral reflectance rather than 'only' color
  - $K>3$ channels
  - At some point in the imaging chain, the visual appearance of the images are important

K = 3
Color Image

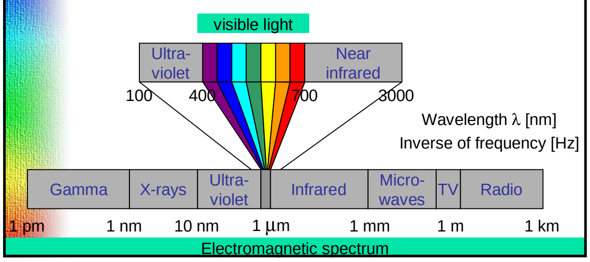


K = 5…15 (?)
Multispectral Color Image



Multispectral color imaging

- It's all in the name…
  - Multispectral imaging, Multi-visible-spectral imaging, Visible spectrum imaging, Multi-channel visible spectrum imaging (MVSI), Hyperspectral imaging, imaging spectroscopy, …



Multispectral color imaging: why?

- An object's color:
  - *f(light, surface, eye/sensor)*
  - $N=3$ variables (R,G,B), (Lightness, Hue, Saturation), (L*, a*, b*), …
- An object's spectral reflectance:
  - *f(surface)*
  - Continuous function of wavelength
  - Can be adequately described by N variables
    - Spectral sampling, e.g. $N=31$
    - PCA analysis: $N=8$? (Parkkinen, 1989), $N=6$? (Lenz, 1996), $N=10$? (Keusen, 1996), …

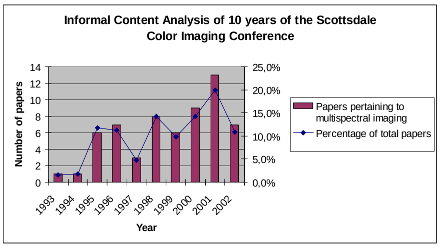
For many applications, spectral reflectance can be more appropriate information than color

Multispectral color imaging

- Applications
  - Fine arts/museum analysis and archiving
  - Medical imaging
  - Hi-Fi printing
  - Textiles
  - Industrial inspection and quality control
  - Computer graphics
  - +++

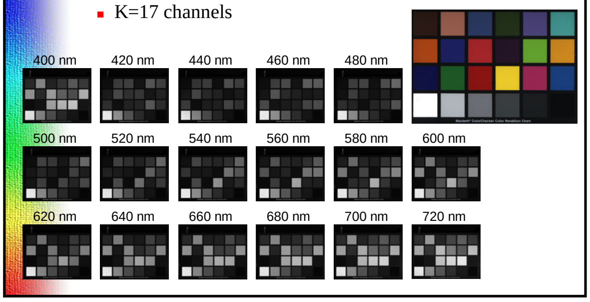
Multispectral color imaging

- Increasing academic and industrial activity
  - RIT, University of Chiba, ENST Paris, RWTH Aachen, University of Joensuu, etc



Multispectral color imaging: Example

- Acquisition of a multispectral image of the Macbeth Color Checker
  - K=17 channels



Outline

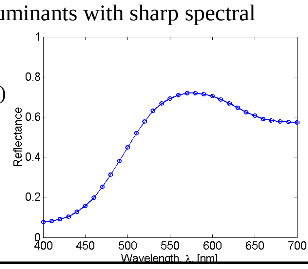
- Introduction
  - What is color and metamerism?
  - Why multispectral imaging instead of color imaging?
- Spectral dimensionality
  - Data reduction
  - Principal Component Analysis
  - Spectral databases
  - Experimental results
- Multispectral color image acquisition systems
- Spectral characterization
- Preliminary conclusions and outlooks

Spectral Dimensionality

- How many components are needed to describe a spectral reflectance?
  - Follow-up question: How many channels should the multispectral image acquisition system have?
    - (Hardeberg, 2002, CGIV)

Spectral Dimensionality

- Spectral Sampling
  - Most color signals are sufficiently bandlimited to allow sampling at 10 nm for imaging application except when illuminants with sharp spectral peaks are used
    - (Trussell and Kulkarni, 1996)
  - With visible range from 400 to 700nm this gives 31 values per spectrum

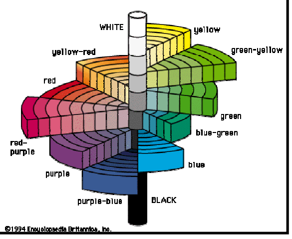


Spectral Dimensionality

- "Real" dimensionality is lower than 31 because spectral reflectances are smooth
  - Can be analyzed e.g. by Principal Component Analysis (PCA)
- Many researchers have made statements about spectral dimensionality
  - Mostly based on their own or previous PCA analyses
  - Widely varying results…

Munsell reflectances

- Cohen (1964):
  - 3
- Eem et al. (1994):
  - 4
- Maloney (1986):
  - 5-7
- Burns (1996,1997):
  - 5-6
- Lenz et al. (1995,1996)
  - 6
- Parkkinen et al. (1989)
  - 8
- Wang et al. (1997)
  - 8



Paint/Artwork reflectances

- Miyake et al. (1997):
  - 5
- Imai et al. (2000):
  - 5-8
- Garcia-Beltran et al (1998):
  - 7
- Maitre et al. (1996):
  - 10-12

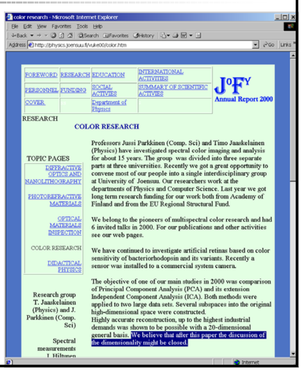
Francisco de Goya, Le Ballon Aérostatique, 1813-1815

Natural/general reflectances

- Dannemiller (1992):
  - 3
- Chiao et al. (2000):
  - 3
- Vhrel et al. (1994):
  - 3-7
- Praefcke (1996):
  - 5
- Keusen (1996):
  - up to 10
- Imai et al. (2000):
  - less than 10
- Laamanen et al. (2000):
  - 20

Laamanen et al. (2000)

- "Comparison of PCA and ICA in color recognition"
  - SPIE 4197
  - Spectral reconstruction with 20-dimensional general basis
- University of Joensuu, Annual Report 2000:
  - "We believe that after this paper the discussion of the dimensionality might be closed"



color research - Microsoft Internet Explorer

Address http://physics.joensuu.fi/vuke00/color.htm

FOREWORD | RESEARCH | EDUCATION | INTERNATIONAL ACTIVITIES | PERSONNEL | FUNDING | SOCIAL ACTIVIES | SUMMARY OF SCIENTIFIC ACTIVIES | COVER | Department of Physics

JoFY Annual Report 2000

RESEARCH

COLOR RESEARCH

TOPIC PAGES: DIFFRACTIVE OPTICS AND NANOLITHOGRAPHY; PHOTOREFRACTIVE MATERIALS; OPTICAL MATERIALS INSPECTION; COLOR RESEARCH; DIDACTICAL PHYSICS

Professors Jussi Parkkinen (Comp. Sci) and Timo Jaaskelainen (Physics) have investigated spectral color imaging and analysis for about 15 years. The group was divided into three separate parts at three universities. Recently we got a great opportunity to convene most of our people into a single interdisciplinary group at University of Joensuu. Our researchers work at the departments of Physics and Computer Science. Last year we got long term research funding for our work both from Academy of Finland and from the EU Regional Structural Fund.

We belong to the pioneers of multispectral color research and had 6 invited talks in 2000. For our publications and other activities see our web pages.

We have continued to investigate artificial retinas based on color sensitivity of bacteriorhodopsin and its variants. Recently a sensor was installed to a commercial system camera.

The objective of one of our main studies in 2000 was comparison of Principal Component Analysis (PCA) and its extension Independent Component Analysis (ICA). Both methods were applied to two large data sets. Several subspaces into the original high-dimensional space were constructed. Highly accurate reconstruction, up to the highest industrial demands was shown to be possible with a 20-dimensional general basis. We believe that after this paper the discussion of the dimensionality might be closed.

Research group T. Jaaskelainen (Physics) and J. Parkkinen (Comp. Sci)

Spectral measurements J. Hiltunen

Principal Component Analysis

- A.k.a. Karhunen-Loève transform
  - Or Eigenvector Analysis
- Goals:
  - Acquire information about the data dimensionality
  - Allow a compression of spectral data

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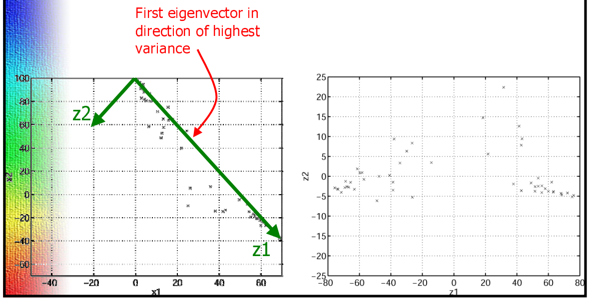
Principal Component Analysis

- Illustration with 2D data



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PCA of a reflectance set

- A set of P reflectances $\mathbf{r}_i$ measured at N wavelengths
  $$\mathbf{R} = [\mathbf{r_1 r_2 \ldots r_P}]$$
- Centering of data for PCA analysis
  $$\mathbf{X} = \left[\mathbf{r_1} - \bar{\mathbf{r}} \quad \mathbf{r_2} - \bar{\mathbf{r}} \quad \cdots \quad \mathbf{r_P} - \bar{\mathbf{r}}\right]$$
  - Note that centering might not be necessary – see an upcoming paper in CRA by Tzeng and Berns
- Implementation by Singular Value Decomposition
  $$\mathbf{X} = \mathbf{UWV^t}$$

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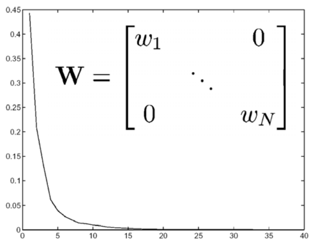
PCA of a reflectance set

