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COLOUR TELEVISION CAMERAS— THE DESIGNER'S CHOICE

In early 1964 there were clear indications that, not only was colour television gaining rapidly in the United States, but that the introduction of a colour service in several European countries was imminent. Although the failure of the C.C.I.R. conference in Vienna to agree on standards has caused delay in some European countries, the long struggle to obtain public acceptance in the United States has now been won, and in Canada also a colour service has been authorized.

With the clear emergence of this situation at the beginning of 1965, The Marconi Company embarked upon a major programme designed to evaluate the various types of camera which have been proposed, and to decide which type would best fulfil the operator's requirement. The following article sets out to describe how this process evolved, and on what grounds the eventual choice was made.

JUST AS THE ADDITION of the third dimension multiplies out of all proportion the number of possible ways of fitting several objects into a given space, so the dimension of colour greatly increases the number of different configurations possible for a television camera. To complicate further the problem confronting the designer, he has not only to consider the multiplicity of physical configurations open to him, but also the number and types of camera tube which he should use and the degree of operational flexibility he should offer.

To put the various factors governing the choice of camera into some sort of perspective it is helpful to list them in approximate order of priority, approximate because opinions are bound to differ to some extent according to the particular standpoint adopted.

FACTORS GOVERNING THE CHOICE

Performance and Reliability

Under this heading must be considered all those factors which now apply to black-and-white television cameras, for example resolution, grey scale, picture geometry and linearity, freedom from noise and smear and, last but not least, stability which is absolutely essential in maintaining a high standard of operation in colour. In addition, we must consider colour fidelity and accuracy of registration, factors which relate specifically to colour cameras. It is of course important to remember that these factors must be assessed in relation to both the colour and to the compatible black-and-white picture.

Operational Flexibility

Having established that the camera should have adequate performance, it is next necessary to ensure that it will be suitable for all normal applications, both in the studio and outside. The criterion here is that it should approach as nearly as possible the degreee of operational flexibility offered by the modern black-and-white camera. Also, bearing in mind the inevitably higher costs involved in colour operation, as much as possible of the design should be suitable for use as either a live or a film camera channel. This offers considerable economies in the area of operating and maintenance costs. On the same basis it is obviously an advantage if the camera is capable of rapid conversion to black-and-white working at full sensitivity.

Cost

This factor, which includes both capital and running costs, has been placed third in importance because considerations of reliability and stability, vital to high-quality colour television operation, inevitably mean that cost must be commensurate with the complexity of the equipment.

Sensitivity

We are able to relegate sensitivity to fourth place because modern techniques enable the designer to achieve sensitivities little inferior to those required for normal black-and-white studio operation. There is no real question therefore of having to accept light levels considerably in excess of those likely to exist in modern studios.

Size and Weight

This consideration is similar to that in respect of sensitivity, and the provision of a camera of acceptable size and weight is no longer likely to be a major issue in the design.

Immunity to Environmental Conditions

While this factor may be considered as just one aspect of performance, it is perhaps worth singling out since a colour camera, by its very nature, is likely to be far more susceptible than a black-and-white one both to extremes of temperature and to external magnetic fields. Therefore, whilst immunity to environmental changes may not be considered important in most normal applications, it is certainly a factor which must be taken into account in designing a camera for world-wide use. The earth's magnetic field and high local, man-made fields can affect performance unless adequate precautions are taken; also, though studio use is not likely to be affected, OB operation in hot climates (where ample sunshine may prompt earlier introduction of colour) must be considered.

Having established our basis for selection, we must now investigate the various choices open to the designer.

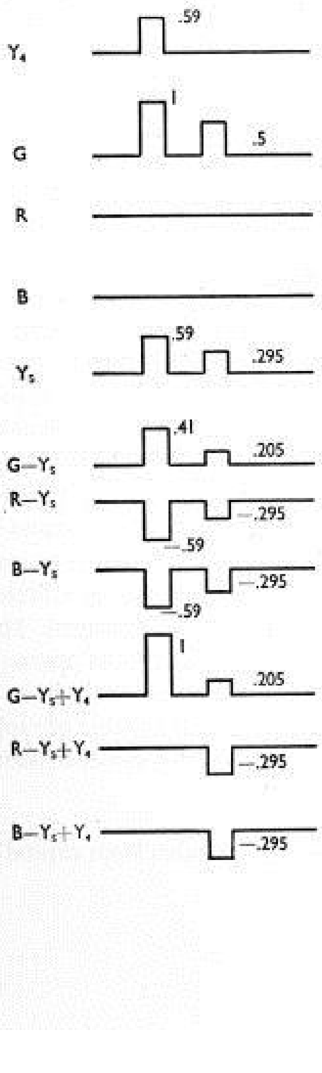

Fig. 1.

