Building a Precision Colour Imaging system

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Abstract

The construction of a system that uses CIE co-ordinate, and reflectance curve specified colour imaging as a colour communication tool is presented. Images are stored and manipulated as object hierarchies, with both an intrinsic object colour, and an object colour-set representing surface detail and texture.

Introduction

Colour plays a vital part in the development, marketing, and sales success of a wide range of products. In textile manufacture, it is accepted practice to work to production colour tolerances of less than Delta E 2 (CIE L*a*b*) under three different Illuminants, and colour management systems have been developed in textile manufacture and retailing, which enable both the design and production processes to be controlled to this level [1].

Colour communication systems developed by UMIST have found important industrial applications in the rapid flexible development of new coloured textile products. The Shademaster System [2,3], developed and licensed in the early 90s is credited with reducing lead times by up to six months for the development of new colour ranges for textile products, and bringing them into mass production.

Precise Colour Communication

Two key developments enabled the visualisation and communication of a large gamut of precise colour specifications in the Shademaster System. The first of these is the calibration of a computer monitor screen, so that it can be driven by, and will accurately reproduce colours to CIE specifications. This system has been shown [4], to give on-screen colour reproduction of in-gamut CIE specifications to better than Delta E 1 (mean) CIE L*a*b* D_{65} 10 Deg. Observer colour difference, across the monitor gamut. Exhaustive testing has shown a worst case Delta E of less than 5 [4]. The calibration system requires at most 30 calibration points out of the infinite CIE gamut, and can be run in under five minutes [5].

The second major advance in colour communication was the use of both measured and synthetic reflectance curves to communicate full colour specifications digitally [6]. This method is now regularly used to transmit production colour specifications to remote production units. At the receiving site the reflectance curve is used as input to a local colorant recipe formulation computer system, which reproduces the desired colour to Delta E 1 or better under multiple illuminants (i.e. a close reflectance curve match).

Precision Colour Imaging

Having put in place the essential elements of colour communication, the UMIST Colour Communication Research Group has addressed the problem of modelling the complex surface texture of textile materials. This required the development of computer systems to capture, store, process, and analyse CIE specified colour images typically at 3000 X 2000 pixel resolution, often derived from 24 bit RGB originals.

The objectives are

1. To enable early prototyping decisions to be based on photo-realistic and colorimetrically accurate images of potential products and product colours.
2. To enable 'CAD conferencing' in close buyer-supplier partnerships, and across supplier production sites.
3. To add surface texture simulation to the colour communication process, without sacrificing precision of colour specification.

Building The System

The paper describes and illustrates the building, testing, and verification of the key components of the working prototype Imagemaster demonstrator system.

The essential elements of Imagemaster can be summarised as follows :-

1. A calibration system capable of reproducing any colours that lie within the current gamut of the computer monitor, to within a mean tolerance of 1.0 delta E (CIE L*a*b*) [7].
2. Colour communication systems capable specification and bi-directional translation of colour definitions at all levels from full spectral reflectance at 1nm intervals or better, through illuminant/observer specific colour co-ordinates including L*a*b*, XYZ, LCh, etc. as specified by the CIE [7] and others. The system also provides dynamic, variable calibrated transformations to device specific co-ordinates such as RGB, CMY, etc.
3. An image capture system capable of up to 3000 X 2000 pixel resolution in 24 Bit colour, which is used to image detail of structure down to the 20 Micron level in close-up, full fabric texture at 1:1 magnification, and full garment images on models.
4. A system for converting captured images into CIE specified colours, storing and analysing them into hierarchies of logical objects based on colorimetric and spatial parameters.
5. A system for mapping single spectral curve defined intrinsic object colour definitions, into colour-sets representing the light, shade and textured appearance of the object (1:Many) mappings.
6. A system for displaying images, as they would appear under a wide range of illuminants, either of existing objects in new colours, or of synthesised objects, .
7. Colorimetrically faithful hard copy output to illustrate the CIE specified product colours agreed.
8. Full visualisation of available production colour gamut limitations, and texture effects using spectrally specified master colour definitions.