- Matrix **W** with singular values of **X**
  - Rapidly decreasing magnitude



$$\mathbf{W} = \begin{bmatrix} w_1 & & 0 \\ & \ddots & \\ 0 & & w_N \end{bmatrix}$$

- The singular values of **X** correspond to the square roots of the eigenvalues of $\mathbf{XX}^t$

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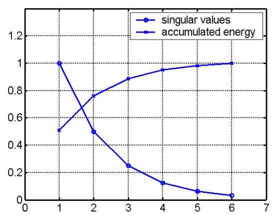
Accumulated and residual energy

- Accumulated energy
  $$E_a(\tilde{P}) = \frac{\sum_{i=1}^{i=\tilde{P}} w_i}{\sum_{i=1}^{i=P} w_i}$$
- Residual energy
  $$E_r(\tilde{P}) = 1 - E_a(\tilde{P})$$



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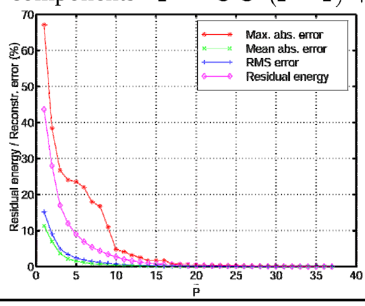
PCA of reflectance sets

- Encoding of spectra using $\tilde{P} < P.N$ principal components $\tilde{\mathbf{r}} = \tilde{\mathbf{U}}\tilde{\mathbf{U}}^t(\mathbf{r} - \bar{\mathbf{r}}) + \bar{\mathbf{r}}$



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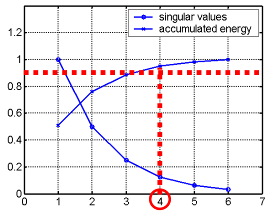
Effective dimension

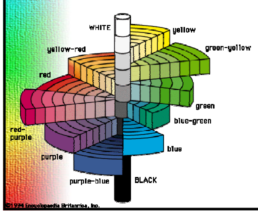
- The number of singular values required to achieve a certain accumulated energy E_{req}
  $$D_e \stackrel{\text{def}}{=} \min\{\tilde{P} | E_a(\tilde{P}) \geq E_{req}\}$$
- Propose $E_{req} = 99\%$ in accordance with literature

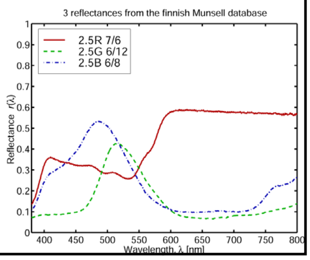


Database: Munsell

31

- 1269 Munsell chips (matte finish)
- Available online at Joensuu
  http://cs.joensuu.fi/~spectral/

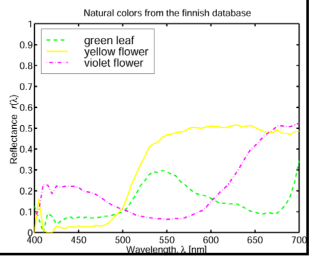




Database: Natural

32

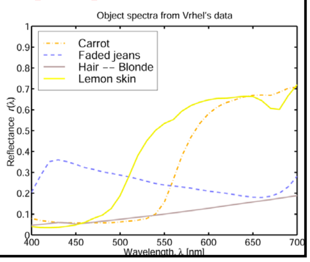
- 218 colored samples collected from nature
- Also from Joensuu



Database: Object

33

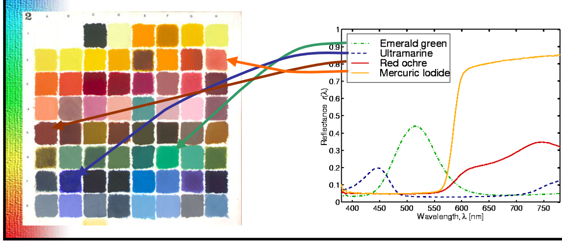
- 170 natural and man-made objects
- Available online courtesy of Michael Vhrel at
  ftp://ftp.eos.ncsu.edu/pub/spectra/



Database: Pigments

34

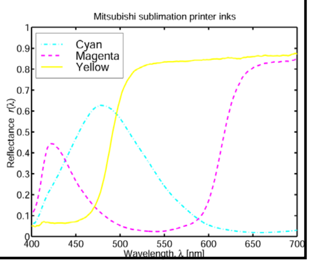
- 64 oil pigments used in painting restoration
- Provided to the ENST by the National Gallery under the VASARI project



Database: Sublimation

35

- 125 equally spaced patches of a Mitsubishi S340-10 CMY sublimation printer



Results: Singular values

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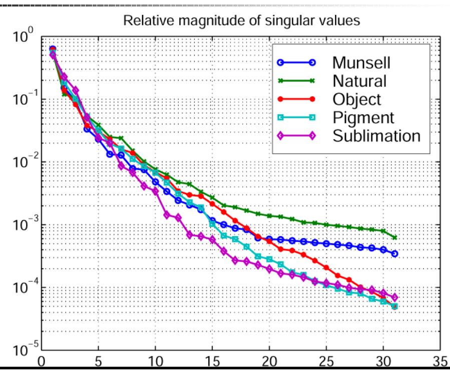
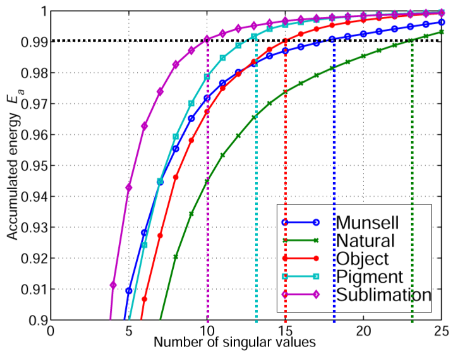


Results: Accumulated Energy



Results: Effective Dimension

- Substantial variation in dimensionality
  - MUNSELL: 18
  - NATURAL: 23
  - OBJECT: 15
  - PIGMENTS: 13
  - SUBLIMATION: 10
- A dimensionality of 20 as proposed by Laamanen et al. is not so bad
- Results suggest that a multispectral color imaging system should be optimized for the application (Hardeberg, 2003, PICS)

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  - Principles
  - Examples
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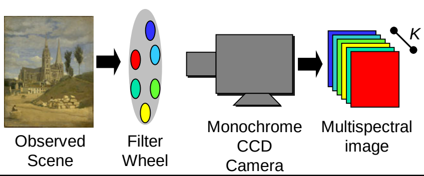
Multispectral color image acquisition

- Methods for multispectral color image acqusition
  - Hyperspectral scanner/camera
    - Grating/prism
    - Expensive
  - Point-scan spectrophotometer
    - Slow & low spatial resolution (or maybe not?)

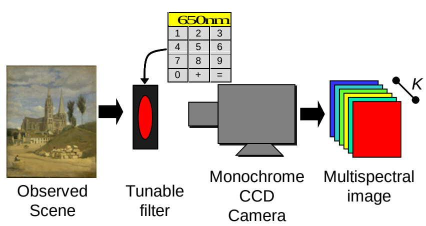
Multispectral color image acquisition

- Methods for multispectral color image acqusition
  - Monochrome CCD camera with several color filters
    - Rapid & high spatial resolution
    - Two variants
      - Passive type: filters in optical path
      - Active type: filters in light path



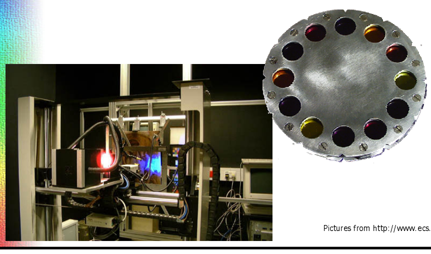
Multispectral color image acquisition

- Methods for multispectral color image acqusition
  - Camera with Liquid Crystal Tunable Filter (LCTF)
    - Easy tuning of spectral sensitivities
    - E.g. (Hardeberg et al., 2002, OE)



Multispectral color imaging: Examples

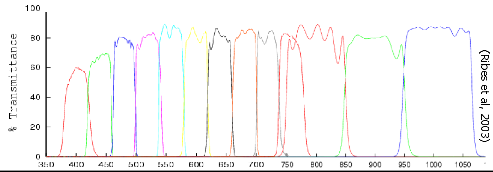
- VASARI system at the National Gallery/University of Southampton
- Recent change from 7 to 12 channels



Pictures from http://www.ecs.soton.ac.uk/~km/projs/vasari/

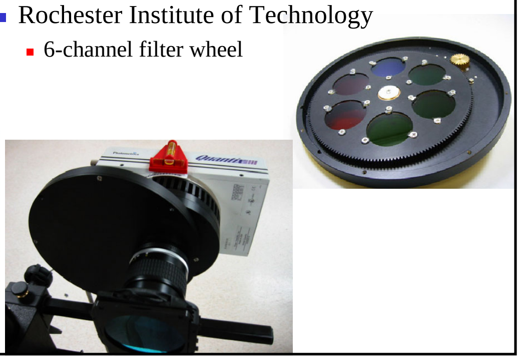
Multispectral color imaging: Examples

- CRISATEL European Project
  - ENST (Paris, France), National Gallery (London, UK), Lumiere Technology (Paris, France)
  - Linear CCD array with optical filters and dedicated illumination system
  - Very high resolution
  - 2 talks in PICS03



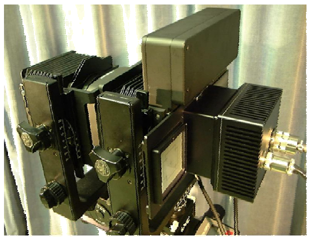
Multispectral color imaging: Examples

- Rochester Institute of Technology
  - 6-channel filter wheel



Multispectral color imaging: Examples

- Mitsubishi's multispectral camera
  - Collaboration with Chiba University
- Max 8 channels
  - Optimally 5 for oil painting