AVAILABLE CHOICES

Number of Camera Tubes

In the early fifties the majority of colour television engineers would have prophesied that by the mid-sixties a single-tube colour camera would have been a serious contender in the field. It is not, however, a reduction from three to one that we must now consider but an increase from three to four tubes, one being for luminance and three for colouring. The advantages of four-tube cameras are now widely accepted, for not only is the quality of the compatible black-and-white picture independent of camera registration, but the degree of misregistration which can be tolerated when viewing the picture in colour is considerably greater. The technique of using four tubes offers a further advantage which stems from the fact that redundant information is available at the low end of the video frequency spectrum. Two luminance signals are available: Y_4 from the luminance tube and Y_s, the synthetic luminance signal obtained by adding together the appropriate fractions of the colouring signals.

$$Y_s = 0{\cdot}59G + 0{\cdot}3R + 0{\cdot}11B$$

The overall system is so arranged that, when conflicting information is obtained, the luminance value reproduced in the picture is that obtained from the luminance tube alone. The importance of this property in reducing the objection to colouring tube errors may be clearly seen from the following example (Fig. 1). In this the camera output signals are seen to represent a genuine green highlight followed by a green error signal, for instance a blemish on the tube face. The argument, however, applies equally to the effects of shading, noise, misregistration, ghost images, etc.

Awarding the appropriate luminance factors to the three error pulses, the resulting luminance value of the error is seen to be

$$0{\cdot}59 \times 0{\cdot}205 - 0{\cdot}41 \times 0{\cdot}295 = 0.$$

Although the simple illustration in Fig. 1 assumes a linear system, an accurate analysis with $\gamma = 2{\cdot}2$ shows that relative to the case of the simple RGB camera, the luminance value of the reproduced error is reduced by at least 20 : 1.

In addition to the improved performance obtainable from the four-tube arrangement, the use of a separate tube for the luminance signal also greatly facilitates the rapid conversion of the channel to full-sensitivity black-and-white working.

The Type of Camera Tube

On the basis of the above arguments we need only consider the four-tube camera and the question of tube types may be split into two parts: the type to be adopted for the luminance channel and that for the colouring channels. For the luminance tube of a live colour camera there are only two serious contenders, the image orthicon and the Plumbicon. If we were concerned solely with the excellence of the compatible black-and-white picture our choice would undoubtedly swing to the 4½-in. image orthicon, which has become the acknowledged standard by which tubes for black-and-white operation are judged. It has the undoubted advantage over the Plumbicon that a much wider range of scene illumination can be handled. If, however, linear tracking between the luminance and colouring tubes is to be maintained in the interests of good colour pictures this particular advantage of the image orthicon is of little value, since we must restrict ourselves to the reasonably linear portion of the taking characteristic.

For the colouring channels, we may restrict ourselves, from considerations of size and adequacy of performance, to the various types of photo-conductive tubes now available, the vidicon and the Plumbicon being the best established at the present time. If the designer is to take reasonable advantage of the benefits of four-tube working, he will wish to operate the colouring tubes at a relatively low signal current, and to use a minimum of faceplate illumination. At once we see that we wish to use these tubes under the conditions where the vidicon is at its weakest, firstly because of lag and secondly because of dark current. The Plumbicon, however, is relatively free from both these undesirable features, although it is inferior to the vidicon in another respect, namely the spectral response which is poor at the red end of the visible frequency spectrum. Paradoxically, however, this limitation is less significant in a colour camera than in a black-and-white one. The reason is that we may compensate for the lack of red response by increasing the overall gain of the red channel. The introduction of the necessary compensation by purely optical means, as would be necessary in a black-and-white camera, would be quite impracticable on the grounds of sensitivity.

Considering the overall situation, we see that the Plumbicon has significant merit for both luminance and colouring positions. By adopting it for both functions we obtain the additional advantages which accrue from the use of similar tubes throughout, the problems of accurate registration and of matching the performance in respect of gamma, geometry and shading all being greatly reduced.

Finally, the Plumbicon being a linear tube, the choice of four Plumbicons enables sensitivity to be exchanged for signal-to-noise ratio without upsetting the grey-scale tracking between the luminance and colouring tubes. Maximum advantage may thus be taken of the available ambient light level.

The Type of Optical System

The necessity for forming a number of component images presents the designer with what is probably his most difficult choice, since each particular arrangement possesses its own particular advantages but none possessing them all. The basic choice is between an optical system which is capable of forming the four component images directly, or alternatively a system which forms a single primary image which is relayed to the individual tubes (Fig. 2).