The system components

The key functions of the system are the visualisation, modification, communication and management of CIE and reflectance curve specified colour images.

The central feature is a data type that can be passed around the system to support a single instance of a colour. The elements that comprise this data type are provided to reduce the time it takes to process information from the core colour definition, specifically its :-

Identifier.

Base colour definition (reflectance curve).

Full CIE co-ordinate data under current operating illuminant and observer.

Backup colour definition (to support single instance undo function).

Device and normalized RGB under current operating illuminant and observer.

Inverse (logically opposite colour) CIE specification, under current operating illuminant and observer.

Visualisation

A vital element in the correct visualisation of CIE co-ordinate specified colour, is ‘ colour in context ‘.The default display environment used is a simulation of D_{65} illumination in a standard light matching booth. Alternative environments can be constructed on-screen, and any alternative illuminant used which has a known spectral power distribution (SPD).

An important principle is the elimination of windowing features from the field of view during colour judgement. Information screens and tools are only displayed and accessed (from pop-up menus) as and when required.

The system has been tested both industrially and in the lab for visual match quality between physical samples in the matching booth, and the on-screen simulation of the measured CIE co-ordinates. The quality of visual match is rated high enough to communicate an accurate visualisation of a measured CIE colour specification under a range of alternative illuminants [1,3].

It would be a relatively simple process, to implement one or more of the new colour appearance formulae such as RLAB or Hunt's model to modify the displayed colour. The authors have decided to implement only CIE L*a*b*, as a stable widely accepted model, with good performance.

CIE L*a*b* does not simulate colourfulness effects attributed to light intensity differences, or colour in context effects. In the Imagemaster system, these are controlled and minimised by

1. Controlling the light intensity in the light matching booth
2. Presenting colours in a visual context which closely simulates a ' virtual illuminant ' of the correct colour.
3. Using visually realistic images of surface texture
4. Setting all colours in the appropriate context spatially.

Modification

Single colours, and colour libraries can be built up from direct measured instrumental input, numerical colour data input and manual / visual colour selection. The colour modification tools pay particular attention to the properties of colour space, and use intuitive techniques to locate colours in colour space. Internal functions convert 2D mouse input co-ordinates into colour space data and visa versa. This provides a seamless method of converting the mouse press in a colour bar or diagram to a CIE specified colour.

When new colour (CIE) co-ordinates are generated, a synthetic spectral curve is also generated and used as the master colour definition. Alternatively a spectrophotometer, interfaced and controlled by the system can be used to generate the reflectance curve, if a physical sample of the colour is available.

User interaction with colour definitions

For all active objects in a screen simulation, a window providing feedback on the colour data is available, both in CIE co-ordinate form and as spectral data. This includes graphical data on the selected object(s) spectral curve(s), making it easy to study the difference between selected objects and colours. If more than one object in the system is selected the colour difference between each is displayed (using a range of difference equations).

Colour Management in the System

In excess of 1 million colours are frequently used, and logically grouped as an on-screen object simulation. A method of storing and managing coloured objects, and colour ways is provided. The system also has a range of display and re-ordering functions for objects. Flexible modules allow large numbers of objects to be manipulated simultaneously, and laid out automatically in the on-screen simulation allowing the build-up of complex colour judgement environments. This allows the system to be used in colour database applications (with no limit on the number or type of objects) as well as in the colour CAD function.

All the general files in the system such as illuminant data, observer data, and input device configurations can be loaded into a modular flexible system configuration format. In future versions the whole system should be able to react flexibly, for example, allowing a user to transmit an illuminant to a another system.

The advantages of using calibrated colour images

There are a number of important consequences following the adoption of CIE specified colour, for image definition and processing.