Picture courtesy of Hiroaki Sugiura

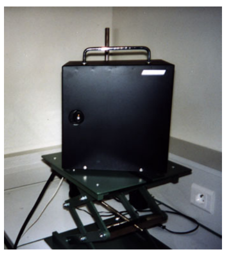
Multispectral color imaging: Examples

- ColorAIXperts' multispectral scanner
  - With RWTH Aachen
- 16 channels
- Targeted towards textile applications

Picture courtesy of Patrick Herzog

Multispectral color imaging: Examples

- University of Burgundy, Dijon
  - Low-cost camera + filter wheel
    - 9 channels – 380-1000nm
    - 1 sec. acquisition time



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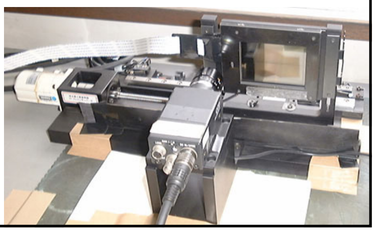
Multispectral color imaging: Examples

- Saitama University (Japan)
  - With Univ. of Joensuu (Finland)
  - Rewritable filters with optimal transmittances
  - LC spatial modulator and linear variable filter



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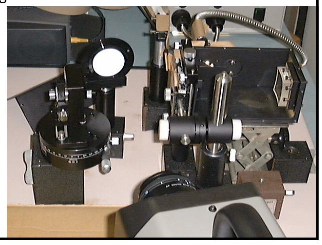
Multispectral color imaging: Examples

- Saitama University (Japan)
  - With Univ. of Joensuu (Finland)
  - Active type – light source is spectrally tuned
    - Concave gratings
    - LC-panel
    - Polarizers



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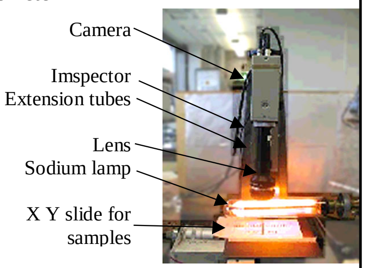
Multispectral color imaging: Examples

- University of Loughborough
  - Monochrome camera together with grating-based spectrophotometer



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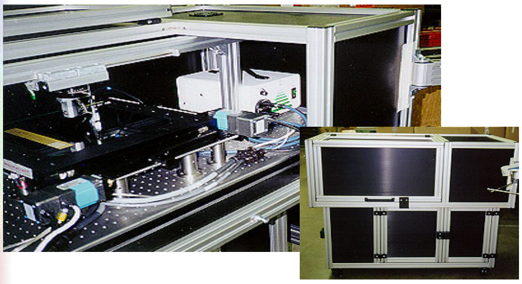
Multispectral color imaging: Examples

- Spectral Masters, Inc.
  - Scanning spectrophotometer



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Multispectral color imaging: Examples

- Ecole Nationale Supérieure des Télécommunications (Paris, France)
  - Monochrome CCD camera
  - LCTF tunable filter

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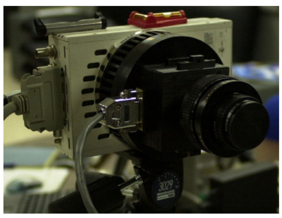
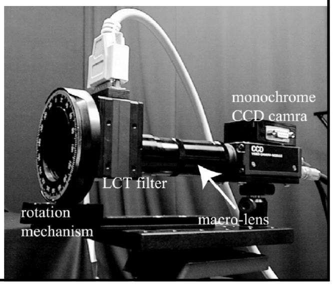
Multispectral color imaging: Examples

- Rochester Institute of Technology
  - Roper Scientific Quantix Photometrics Camera
  - CRI Inc's VariSpec LCTF



Multispectral color imaging: Examples

- Osaka Electro-Communication University
  - Monochrome CCD and LCTF



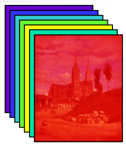
Outline

- Introduction
- Spectral dimensionality
- Multispectral color image acquisition systems
  - Principles
  - Examples
- Spectral characterization
  - Motivation – model-based spectral reconstruction
  - Theory and practice
- Preliminary conclusions and outlooks

Spectral characterization

- How to use the camera output?
  - How to get objective, device-independent information out of the acquired images?
  - Goal: Spectrophotometric measurement

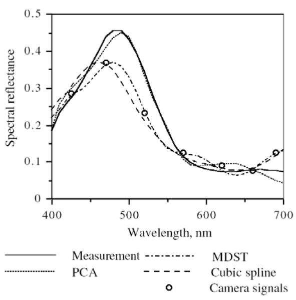
Spectral characterization



- Two main approaches
  - Direct methods
    - Use a filter/channel response as representative of its dominant wavelength
    - Supposes narrow-band sensitivities
  - Model-based methods
    - Need to establish a spectral model of the acquisition system
    - Enables reconstruction of the spectral reflectances in each pixel by inversion of the model

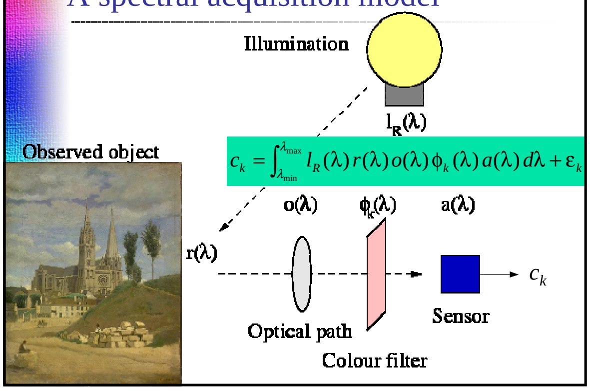
Spectral characterization

- Direct interpolation-based spectral reconstruction methods do not work with wide-band sensitivities
- Conclusion: need spectral model



(Burns and Berns, 1996)

A spectral acquisition model



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A spectral acquisition model

$$c_k = \int_{\lambda_{min}}^{\lambda_{max}} l_R(\lambda)\, r(\lambda)\, o(\lambda)\, \phi_k(\lambda)\, a(\lambda)\, d\lambda + \varepsilon_k$$

$$c_k = \int_{\lambda_{min}}^{\lambda_{max}} r(\lambda)\, \omega_k(\lambda)\, d\lambda + \varepsilon_k$$

$$c_k = \mathbf{r}^t \omega_k + \varepsilon_k$$

- ω_k = vector of unknown spectral sensitivity
  - illuminant, filters, optics, sensor
- $\mathbf{r}$ = vector of spectral reflectance
- ε_k = acquisition noise

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Inversion of the spectral model

- Acquisition model $\mathbf{c}_K = \Theta^t \mathbf{r}$
- Simple **Pseudoinverse** $\tilde{\mathbf{r}} = (\Theta\Theta^t)^{-1}\Theta\,\mathbf{c}_K$
  - Poor spectral quality
- Taking **a priori** information into account, minimizing the spectral error $\tilde{\mathbf{r}} = \mathbf{R}\mathbf{R}^t\Theta(\Theta^t\mathbf{R}\mathbf{R}^t\Theta)^{-1}\mathbf{c}_K$
  - **R**: matrix of representative spectral reflectances
  - Similar to Wiener inverse
  - Good spectral quality in the simulations (Hardeberg, 1999)
- Principal Eigenvectors method
  - Necessary in the presence of noise (Hardeberg et al., 2002)
- Non-linear methods
  - E.g. Neural Networks (Ribés et al., 2001, 2002)

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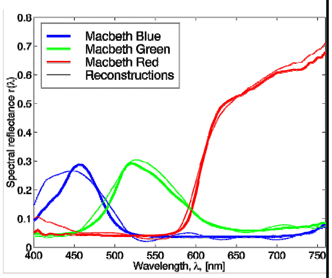
Inversion of the spectral model

- Examples of experimental spectral reconstructions
  - Principal Eigenvectors
  - 9 filters
  - PE(5)
  - Mean spectral RMS error = 0.244
  - Mean ΔE_{ab} = 3.33



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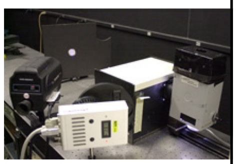
Spectral characterization: Approaches

- Determine the sensititivity of the system $c_k = \mathbf{r}^t \omega_k + \varepsilon_k$
- Direct approach:
  - Measure all the components
    - Light source
    - Filters
    - Camera and optics
  - Requires relatively expensive equipment
    - Spectroradiometer
    - Monochromator



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Spectral characterization: Approaches

- Indirect approach:
  - By observing the camera responses to a color target of *P* samples with known spectral reflectances
- $\mathbf{R} = [\mathbf{r}_1\ \mathbf{r}_2 \ldots \mathbf{r}_P]$: matrix of *P* reflectances $\mathbf{c}_{k,P} = \mathbf{R}^t \omega_k + \varepsilon_k$
  - $\mathbf{c}_{k,P}$: vector of *P* camera responses
- $\hat{\omega}_k$: estimation of the spectral sensitivity $\hat{\omega}_k = f(\mathbf{c}_{k,P}, \mathbf{R}, \varepsilon_k)$
- Inverse problem (again)
  - (Pratt et Mancill 1976, Sharma et Trussell 1993;1996, Farrell *et al.* 1994, Hubel *et al.* 1994, Maître *et al.* 1996, Hardeberg *et al.* 1998, Hardeberg 1999, 2001, …)

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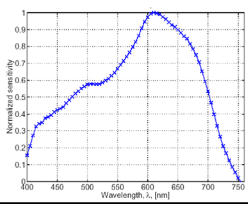
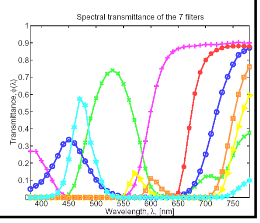
Spectral characterization: Approaches

- In practice, when using external filters:
  - Characterize camera+illumination by indirect approach
  - Measure filters directly





Optimising Optimisation Techniques for Camera and Scanner Spectral Calibration

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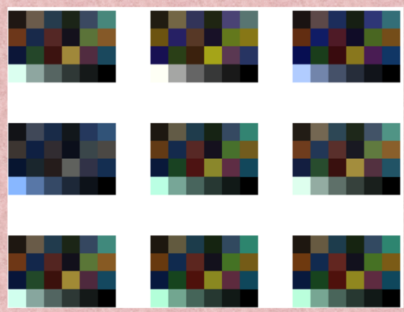
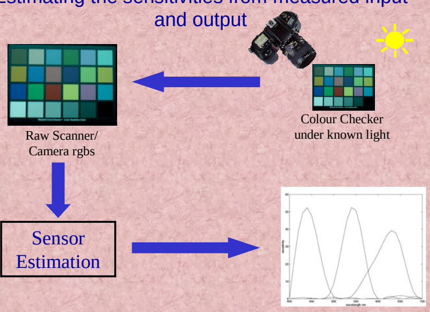
United Kingdom

The basic problem
Different cameras result in different image colours



The idea

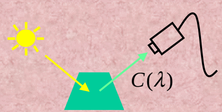
Estimating the sensitivities from measured input and output



Preliminary issues

- How does a camera see colour?
- Why do we need device sensitivities?