The former system is relatively new, advantage being taken of the fact that zoom lens designers find it convenient to provide a long back conjugate which enables the splitting system to be placed directly between the lens and the camera tubes. When four tubes are employed, however, the maximum conjugate which can be provided is barely adequate, especially where zooms capable of wide-angle shots are concerned. In practice, the four tubes tend to be overcrowded, and it is usually impossible to achieve an arrangement with the four scanning yokes approximately parallel to each other and with similarly orientated images on the four tubes. This is a highly desirable feature where the effects of external magnetic fields are concerned.

Another limitation is that imposed on the maximum diameter of the scanning yokes which also tends to be rather restricted. A further and more significant disadvantage of this type of optical system is that of operational inflexibility, for such a camera can only employ lenses, whether zoom or fixed focal length, which have been specifically designed, not only to have a particular back conjugate, but also to operate with exactly the amount of glass, of the particular refractive index and dispersion, which has been employed in the light-splitting system.

The second alternative of using a relay system completely overcomes this last problem since any standard television lens may be used, the primary image being formed at the standard distance behind the lens. The disadvantage of this technique is the loss in resolution and sensitivity introduced by the relay system. In the four-Plumbicon design this loss may be minimized by employing a primary image of standard image orthicon format, a feature which also makes available a wide range of existing lenses. The greater design flexibility offered by this approach also enables the designer to place the yokes in the optimum positions, and to obtain similarly orientated images throughout.

While the relay optical system is the obvious choice on operational grounds, the choice on grounds of technical performance is not so clear. However, the restricted bandwidth available for the luminance component of the colour signal itself curtails the resolution of the overall system. The loss in sensitivity, estimated at between 10% and 20% or less than a quarter of a stop, is considered to be far outweighed by the operational advantages, and the choice must therefore lie with the relay system.

It is also worth remembering that modern zoom lenses with ratios of 10 : 1 and higher are still relatively new devices, and that by using standard lenses full advantage may be taken of new developments in the field of lens design as they emerge.

Another area in the optical system where a number of different approaches must be evaluated is that of the light-splitting system. Early cameras employed plate-type dichroic filters which tended to produce ghost images and also introduced astigmatism to a degree where bulky correctors were required. The alternative of mounting the dichroic filters in prisms eliminates both these problems, although the change of spectral response with the change of angle of incidence across the field tends to be worse. The defect may be minimized by placing the colouring tubes in a vertical plane, thus minimizing the change of angle over the field, and also by maintaining the angle of incidence with the normal to the dichroic surface as small as possible. Provided these precautions are taken, the advantages of prism dichroics may be considered to predominate.

MAKING THE CHOICE

Space only allows a detailed consideration of the major factors. Over the last few years many possible arrangements have been evaluated in considerable detail. The more significant features of each basic configuration are given in Table 1.

It is never easy to establish an acceptable scale for assessments of this type. To facilitate rapid appraisal of the relative standards of performance against each heading the majority of performance parameters are assessed as VG (Very Good), G (Good), F (Fair) or P (Poor). In a few instances, however, it has been considered preferable to give actual figures. Whether the assessment is given in relative or absolute terms, it is stressed that in each instance the marking is based on design studies carried out by The Marconi Company. To the degree that these were all made by the same design team the relative merits of each arrangement may be considered to be more meaningful than an assessment based on existing designs from teams with differing terms of reference.

THE MARK VII FOUR-PLUMBICON CAMERA FOR STUDIO AND OUTSIDE USE

On the basis of the foregoing design study it was decided to develop a four-Plumbicon live camera capable of using standard I.O television lenses.

Optical System

The minimum size coupled with the optimum disposition of the scanning yokes and tubes resulted in a design using four separate relay lenses, each channel being optimized over the appropriate portion of the spectral band. A feature of the optical system is the combination of the functions of the luminance–chrominance light-dividing filter with the luminance-trimming filter so that, at each individual wavelength, all the light surplus to the requirement of the luminance tube is available to the colouring channels. For black-and-white operation at maximum sensitivity, this same surface may easily be replaced by a fully reflecting surface so that all the light is diverted to the luminance tube. A simple dual-purpose prism enables this change to be made without removal of any of the optical components.

Scanning Yokes

The yokes are fully screened so that, coupled with their near parallel disposition, the effects of changes in external magnetic fields are minimized. The symmetry of the four optical paths resulting in the same image orientation throughout is essential if any benefit of the favourable yoke layout is to be gained.