1. It becomes possible (and necessary) to define simulated colour by reference to input measured colour specifications, and also to compare the on-screen simulation with the physical samples originally measured.
2. It is possible to visualise remotely generated colour specifications and texture simulations.
3. Intrinsic colour differences, and internal colour relationships within images can be captured analysed and used to simulate and define known textures.
4. It has been shown that internal colour relationships are preserved to a great extent, when image colour-sets are moved as a body within CIE L*C*H* or CIE L*a*b* colour space. It is thus possible to move an entire image colour-set quite a long way inside 3D colour-space, thus recolouring the object without losing correct and reproducible appearance. This is illustrated with textile, skin tone, plastics and cosmetic examples.

5. CIE based colorimetric analysis is demonstrated as a very powerful method of abstracting logical object hierarchies from images, for gamut limit handling, and also for advanced colour reduction strategies.

On the debit side :-

Preservation of internal colour-set relationships can easily cause high chroma set-members to pass outside of the gamut limit for reproducible on-screen colours. The image definition remains valid, and no information is lost, but the on-screen simulation needs careful optimisation to give an acceptable visualisation. An out-of gamut colour optimisation algorithm has been established for Imagemaster, which preserves the precise Hue of each out-of-gamut colour, and maps it onto the nearest available gamut limit colour.

Exact visual matches between physical samples, and screen simulations with the same CIE specification are only possible provided ambient lighting is carefully controlled, and the physical sample is viewed in a lighting booth which has both correct light intensity to match the screen, and also the correct colour temperature and spectral power distribution.

For optimum benefit precision colour imaging is best used as part of an overall 'precision colour culture', in which all colours are habitually measured and managed by reference to the CIE system.

Calibration

Without calibration, the colours displayed by computer monitors are indeterminate. Typically, the colours seen relate approximately to the three CRT RGB values and resulting gun voltage levels. Because of the intrinsic variation, two monitors, even samples of an identical model, will rarely have the same visual colour when asked to reproduce a given set of RGB co-ordinates.

Colour calibration is handled by the UMIST Adaptive Driver system [5], which maintains a dynamic mapping between screen RGB drive values and CIE XYZ co-ordinates, based on feed-back measurement of screen colour using a Minolta CA100 colour analyser under system control. The CRT analyser is used to feed displayed CIE co-ordinates back to the calibration software allowing a unique mapping to be built between independent CIE co-ordinates and device RGB co-ordinates. A typical calibration process takes approximately three minutes and uses eighteen main calibration points out of the infinite CIE gamut.

Long term exhaustive trials have shown that across the monitor gamut, the system is capable of reproducing CIE colour specifications to within an average of 0.5 delta E (CMC 2:1). The largest errors occurring at the gamut limits, where gun quantisation is at its greatest. Table 1 below illustrates the mean reproduction errors after sampling at five degree hue intervals. For each hue interval, all possible combinations of Chroma and Lightness based on reproduction of CIE specified colours at five unit intervals of L C and H^o, up to and including the gamut limits.

Co-ordinate Set	Min Error (DE CMC2:1)	Max Error (DE CMC 2:1)	Mean Error (DE CMC 2:1)	Mean differences h c l	number of Samples measured
Example Hue page ($H = 30^o$)	0.025	1.348	0.487	0.658 0.794 0.097	1908
Full set of 72 Hue pages	0.01	1.969	0.484	0.650 0.792 0.148	124,968

Table 1. Monitor screen calibration performance.

Full data for all 72 Hues is available from the authors.

Colour Communication

A generic colour specification system has been developed in software that is capable of defining any colour as its spectral reflectance data, its CIE colour co-ordinates and its current device reproduction co-ordinates.

Reflectance data is supported at any resolution from one nanometer interval down to 20 nanometer interval data. Typically, ten nanometer data is used in keeping with common practice within the Textile industry.

Colour co-ordinates, either defined by the CIE or others such as Hunter [8], Luo [9] etc. are held as reflectance curve colour definitions. Device reproduction co-ordinates such as RGB are maintained on a transient basis, and are necessarily updated whenever a calibration occurs.