Understanding how a device sees colour



$$r = \int_\omega R(\lambda)C(\lambda)d\lambda$$
$$g = \int_\omega G(\lambda)C(\lambda)d\lambda$$
$$b = \int_\omega B(\lambda)C(\lambda)d\lambda$$

Device sensitivities are not colour matching functions

⇒ Devices see colour differently to humans

 ≠ 

Why we need the device sensitivities

To understand how a device sees colour
- *to predict device rgbs*

To relate device colours to colorimetric colours
- *relate rgbs to XYZs*

To enable colour correction
- *map device colours to a colorimetric space*

For physics-based vision algorithms
- *for example colour constancy algorithms*

How can we get the device sensitivities?

Ask the manufacturer

- *doesn't always make data available, data is device specific.*

Measure them

- *monochrometer/narrow-band filters [Hubel,Farell et al] - expensive*

Estimate them

- *by unconstrained regression [Sharma, Hardeberg et al.]*
- *by constrained regression [Finlayson, Hordley, Barnard,Dyas]*

Sensor estimation as regression

$$\rho = \int_{400}^{700} R(\lambda)C(\lambda)d\lambda \quad (1)$$

We want to solve (1) for $R(\lambda)$

Represent spectral functions as discrete approximations [Nyquist]:

$$R(\lambda) \cong [R(400),\ R(410),\ R(420),\ \cdots,\ R(700)]^t = \underline{R}$$

$$C(\lambda) \cong [C(400),\ C(410),\ C(420),\ \cdots,\ C(700)]^t = \underline{C}$$

Simplifying the integration

Replace the integral by a summation

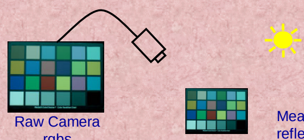
$$\rho = \int_{400}^{700} R(\lambda)C(\lambda)d\lambda \approx \sum_{i=1}^{31} \underline{R}(\lambda_i)\underline{C}(\lambda_i)$$

$$\rho = \underline{R}.\underline{C}$$ Summation is the vector dot product

$$\rho = \underline{C}^t \underline{R}$$ Dot product is a matrix multiplication

We have 1 equation and 31 unknowns ⇒ Need more equations

The camera response to N colour signals



Raw Camera rgbs (unrendered)

Measure illuminant with a spectroradiometer: $E(\lambda)$

Measure surface reflectances with a spectrophotometer: $S_i(\lambda)$

$$C_i(\lambda) = E(\lambda)S_i(\lambda)$$

$$\begin{array}{ccc} p_1 & = & \underline{C}_1^t \underline{R} \\ p_2 & = & \underline{C}_2^t \underline{R} \\ \vdots & \vdots & \vdots \\ p_N & = & \underline{C}_N^t \underline{R} \end{array}$$

Solving for <u>R</u>

Place all N colour signals in a matrix **C**:

$$\underline{p} = C\,\underline{R}$$

Nx1 vector of red camera responses

Nx31 colour signals

31x1 vector: red camera sensor

We now have N equations and 31 unknowns ...

*… if we know **C** and <u>p</u>, we can solve for <u>R</u>*

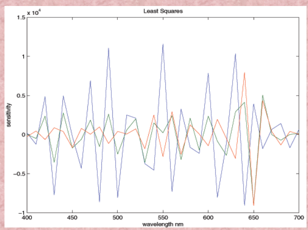
This work

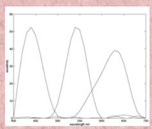
- A geometric analysis of spectral calibration
- Recovering spectral sensitivities with uncertainty
- Selecting surfaces with integer programming
- Spectrally calibrating sharp sensors

Solving by unconstrained regression

$$C\underline{R}-\underline{p}$$

Find $\underline{R}(\lambda)$ which minimises: $\left\| C\underline{R}-\underline{p} \right\|$ (least-squares regression)





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Problems with least-squares regression

- The colour signal matrix is rank deficient:

$$C(\lambda) \approx \sum_{i=1}^{m} b_i B_i(\lambda) \quad m = 6,7$$

$\Rightarrow$ *unconstrained regression is sensitive to noise*

- Note that the sensor is in a 31 dimensional space while the colour signal matrix has only 6 to 7 dimensions.

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So what is a rank deficient matrix?

- A matrix A is rank deficient if its rows or columns are linearly dependent:

$$A = \begin{pmatrix} 1 & 1.5 & 3 \\ 2 & 3 & 6 \\ 3 & 4.5 & 9 \end{pmatrix}$$

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How do we examine if a matrix is rank deficient?

- The singular value decomposition of the colour signal matrix *C* can be written as:

$$C = UDV^T$$

- Where:

$$UU^T = I,\ VV^T = I$$

and

$$D = \begin{bmatrix} \sigma_1 & 0 & 0 & 0 \\ 0 & \sigma_2 & 0 & 0 \\ 0 & 0 & . & 0 \\ 0 & 0 & 0 & \sigma_n \end{bmatrix}$$

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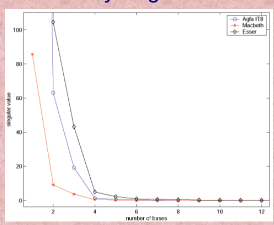
- Examining the colour signal matrix *C* for available calibration targets we find that the singular values in matrix *D* tend to decrease rapidly from a very large value to zero



- A rapid drop in the singular values is typical of rank deficient matrices.

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- To see how this affects the spectral calibration problem we rewrite the colour formation equation as:

$$\underline{p} = UDV^T \underline{R}$$

- From the properties of *U*,*V* and *D* we can write the spectral sensitivities as:

$$\underline{R} = \sum_{i=1}^{n} \frac{\underline{v}_i \underline{u}_i^T}{\sigma_i} \underline{p}$$

$$\frac{\underline{v}_i \underline{u}_i^T}{\sigma_i} \underline{p} = \frac{0}{0} = 0, \quad \frac{\underline{v}_i \underline{u}_i^T}{\sigma_i} \underline{p} = \frac{0.00000001}{0} = \infty$$

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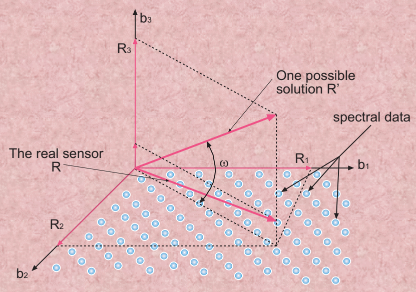
A geometric example of a rank deficient system

Let us try to solve for r_1, r_2 and r_3

$$\begin{pmatrix} c_{11} & c_{12} & 0 \\ c_{21} & c_{22} & 0 \\ c_{31} & c_{31} & 0 \end{pmatrix} \begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}$$

not that r_3 can assume any value without affecting the results

A geometric example of a rank deficient system



The truncated singular value decomposition **TSVD**

- One way to control the least squares solution is by including only those singular values that are greater than a certain threshold.

$$\underline{R} = \sum_{i=1}^{r} \frac{\underline{v}_i \underline{u}^T{}_i}{\sigma_i} \underline{p}$$

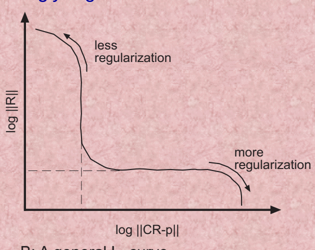
Tikhonov regularisation

- The main problem with the least squares solution is that the solution's norm is very large. Tikhonov regularisation addresses this problem by introducing a penalty term on the recovered sensor norm:

$$\min_{\underline{R}} \left(\left\| C\underline{R} - \underline{p} \right\| + \lambda^2 \left\| I\,\underline{R} \right\| \right)$$

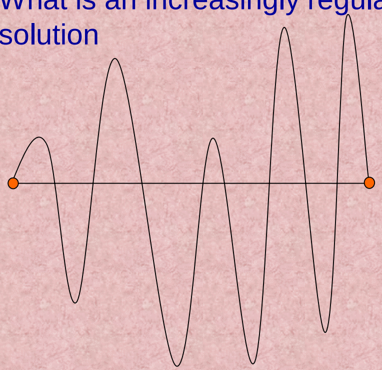
The regularisation parameter

- Increasing the regularisation parameter results in an increasingly regularised solution.