Table 1

PERFORMANCE COMPARISON		Separate Lens: 3 3-in. image orthicons	Separate Lens: 4½-in. image orthicon plus 3 vidicons	Separate Lens: 4½-in. image orthicon plus 3 plumbicons	Separate Lens: 4 plumbicons	Separate Lens: 3 plumbicons	Integral Zoom: Image orthicon plus 3 vidicons	Integral Zoom: Image orthicon plus 3 plumbicons	Integral Zoom: 4 plumbicons	Integral Zoom: 3 plumbicons
Performance	Resolution	G	VG	VG	VG	G	VG	VG	VG	G
	Registration	F	G	G	VG	G	G	G	VG	G
	Stability	F	G	G	VG	G	G	G	VG	G
	Colour fidelity (inherent in system)	VG	G	G	G	VG	G	G	G	VG
	Colour fidelity (inherent in tubes)	VG	VG	G	G	G	VG	G	G	G
	Luminance fidelity (inherent in system)	F	VG	VG	VG	F	VG	VG	VG	F
	Luminance fidelity (inherent in tubes)	VG	VG	VG	F	G	VG	VG	F	G
	Grey scale tracking	G	F	F	VG	VG	F	F	VG	VG
	Lag	VG	P	VG	VG	VG	P	VG	VG	VG
	Signal noise ratio	F	VG	VG	VG	G	VG	VG	VG	G
	Spurious effects (e.g. shading)	F	F	G	VG	G	F	G	VG	G
Operational	Lens	VG	VG	VG	VG	VG	P	P	P	P
	Adaptation for B & W working	P	VG	VG	VG	P	VG	VG	G	P
	Proportion of channel common to film camera	F	F	F	VG	VG	F	F	F	F
Sensitivity	(See note 1)	350	320	260	230	230	310	250	210	200
Size	Length (in.)	44	27	27	26¼	25	28	28	20	25½
	Width (in.)	21½	16	16	13¼	12½	17½	17½	16	15¼
	Height (in.)	18½	18	18	18¼	18¼	19	19	22½	17
Weight	Pounds (without lens)	330	180	180	160	150	175	175	150	140
Immunity to environment	Temperature	F	F	G	VG	G	F	G	VG	G
	Magnetic fields	P	G	G	VG	G	F	F	F	F

Note 1. The sensitivity figure represents the incident illumination in foot candles required for a scene with a peak reflectance of 60%. The lens aperture is taken as *f*/8 related to the standard I.O format. The figures used throughout these assessments assume average performance for tubes, filters and all other components affecting sensitivity. The use of lower limit values increases the required illumination by approximately 30%, i.e. the sensitivity is reduced by half a stop.

Note 2. The assessment in respect of colour and luminance fidelities is based on the use of currently available Plumbicons. The availability of red-sensitive tubes will naturally improve this situation.

Note 3. The Three-image Orthicon Camera was not seriously considered for the present requirement and the figures included in the table are based on the existing Marconi design, and are primarily included for reference.

