Color Reproduction—Past, Present and Future

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Abstract

A survey is given of the paths by which additive and subtractive color reproduction in photography, television, and printing, have led from their early beginnings to their present states. The outlook for the future in each field is reviewed.

Introduction

Henry Ford may have said 'History is bunk', and, if excessive pre-occupation with the past retards innovation, its study may be regarded as harmful. But the routes by which our modern systems of color reproduction have reached their present positions are certainly interesting, and may well provide some pointers for the future. Hence, a study of the past, present, and future, seems to be a worthy exercise.

Spectral Color Reproduction

To reproduce the same spectral power distributions in the picture, as in the original scene, is the only way to avoid metameric disturbances caused by changes in illuminants and observers. It is therefore a desirable aim in some applications, such as mail-order catalogues. Early methods of achieving spectral reproduction included the Lippmann interference method, which was quite widely used at the beginning of this century. In the printing industry, more than three colored inks are sometimes used to extend the reproducible color gamut, and closer approximations to spectral reproduction may then occur. But, in general, color reproductions are *trichromatic,* seeking only to obtain the same responses in the three different types of cone in the retina, rather than to reconstruct the same spectral composition.

Electronic Cameras

Early electronic cameras for broadcast television depended on the use, with dichroic beam-splitters, of three tubes of the types used for monochrome television. The introduction of the Plumbicon type of lead-monoxide tube, with its low dark current, stable operating characteristics, and compact photo-cathode, improved the performance, and reduced the size, of three-tube cameras very considerably. For a time, some use was made of four-tube cameras, resulting in separate luminance, and red, green, and blue, signals; but, because of complications resulting from gamma-correction, and because of the development of automatic registration devices for cameras, four-tube cameras are not widely used now.

The development of light-sensitive charge-coupled devices (CCDs) has led to color cameras that are even more compact than those using Plumbicon type tubes. CCD arrays can be used either in triplicate, with dichroic beam-splitters, or with a regular array of red, green, and blue filters over a single array. Alternatively, a single beam-splitter can be used with a monochrome CCD array to give the luminance signal, and a red-green-blue array to give the chrominance signals. CCD arrays are widely used in camcorders for consumer use and for electronic news gathering, and they are also used in electronic still cameras for newspaper work and for studio catalogue work. The resolution of CCD sensors is set by the number of their pixels, and their cost rises steeply as the number of pixels required increases and as the number of allowable defective pixels decreases towards zero. The number of pixels required is about 100,000 for camcorders, about 400,000 for broadcast television, about 2 million for high-definition television, and about 8 million for high quality still pictures. These numbers are for each color, so that for red-green-blue arrays the numbers may be three times as great.

Additive Displays

Additive trichromatic color displays started in 1861 with Maxwell's demonstration of triple projection at a Royal Institution Discourse in London. His triple projection method is still used in projection television displays (as often used in lecture theaters and for in-flight movies in aircraft); but it suffers from the disadvantages of requiring elaborate equipment, being sensitive to mis-regis-tration of the three images, and usually producing screen luminances which are only just adequate. The registration problems can be alleviated, and greater optical efficiency can be achieved, by using dichroic interference mirrors to split the light from a single source into its red, green, and blue components into which three separate light modulators are inserted. These modulators can be liquid crystal displays (LCDs), in which the light between two crossed polarizing filters has its direction of polarization changed as a function of signal voltage. Three more dichroic mirrors then recombine the three beams for projection through a single lens. Higher screen luminances in all of these systems can be obtained by using back-projection, especially if use is made of highly efficient screens that limit the spread of the light in the vertical direction to the likely viewing angles. Higher screen luminances can also be achieved by using one of the various forms of light valve projector (such as the Eidophore, the Talaria, or the Digital Mirror Device).

Much ingenuity was shown in the early days of color television to produce satisfactory display devices as alternatives to triple projection; such devices included the following. Virtual images were superimposed using dichroic mirrors (as in the Trinoscope), but this suffered from many of the same disadvantages as triple projection. The red, green, and blue images were displayed in rapid time sequence (the field sequential system), but this suffered from waste of light in the display filters, and in being incompatible with monochrome displays; however, the principle has been revived recently in one form of the Digital Mirror Device without resulting in incompatibility.

The complexities of triple projection, and these other systems, have led to the development of display devices that are more simple and less costly. Leaving aside for the moment the subtractive methods, the other type of display device that is most widely used is the mosaic, in which small areas of red, green, and blue are viewed from a distance such that the individual areas cannot be resolved by the eye, so that the red, green, and blue light is added together just as effectively as in triple projection. Additive mosaic systems were widely used in photography until the 1930s, the best known processes being Autochrome (which depended on a random mosaic of dyed starch grains), and Dufaycolor (depending on a regular array of areas of dyed gelatin). A revival of the additive mosaic method in photography occurred in the 1970s when Polaroid introduced their Polavision process for instant movies and Polachrome process for instant slides. However, in photography, the red, green, and blue colorants inevitably result in the loss of at least two-thirds of the light, and this reduces the attainable screen luminances and prevents their use for reflection prints. The presence of the mosaic also limits the resolution. Photography has therefore gone over almost entirely to the subtractive method.