B: A general L_curve representation

What is an increasingly regularized solution



Regularization with orthogonal eigenvectors

$$C\underline{R} = \underline{p}$$

$$C^T C\underline{R} = \underline{C^T p}$$

$$C^T C = \left(UDV^T\right)^T \left(UDV^T\right) = VD^2V^T$$

$$\sigma_i^2 = \underline{v}_i^T C^T C\underline{v}_i$$

Add the constraint $\varphi\tilde{V}^T \underline{R} \approx 0$

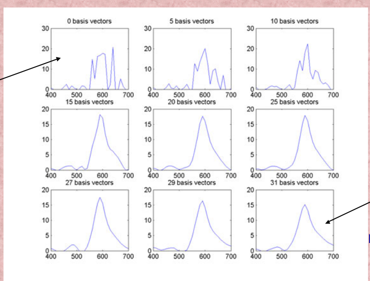
where $\tilde{V}^T$ are the orthogonal eigenvectors

A modified colour formation equation

$$\begin{pmatrix} C \\ \varphi\tilde{V}^T \end{pmatrix} \underline{R} = \begin{pmatrix} \underline{p} \\ \underline{0} \end{pmatrix}$$

An increasing number of orthogonal eigenvectors leads to an increasingly regularized solution

This is positive least squares



This is Tikhonov regularization

Recovering spectral sensitivities with uncertainty

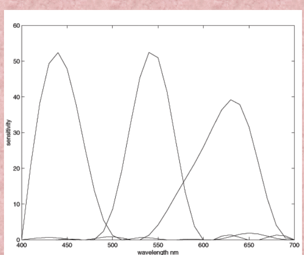
- A rank deficient system has an infinite number of solutions

$$\begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 3 & 1.5 \\ 1 & 0 & 1.5 \\ 1 & 0 & 0 \end{pmatrix} = 3$$

- Using objective functions results in one possible answer:

$$|C\underline{R} - \underline{p}| \qquad \|C\underline{R} - \underline{p}\| \qquad \|C\underline{R} - \underline{p}\|^x$$

Adding domain knowledge
What do real sensors look like?



Positive

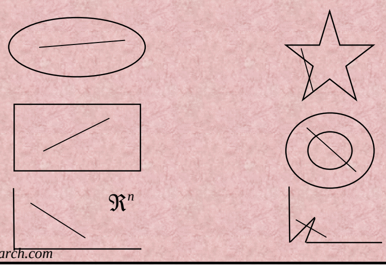
Band-limited (smooth)

Limited modality

The constraints are convex sets

- Definition. A set C in R^n is convex if for every x and y in C, the line segment joining x and y also lies in C

Convex | Non Convex



Sensor Functions are Smooth

$\underline{R}(\lambda)$ can be represented as a linear combination of a finite number of basis functions:

$$R(\lambda) = \sum_{j=1}^{m} b_j B_j(\lambda)$$

This is a constraint on the smoothness of $\underline{R}(\lambda)$

$$|R(\lambda_{i+1}) - R(\lambda_i)| \le \varepsilon$$

This is a constraint on the first derivative and hence the smoothness

$$C_S = \{R_i \in R^N \,|\, |R(\lambda_{i+1}) - R(\lambda_i)| \le \delta\}$$

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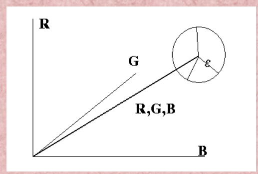
The noise contribution to the response is bounded

$$p_i - \varepsilon \le \hat{p}_i \le p_i + \varepsilon$$



$$C_N = \{R_i \in R^N \,|\, |CR_i - p_i| \le \varepsilon\}$$

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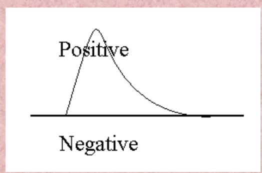
All sensors are positive functions

$$R_i \ge 0, i = 1,2,3,\ldots,31$$



$$C_P = \{R_i \in R^N \,|\, R_i \ge 0\}$$

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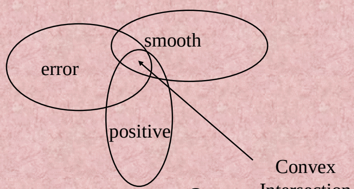
The intersection of n convex sets is convex



$$C = \bigcap_i^3 C_i$$

Any sensor satisfying all the constraints is equally likely to be the real sensor of the device

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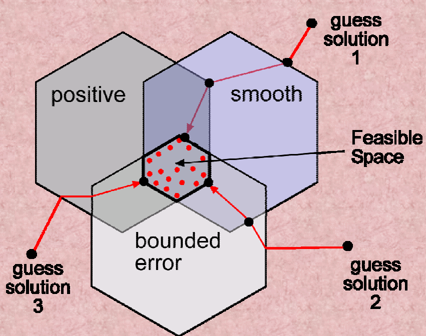
Projection onto convex sets



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Computing the intersection Region

- Basically each constraint is defined by a set of hyperplanes
- Intersecting hyperplanes is solved with efficient algorithms (such as Qhull)
- The intersection region is represented by a set of vertices
- We are interested in the mean of the whole set (not the mean of the vertices)

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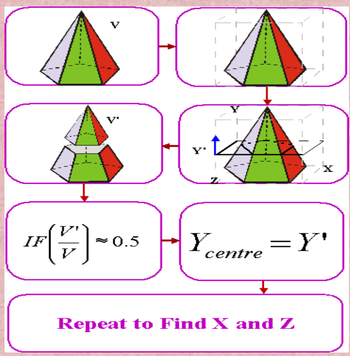
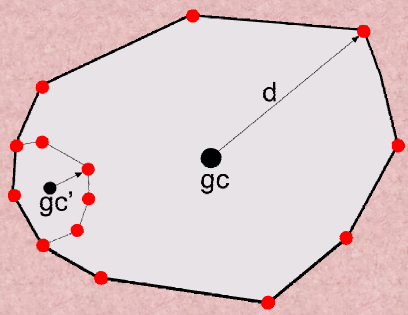
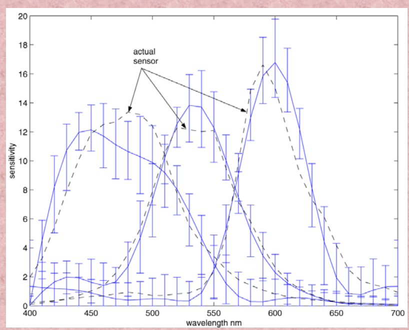
Finding the centre of a convex hull



The uncertainty is the distance from the mean to the extremes

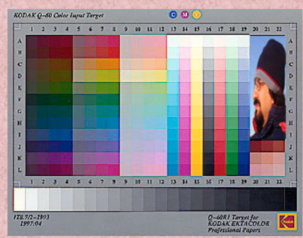


Actual results MegaVision (a HP camera)



Selecting surfaces with integer programming

- How many surfaces out of a large set are needed to spectrally calibrate a device?



Why do we need a large number of surfaces?

- Until you have answered all my questions I can't say that I know who you really are.
- For a camera the questions are spectral data and the answers are rgb responses.

Why do we want a reduced set?

- Measuring the spectral data and the corresponding *rgb* responses is a tedious task and human error is expected.
- Results in smaller and cheaper calibration targets
- Reduces the dimensionality and complexity of the problem.

A measure of similarity

- The colour formation equation states:

$$C\underline{R} = \underline{p}$$

- The least squares estimate of a sensor is:

$$\underline{\hat{R}} \approx \left(C^T C\right)^{-1} C^T \underline{p}$$

$$\underline{\hat{R}} \approx \left(C^T C\right)^{-1} C^T C \underline{R}$$

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Matrix $C^T C$ drives the estimate.

- What is the structure of $C^T C$?

$$C^T C = \sum_{i=1}^{m} \underline{c}_i^T \underline{c}_i$$

- Rewriting

$$\beta C^T C = \sum_{i=1}^{m} \alpha_i \underline{c}_i^T \underline{c}_i$$

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An integer programming problem

$$\min \left\| \beta C^T C - \left[\alpha_1 \underline{c}_1^T \underline{c}_1 + \alpha_2 \underline{c}_2^T \underline{c}_2 + \cdots + \alpha_m \underline{c}_m^T \underline{c}_m\right] \right\|^2$$

$$\alpha_i = 0, \ or \ \alpha_i = 1$$

$$\sum_{i=1}^{m} \alpha_i = k$$

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Creating Light with Arbitrary Spectral Power Distribution

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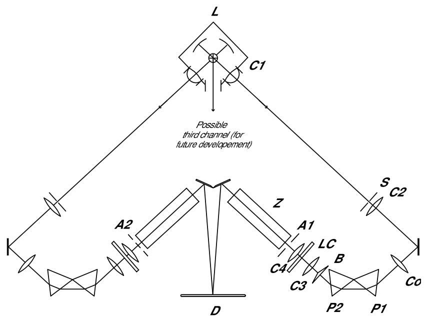
25th November 2003

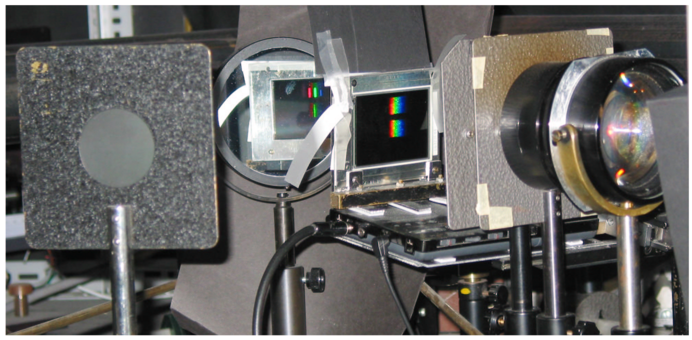
Outline of the Presentation

- The spectral integrator
- Properties of the spectral integrator
  - White spectrum
  - Black spectrum
  - Bandwidth
- Executive software for the spectral integrator
- Characterisation of the spectral integrator
- Calibrating routine
- Evaluation of the calibrating routine
- Potential applications of the spectral integrator
- Conclusions and further work

The Spectral Integrator

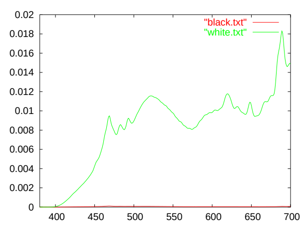


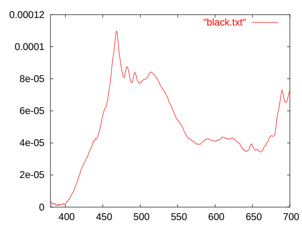
The Spectral Integrator



Properties of the Spectral Integrator: Contrast

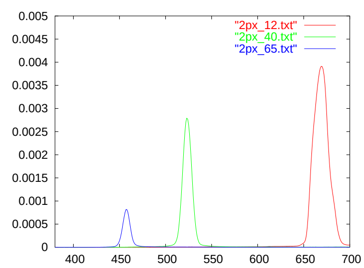
Black and white spectra:





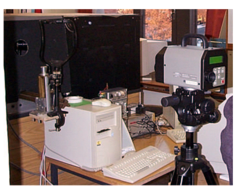
Properties of the Spectral Integtrator: Bandwidth

The bandwidth is mainly limited by the slit width:



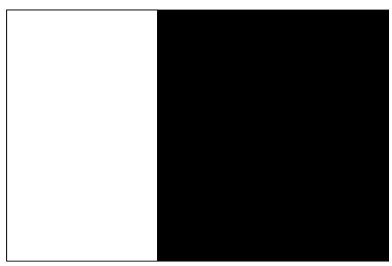
Executive Software for the Spectral Integrator

- Developed as a student project
- Written in Microsoft Visual Studio .NET C++
- Kernel with basic functionality and GUI
- Modules (DLL files) for
  - Spectral integrator (LCD Panel)
  - Spectroradiometer
  - Calibration
  - Script parser
  - User input




Characterisation of the LCD Panel: Position

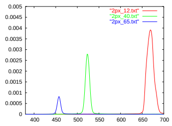
Binary search for finding the four edges of the position of the spectrum on the LCD panel.