A full bi-directional translation system has been developed, allowing the translation from spectral data to CIE colour co-ordinates under any given or desired illuminant and observer conditions [7,8,9,10], accurate translation from colour appearance co-ordinates to device co-ordinates is achieved using the mapping derived from the current calibration state. These two translations are relatively simple many-to-one mappings, whereas the inverse translation is less well defined.

Translation from a device co-ordinate to CIE co-ordinate is achieved by reversing the mapping derived by calibration. This inverse function maps a single device co-ordinate onto an infinite number of CIE colour co-ordinates between close bounds in each dimension, since systems such as the CIE are inherently analogue. By contrast, the device co-ordinates change in integer steps. This means that translations such as CIE L*a*b* to RGB to CIE L*a*b* are not fully reversible due to the quantisation of RGB, in practice however, the quantisation steps are small enough to avoid any visually perceptible errors, particularly as colours tend to lie away from the gamut limits.

Translation from a colour co-ordinate specification, to spectral data is similarly a one to many mapping, with an infinite number of spectral curves that will generate the same CIE colour co-ordinate definition under given lighting and observer conditions. Therefore a translation such as spectral data to CIE XYZ to spectral data will normally generate a different curve to the original. The two colours are a metemeric pair, and have the same apparent colour under the illuminant and for the Observer used to calculate the CIE XYZ specification. Several spectral curve synthesis algorithms are employed by the Imagemaster system, generating colours with slightly differing spectral properties. The choice of generator depends on the application, with a default that is aimed towards the textile dying application.

Image capture

A wide range of scanners, video, digital, and photo-CD imaging methods have been investigated.

Any useful system must -

1. Not introduce significant colour artefacts into the image.

2. Have a good dynamic lightness and colour range to avoid compressing either highlights or shadow detail.

3. Have adequate detail resolution.

4. Be at least colorimetrically stable, (if not colorimetrically accurate), and linear or at least smooth and locally near linear in response, preserving intrinsic intra-object colour differences.

This is a tough specification and there is no current digital camera offering that meets it, no matter what the price. The chief problems are lack of dynamic range, poor blue-end spectral response, generation of colour artefacts, and exposure related colour instability. They can be made to take pretty pictures, but they are not intended for use as colorimetric image capture devices .

Flat bed scanners suffer from depth of focus and colour artefact generation problems (with the possible but untested exception of one very expensive example). Video camera technology has been found to be potentially useful, but careful testing for colour artefact generation is important.

Conventional photographic imaging using professional quality low speed colour slide film, and a conventional camera with a high quality lens, are currently used. In the development programme the images have been digitised using the Kodak photo-CD system, which has been shown during the development of Imagemaster to be reasonably free of colour artefact generation. The dynamic range of correctly exposed professional film stock, and its colorimetric linearity and stability are encouraging. As a result good quality images are demonstrated, which have been captured and processed satisfactorily in Imagemaster.

Image Storage

Once captured, images are translated into individual image pixel CIE LCh co-ordinates using the current calibration state, and are thereafter independent of both device resolution, and device colour reproduction variables.

Images are stored in such a way as to make non contiguous object components simple to manage and reproduce, this is vital in the lace industry where the holes between the yarns are as important as the yarns themselves. The Imagemaster storage method allows lace and any other images to be stored as a logical component hierarchy. Each component can then be re-coloured or moved independently, as there are no limits to either spatial or colour co-ordinates imposed on the image format. The only factors governing visualisation on-screen are the gamut, resolution, and spatial size of the reproduction system. Images are not limited by these factors, and may be both larger than the screen, and / or of higher resolution. The reproduction system however typically maps the appropriate part of the image, into the physical (on-screen visual) domain.

In areas, such as lace and printed fabrics, each of the individual logical colour groups within an object or environment, are stored independently, enabling efficient re-coloration and simulation. The spatial nature of the image storage method also allows inherently multi-layered scenarios such as translucency to be built up on screen from the bottom up, with each element overlaying the previous ones, this also enables several colours to occupy the same physical location on-screen, with only the topmost colour visible until they are reordered. The colour and hierarchy order are easily changeable to offer instant new design concepts, without the need for producing sample products. In the textile field, such prototyping is both expensive and time consuming.