In television, when the picture is produced by eletron-bombardment of phosphors which produce either red, green, or blue light, there is no loss of light because there is no need to use colored filters; and because television systems have an upper limit to their resolution set by the line standard, it is only necessary for the mosaic to reach this limited level of resolution. Furthermore, because television is usually used to display moving images, the production of reflection prints is not normally a requirement. For these reasons, the mosaic method is much more appropriate for television than for photography, and is the method used in very many television display devices.

By far the most widely used display device for television is the shadow-mask tube, in which the red, green, and blue images are produced by the separate modulation, in a single evacuated enclosure, of three electron beams, each of which is arranged to land on phosphor dots or stripes that produce only one of the three colors.

The formidable problems of reducing this concept to marketable practice were solved by years of intensive attention to design and manufacturing details. The main disadvantages of these devices are their bulk, weight, and electrical power requirements.

The alternative to the shadow-mask tube which has been most successful so far is the liquid crystal display (LCD) device; arrays of liquid crystal cells are covered with a regular pattern of red, green, and blue filters to provide color displays. In this case, there is again loss of light in the filters, and this, together with the losses in the polarizing filters and by the electrodes in the cells, results in overall transmittances which may be less than 10 per cent. But, by using back light of high efficacy, such as triple band fluorescent lamps, panel displays of adequate luminance can be achieved. Color LCD units can also be used on over-head projectors, and high-wattage tungsten-halogen lamps or mercury-halogen discharge lamps can be used to increase screen luminance.

Subtractive Methods

Subtractive systems of color reproduction were forecast in remarkable detail by Du Hauron in 1868, but it was not until the early 1930s that Technicolor produced three-color subtractive-dye films, and not until 1935, with the invention of Kodachrome by Mannes and Godowski that a commercially successful tripack (in which the three images are exposed and processed in three emulsions coated on a single support) was achieved; and this delay occurred in spite of the process of color development having been described by Fischer as long ago as in 1912. The problems that had to be overcome included: preventing the sensitizing dyes in the three layers from wandering from their proper locations both before and during processing; and forming the three differently colored images in the three different layers. To achieve the latter objective, the original Kodachrome process involved a very complicated sequence of controlled diffusions, but in 1938 this was replaced by using differential re-exposure of the three layers. Incorporation of the dye-image formers (the couplers) in the three layers became feasible with the inventions, in 1936, of long-chain couplers by Wilmanns, and, in 1939, by their dispersion in oil droplets. The successful operation of a negative-positive system was greatly facilitated by the invention of colored couplers by Hanson in 1943. In later years the quality of color reproduction in photography was enhanced by the extensive use of inter-image effects, in which the amount of dye formed in a layer depends not only on the exposure in that layer but is also decreased to a controlled extent by increasing exposure in another layer.

The widespread commercial success of subtractive color photography, however, required not only the means to produce good quality pictures, but also to do so at a price and with a consistency that would satisfy the customers. This was largely achieved through two inventions in engineering: in 1946 Evans conceived the idea of automatic printing dependent on making pictures that approximately integrated to gray; and in 1956 Russell invented the suction slide hopper method of coating multi-layer films in single passes past the coating station.

In television, the subtractive principle has not been used until very recently when a subtractive liquid crystal display device has been marketed.

Digital Systems

Broadcast television is now set to enter a digital era in high definition systems, and CCD sensors, with their spatial digitization of the image, are being increasingly used in cameras, not only for television but also for still picture capture.

The preference for reflection prints as display devices has provided a strong impetus for the field of desk-top publishing, and both continuous tone and half-tone systems are in use, as well as hybrid mixtures of the two. The display technologies include using photographic film or paper, color electrophotography, dye diffusion thermal transfer, wax transfer, and ink jet. Photo CD provides the means for capturing images on film cameras, with their advantages of simplicity and low cost, and converting the images to digital electronic signals, with their advantages of flexibility and ease of transmission.

The Future

I believe it was Mark Twain who said that forecasting was always difficult, especially if it involved the future! So what will be the pattern of the future in color reproduction? Here are some guesses.

Reference

1. R. W. G. Hunt, *The Reproduction of Colour,* 5th edn., Fountain Press, Kingston-upon-Thames, England (1995).

Image Capture

	Advantages	*Disadvantages*	*Best Markets*
Film	Low cost Reliable High quality Compact Efficient use of light Large dynamic range	Delayed access Not reusable Wet processing	Amateur still Television
Electronic	Instant access Reusable record Computer friendly	High cost Inefficient use of light by filter arrays	Television Amateur movies Professional studios

Reflection Prints

	Advantages	*Disadvantages*	*Best Markets*
Photographic Paper	High quality Fast printing	Medium cost Wet processing	Amateur still
Electrophotography	Low cost materials	Slow printing	Photocopying
Dye-diffusion thermal transfer	High quality	High cost Slow printing	Proofing Low volume printing
Ink Jet	Low cost	Quality variable Slow printing	Desktop publishing

Television Displays

	Advantages	*Disadvantages*	*Best Markets*
Shadow-mask tubes	Existing technology	Small pictures Bulky and heavy	Consumer
Triple CRT Projection	Large pictures	High cost Low luminance (without back projection) Registration	Large Audiences
Liquid Crystal Displays	Flat	Limited resolution	Small displays projectors
Plasma Displays	Flat Large pictures	High cost at present	Consumers