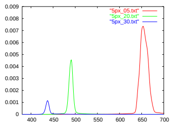
Characterisation of the LCD Panel: Aperture Functions

Due to noise, we must assume that the spectral power distribution has the same shape on a vertical line

2 pixels wide:

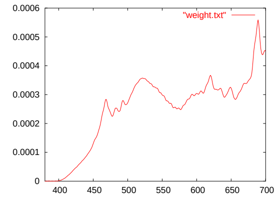


5 pixels wide:



Characterisation of the LCD Panel: Weight Factors

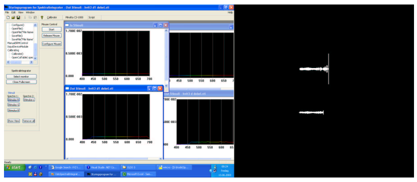
Must find the relative contribution of each pixel by measuring horizontal lines:

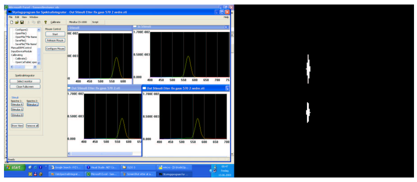


Calibrating Routine

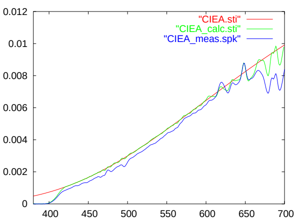
- Using the aperture functions and the weight factors, it is possible two calculate the resulting spectral power distribution from the image on the LCD panel
- Must be inverted in order to come from wanted spectrum to LCD image
- Due to realtime requirement, a heuristic search algorithm has been applied:
  1. Start with all vertical lines black
  2. Calculate resulting spectral power distribution
  3. Calculate difference between wanted and obtained spectral power distribution
  4. For each vertical line, add pixels to compensate for the *power* (not amplitude) difference at the wavelength corresponding to that particular aperture function
  5. If the LCD image is changed, repeat from 2

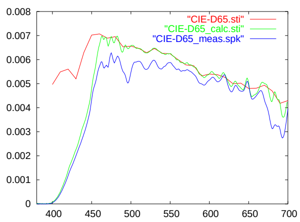
Evaluation of the Calibrating Routine



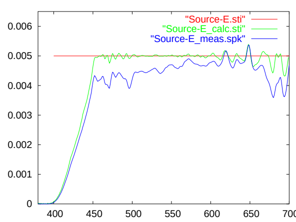


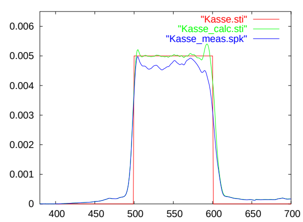
Evaluation of the Calibrating Routine: Examples (1)





Evaluation of the Calibrating Routine: Examples (2)





Potential Applications of the Spectral Integrator

- Colour matching experiments
- Transformability of colour matching functions
- Metamerism
- Charactersing parvocellular response
- Adaptation
- Colour appearance modelling
- Multispectral image acquisition
- Spectral characterisation of digital cameras

Conclusions and Further Work

- Spectral integrator and executive software seems to be working reasonably well by now
- Improve quality of heuristic search algorithm
- Use spectroradiometric measurements instead of calculations from measurements for improving accuracy of particularly important spectra
- Apply the integrator to everything relevant. . .

Multispectral imaging:

- Acquisition systems

& Processing algorithms

P Gouton

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TEL/FAX: 33(0)3-80-39-60-04
pgouton@u-bourgogne.fr
http://www.le2i.com

Equipe **TSI**
(Signal and Image Processing)
Couleur --- Multispectral --- 3D
http://aramis.u-bourgogne

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1. Introduction

2. Optical systems
   - Rotating optical filter :System calibration
   - Tunable system

3. Thermal system

4. Space system

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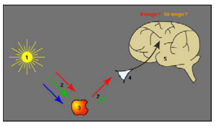
1. Introduction

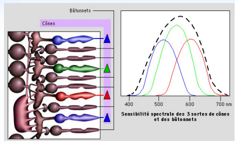
Human vision system

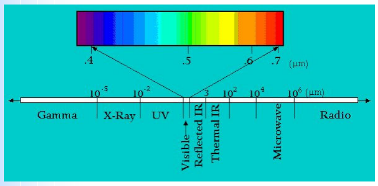
Color sensitivity depends on : - human visual system
- physical radiation

Interpretation of object radiations



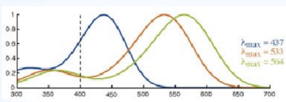
Spatial repartition of cones and rods



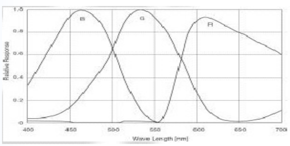


Visible = narrowband

Standard Color Vision and Human Vision



Spectral cones sensitivity of human vision

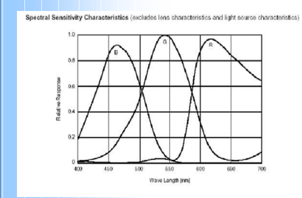


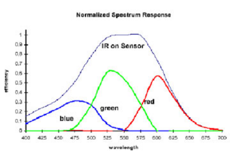
Spectral sensors sensitivity
(MicroPublisher of Q-Imaging)

Two kinds of technology

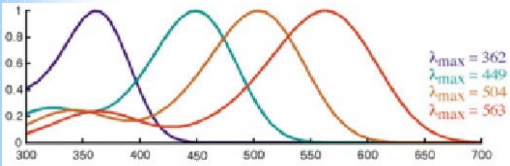
CCD MVsensor

CMOS MVsensor





Non human vision system



Starling vision system according to
I. C. Cuthill and al

2. Optical systems

- Rotating optical filter :System calibration
- Tunable system

Spectral camera for weeds identification

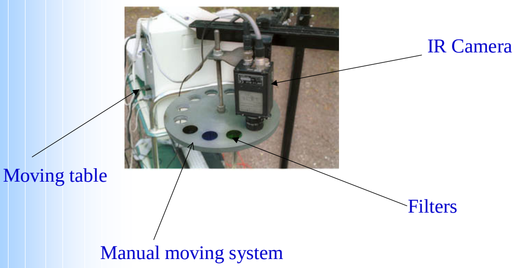
Different problems to be solved

- Non uniform lightning
- Light almost changing
- Large area to scan
- Weather conditions
- Same color objects to separate
- Etc..

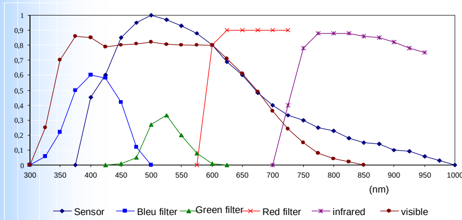
Acquisition device placed in the field of onion