Image Colour Sets

Image-object colour-sets are a vital core concept of the Imagemaster system.

The system maintains a simulation, which represents a complex image containing tens to hundreds of thousands of colours. These are grouped as a small number of logical objects, each of which can be re-coloured independently and efficiently. A mapping algorithm has been developed, between the intrinsic object colour, and the several thousands of colours making up a logical object / component of the simulation. In the textile industry applications, that single colour should ideally be the exact production colour specification that is sent to a dye house, printer, chemist etc.

Central to Imagemaster, is the algorithm that relates an intrinsic object colour to the colour-set representing its surface texture. In practice this intrinsic colour is the colour measured by a typical large aperture bench spectro-photometer. Extensive observer trials are under way to verify the visual match quality of a wide set of texture colour-sets against equivalent intrinsic measured colours. Typical observer trials involve asking a set of observers to match a patch of the plain colour to the complex coloured component and indicate the quality of the representation in terms of standard difference pairs [11]. If observers indicate other than a perfect match, they are asked to correct the plain patch until it is a close match. This gives a quantitative error that can be used in optimising the algorithm.

Dying trials are also being undertaken, in which images of lace are being colorimetrically adjusted to a series of alternative colours on screen .The reflectance specification generated is then sent to the dye house for dyeing. The dyers may have only the numbers to work with, and be unaware of the appearance of the colours on the screen. The results of these dyeings are then compared in observer trials with the on screen specification and corrections made as described previously.

All the single intrinsic colours are stored as a full reflectance data definition, whether measured or synthesised. This becomes the specification for the given object component, and is unaltered through all subsequent simulation, until a new colour is required for that component.

Multiple Illuminant Simulation

Because all colours within an image are either stored as reflectance data or can be translated into reflectance data, it is possible to simulate any colour or image as it would appear under any illuminant. This is very important in the textile industry where garments bought under shop lighting will be worn under either daylight or domestic tungsten filament light bulbs. The colour appearance must be predictable under all such conditions to enable informed design choices. This is particularly important where garments are sold that are usually matched to other garments not necessarily bought from the same supplier, garments that match under one illuminant may look quite dissimilar under another. The simulation of colour appearance during the design stage, and flexibility of synthetic spectral reflectance curve generation allow colours to be designed that are stable across common illumination conditions, thereby reducing the risk of garment miss-matching.

Gamut limitations

The gamut of real colours (the eye's colour response gamut) is different to that of CRT monitor display gamuts. Many real colours have CIE specifications that are outside the gamut of reproducible monitor colours. This is further complicated by the fact that printers and dyes have different overlapping gamuts.

It is therefore necessary to map any colours that are outside the gamut of the monitor into it so that they can be simulated. Any such mapped colour will necessarily be displayed with an incorrect CIE co-ordinate, however it is often better to indicate the approximate colour than not to show the colour at all.

The Imagemaster system currently employs six alternative gamut mapping strategies, two of which simply indicate that a colour is out of gamut by showing a false colour to avoid critical decisions being taken based on incorrect visual judgements. A third method simply clips the device co-ordinates at the edge of their gamut. This is useful for rapid prototyping, but displays colours that are often visually very incorrect.

The three more useful algorithms for indicating the desired colour all maintain the correct hue of that colour. This is because any shift in hue is immediately detectable by the human eye. They adjust the lightness and chroma content of the colours in varying proportions to allow a similar colour of the correct hue to be displayed. The choice of method is dependant on the application with a default method that is applicable to most applications.

The Imagemaster Demonstration System

The slides presented in the lecture represent a wide range of features of the demonstration system, which runs on a Silicon Graphics Indy workstation, with 128 Mb of main memory, MIPS R4000 100 MHz processor and a 9 Gb hard disk drive for Image and code storage and retrieval.

All the colour transformations are verified to ASTM and CIE Publ. 15.2 standard calculation methods

The whole system is programmed in ANSI standard C++, using Open GL , and X-Windows libraries.

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