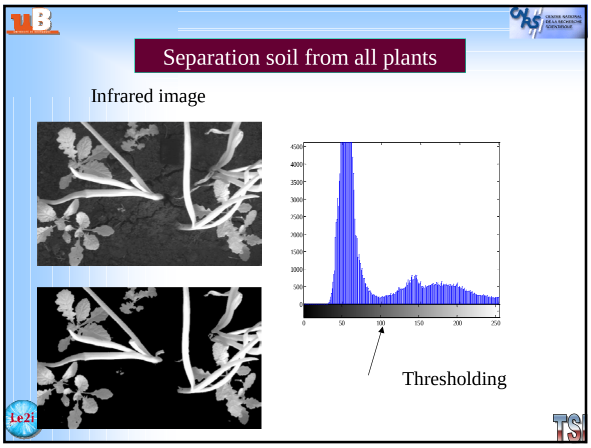
Basic multispectral images acquisition

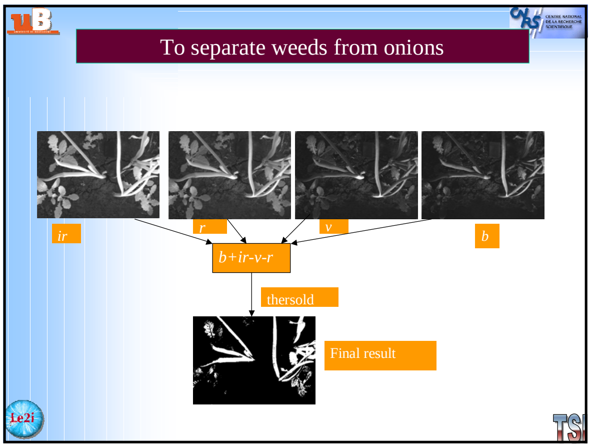
4 overlapping band system

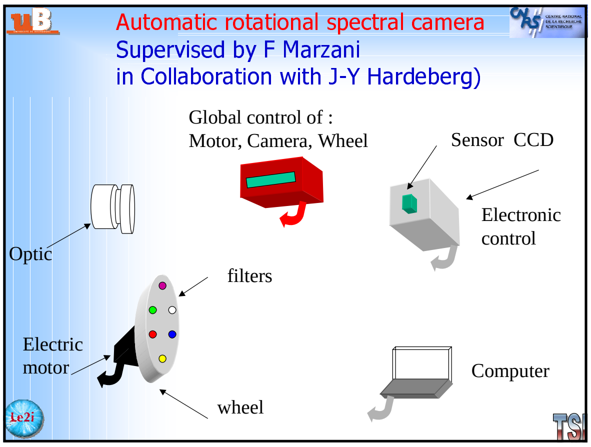


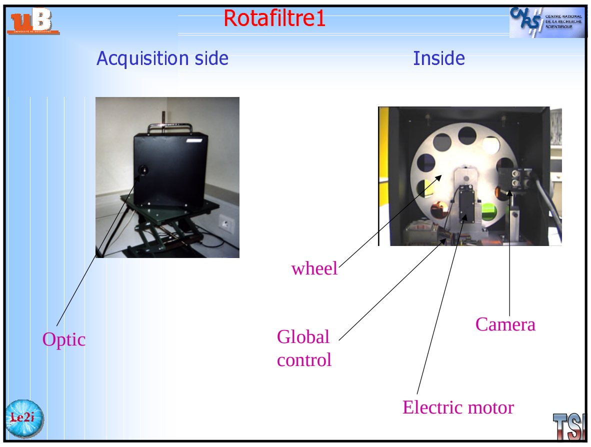
Spectral response of sensor and filters

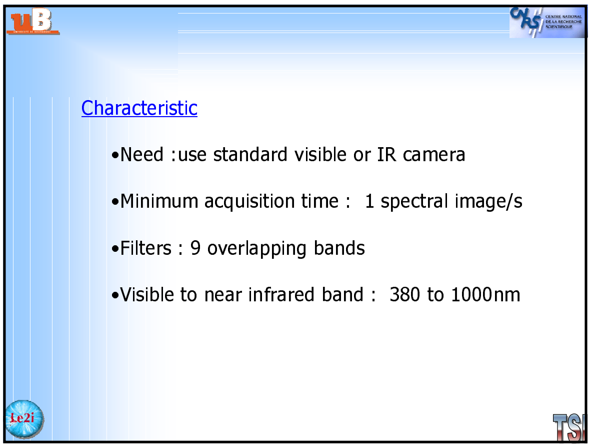


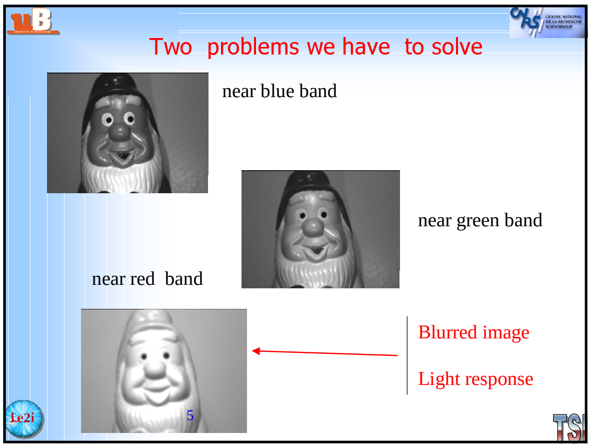

Separation soil from all plants
Infrared image
Thresholding


To separate weeds from onions
ir
r
v
b
b+ir-v-r
thersold
Final result


Automatic rotational spectral camera
Supervised by F Marzani
in Collaboration with J-Y Hardeberg)
Global control of :
Motor, Camera, Wheel
Sensor CCD
Electronic
control
Optic
filters
Electric
motor
Computer
wheel


Rotafiltre1
Acquisition side
Inside
wheel
Optic
Global
control
Camera
Electric motor


Characteristic
•Need :use standard visible or IR camera
•Minimum acquisition time : 1 spectral image/s
•Filters : 9 overlapping bands
•Visible to near infrared band : 380 to 1000nm


Two problems we have to solve
near blue band
near green band
near red band
Blurred image
Light response

Optical analyse

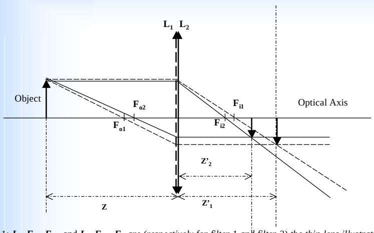


Figure 1: L_1, F_{o1}, F_{i1}, and L_2, F_{o2}, F_{i2} are (respectively for filter 1 and filter 2) the thin lens illustrating the optical system, its first focal point, and its second focal point. The object is at the distance Z from the lens, the CCD camera is at the distance Z'_1. The sharp in-focus image through the filter 1 forms at the distance Z'_1. When we replace filter 1 by filter 2, the image forms sharply at the distance Z'_2. However, because the CCD remains at the distance Z'_1, the image formed on the CCD (at the distance Z'_1) is thus blurred.

By deblurring processing

channel-image 1 when focusing on channel 9

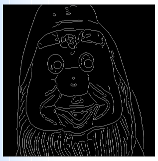
restored image with too small radius, PSNR=13.1667

restored image with optimal radius, PSNR=21.1387

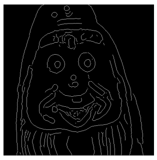
restored image with too large radius, PSNR=8.7166

Evaluation by Canny-Deriche edge detector

Non blurred image

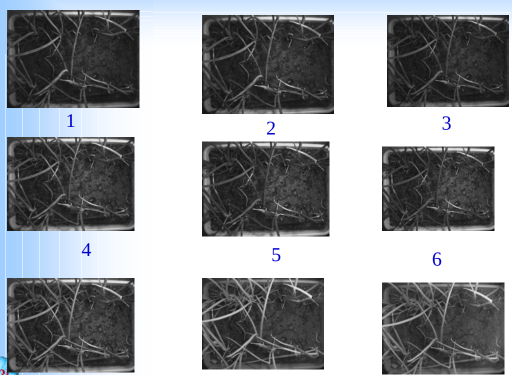


edge image of the restored image

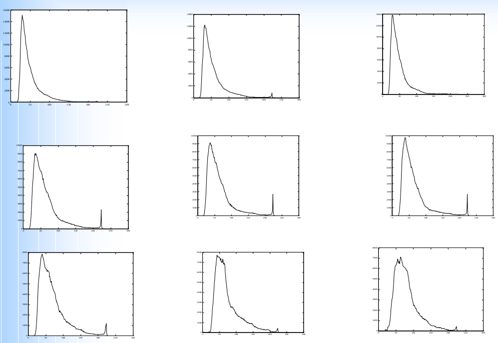


edge image of the blurred image

Application



Histogramme analyse



In Project by 2004

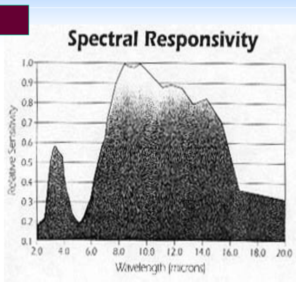
Rotafiltre2 :

Characteristics

- Spectral large band : 200 to 1200 nm
- 20 narrow bands
- Electronic controllable speed
- Time exposure control
- Automatic light calibration
- Reduce blur effect

3. Thermal system

Thermal images acquisition



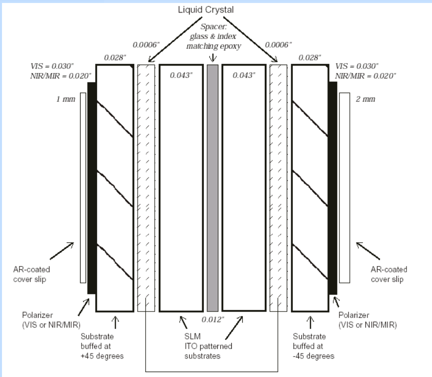
Characteristics

- •Optic : 50mm
  Bandwidth : 8 to 12 nm
- •2 bands of image acquisition
- •Temperature resolution : 0.2 °C
- •Operating temperature : -18 to 523 °C

Problem

- •Difficult to use in the summer season

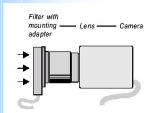
Multispectral system with Liquid Crystal Tunable Filter

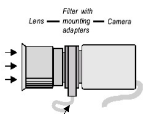


Basic using of tunable filter

Assembling 1

Assembling 2





No problem of optical focussing

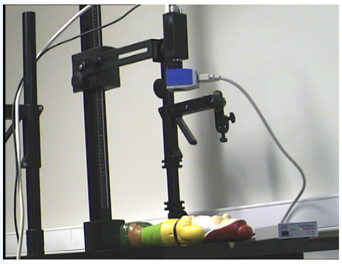
Problem of optical focussing
Due to the changingg of image plan

Basic using of tunable filter

Different elements

Elements assembled

Experimental device using now



A few characteristics

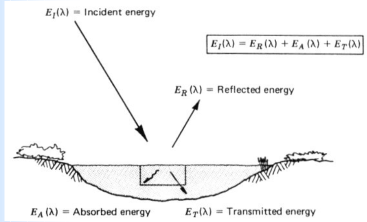
Advantages :
- Non object moving
- No vibration
- Rapid spectral filter changing
- Electronic controllable

Disadvantages :
- Bandwidth gain is less greater
- Non adaptable for small focal length
- Possible creating fringe when using coherent light
- Etc.

Space systems

ALCATEL SPACE (A Roman)

- Energy incident on a surface will be:
  - Reflected, transmitted, absorbed

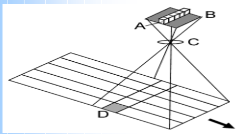


Airborne Imaging Systems

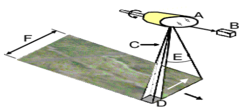
Airborne system

Along Track Scanning systems (pushbroom) – CASI

- have 2 dimensional CCD that builds an image in the direction of the aircraft
  - have better radiometric and spatial resolution – longer dwell time
  - Geocorrection is easier than with whiskbroom type sensors



Pushbroom (CASI)

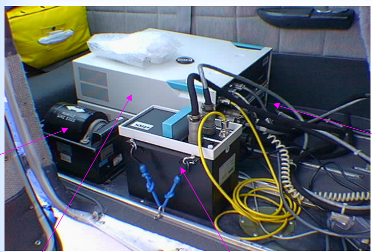


Whiskbroom (AVIRIS)

compact airborne spectrographic imager

=150 000 €

GYRO

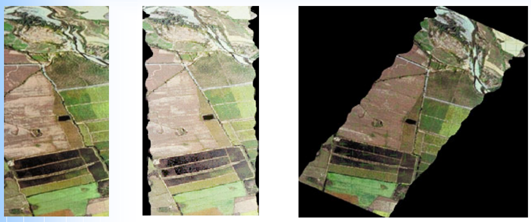


POWER CONTROL

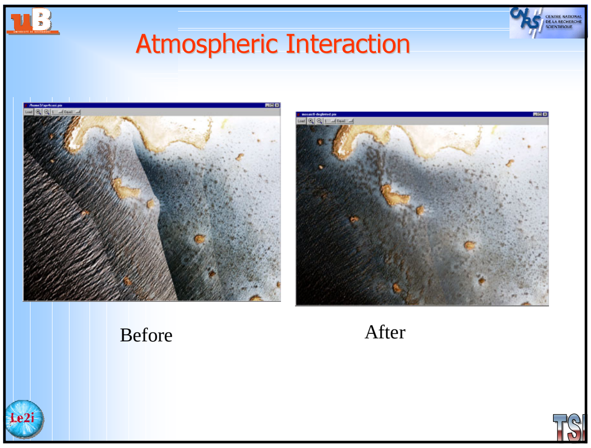
INSTRUMENT CONTROL UNIT

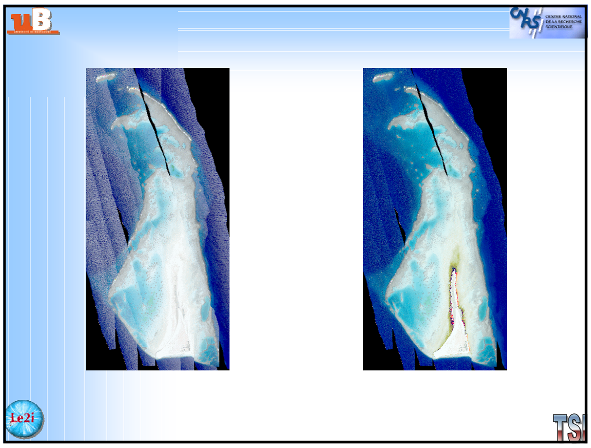
SENSOR HEAD

GEOCORRECTION



Raw Data | Roll Corrected | Geocorrected

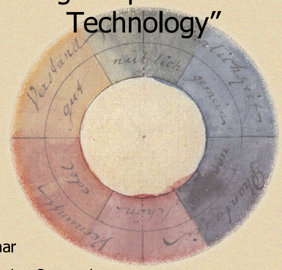

Atmospheric Interaction
Before
After
Le2i


Le2i


THANK YOU
To the organisation team of the
Color Imaging Symposium
For your attention
MERCI BEAUCOUP
Le2i

FOGRA

"Spectral Image Reproduction using Print Technology"



Andreas Kraushaar

Gjøvik Color Imaging Symposium

Nov. 25th, 2003

Agenda

FOGRA

- Who or What is FOGRA?
- "Multispectral World"
- Critical applications
- Current limitations and solutions
- Spectral project at FOGRA
- What the future may hold?

Who or What is FOGRA?

FOGRA

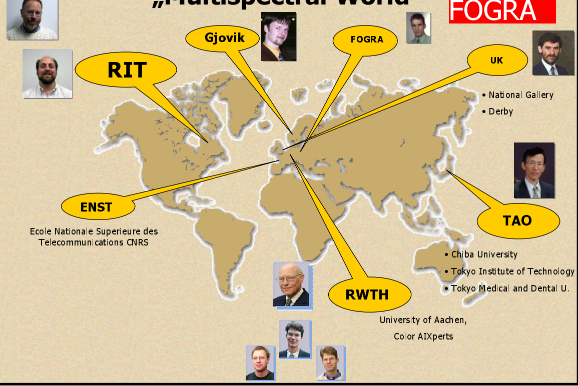
The FOGRA: Graphic Technology Research Association

- Founded in 1951
- is a registered association with about 600 members (about half are graphic arts companies, ranging from prepress to binders, and the other half are suppliers
- operates its own institute in Munich (30 experts)
- Advice and reports based on Research and development
- Knowledge transfer (publications, lectures, seminars, symposia)
- Committee work (standards, ISO)
- Applications for funds, Membership dues, Commercial activities

---

„Multispectral World"

FOGRA

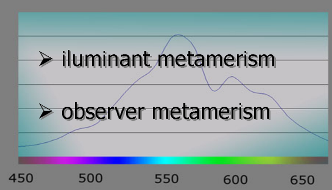


Critical Applications

FOGRA

- ➢ off-press proofing
- ➢ catalogue sales
- ➢ art-book reproductions
- ➢ computer-aided design (virtual product development)

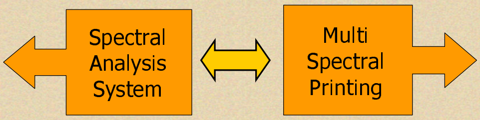
Current Limitations



Solution:
Spectral Match

FOGRA

Optimal ink selection/manufacturing



- coding
- compression
- CIE TC 8-07 (P. Herzog)

Printing models incl. Separation algorithms

Spectral Research at FOGRA

FOGRA

"reducing metamerism for off-press proofing using multi-spectral image reproduction "

goals:
- off-press proofing device with less metamerism
- analytical printing model including separation

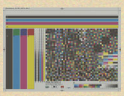
steps:
- collecting representative samples
- set up a 6 or more channel inkjet printer
- mixing inks (dyes) for least metameric match
- developing a printing model incl. separation

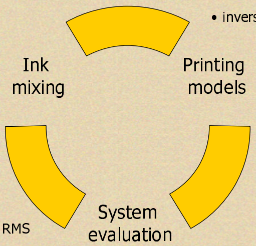
Current Activities

FOGRA

- Ilford, Chiba dyes
- Canon BJC 8500
- Ilford Foto Paper

- modified Neugebauer
- inversion (Jacobi-Matrix)

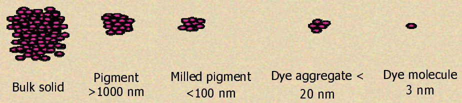


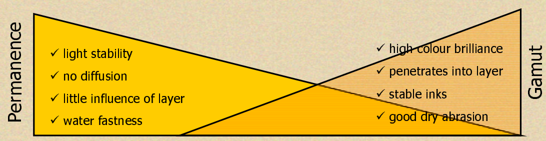


- weighted RMS
- colour difference metrics
- metamerism indices

Pigment vs. Dye

FOGRA

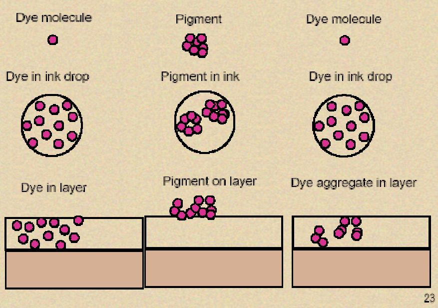




☹ grainy (on film)
☹ lower colour brilliance
☹ prone to abrasion
☹ cost
☹ lower permanence
☹ not diffusion fast

Pigment vs. Dye

FOGRA



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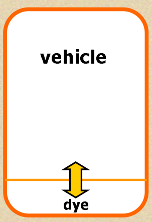
From Dye to Spectra

FOGRA

- inks

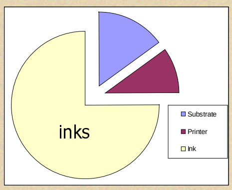


5 – 20 % solvent

0 – 80 % water

additives

Influence on R_λ



- printer (speed, print order, raster algorithm,...)
- substrate

Spectral Synthesizer

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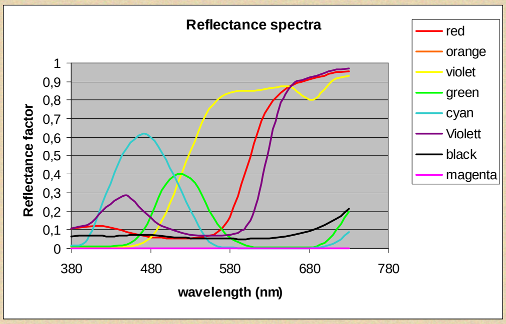

Modifying Concentration

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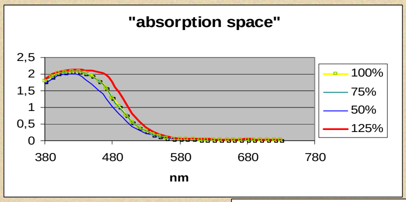
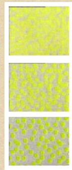
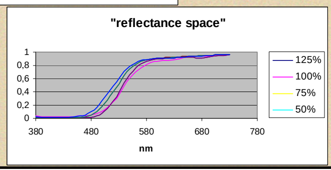




Yellow dye



Printing Model including Separation

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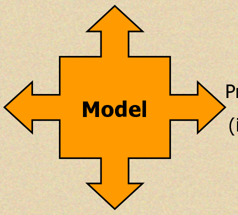
Spectral redundancy

Accuracy



Printing parameters
(ink trapping, print order, optical interactions, ...)

Compact
(few parameters)

What the Future may hold?

FOGRA

- Testing quality metrics
- Setting up a multi-channel inkjet printer (HP, ...)
- Mixing optimal inks for a least metameric match
- Expansion and testing of current printing models
- Printing metamers for testing light sources