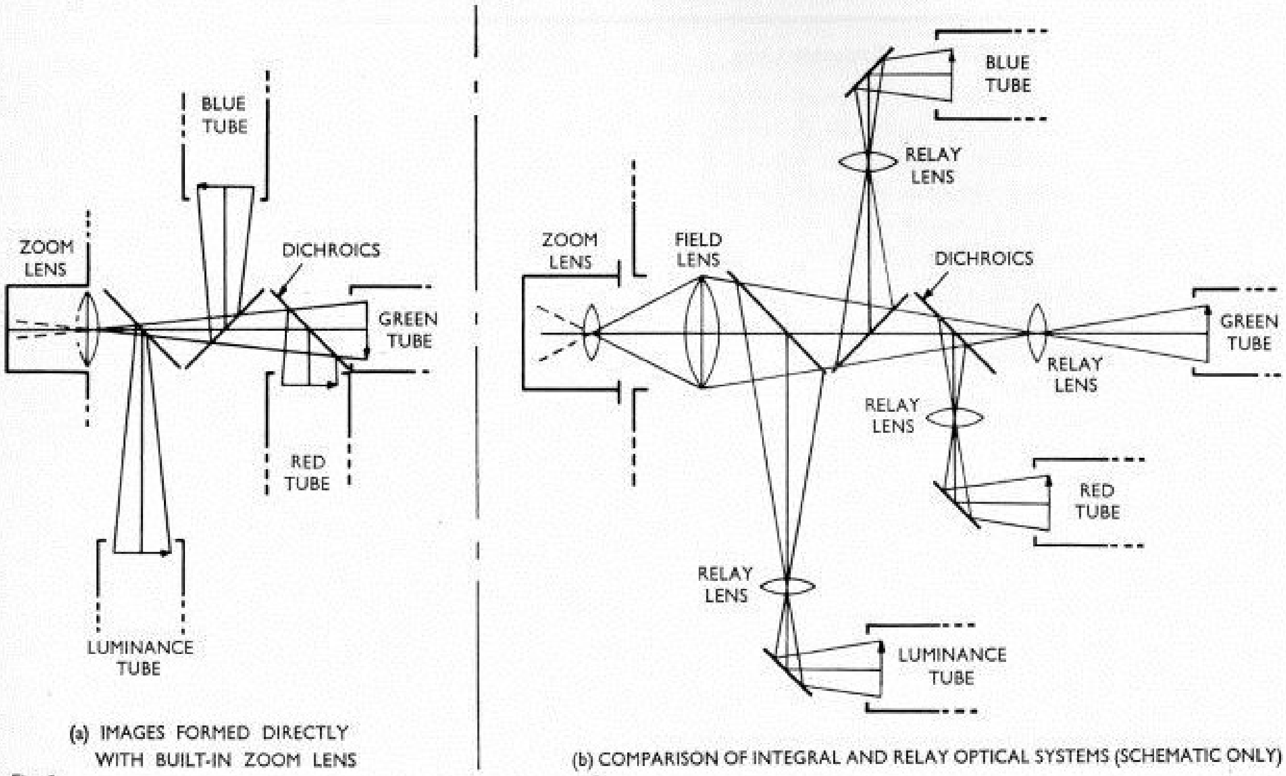

Fig. 2.

Circuit Techniques

For some years the Company have been exploring the possibilities of thin film circuits in connection with television equipment. The majority of work which has been done in this field has largely been in the overall context of miniaturization. The television engineer is not particularly concerned with this aspect, however, although a reduction in size and weight is always welcome if no sacrifice has to be made to achieve it. Early work on thin film circuits suggested that it might be possible to achieve a degree of stability several times better than that obtainable with conventional components. In particular, resistors could be laid down which were for all practical purposes of zero temperature coefficient. The particular attraction of such a property to the colour television engineer is obvious, and it was therefore decided that all critical stages should use this technique. An account of the properties obtainable using thin film circuits appears elsewhere in this journal.[2]

With the exception of the first stage in each head amplifier the entire channel uses only solid-state devices.

The entire channel has been designed for 'hands-off' operation and only those controls normally provided on black-and-white channels are normally provided on the operational control panel.

A full account of the Mark VII Colour Camera Channel appears elsewhere in this issue.[1]

THE MARK VII FOUR-VIDICON FILM CAMERA FOR TELECINE

The increased operating cost in colour encourages all possible economy in design between the live and film camera channels. It was not, however, this aspect alone which prompted the adoption of a design of telecine camera derived simply from the live camera described previously.

Optical Multiplexing

Many of the well-established techniques employed in black-and-white optical mixing systems are not suitable for use with colour systems, either because of poor spectral response or low optical efficiency. For colour the principle of moving mirrors is very attractive on both these counts. In the interests of high operating speeds it is desirable to keep the size of the mirrors at a minimum, and to this end the use of a small primary image, for instance the I.O format which has been employed in the live camera design, is highly attractive.

Optical System

The change of magnification to obtain a vidicon instead of a Plumbicon secondary image is not great and can be simply achieved by relative movement of the field lens, relay lenses and yokes inside the camera. The external multiplexer optical system consists of four moving mirrors, two of which form a cross, providing a total of four outputs. The change is effectively a vertical wipe and taking 0·05 sec. The change between colour and black-and-white is achieved by sliding a single prism inside the camera as in the live channel.

Scanning Yokes

The Plumbicon yokes can be easily modified to accept 1-in vidicons, advantage being taken of the available scanning power to increase the strength of the focusing fields.

Circuit Techniques

The only major changes required in the signal processing amplifiers are to the gamma-correcting circuits and the addition of shading amplifiers to compensate for the effects of the vidicon dark current. Since the Plumbicon and vidicon are both photoconductive tubes, the entire channel can be designed for the dual role without any sacrifice to performance. The number of modules which are not common is relatively small so that the acquisition of a film channel entails practically no increase in the spares holding required.

REFERENCES

1 A. N. Heightman and W. T. Underhill: A New Four-tube Colour Television Camera; in this issue.

2 E. O. Holland and P. R. K. Chapman: Thin-Film Circuit Modules; in this issue.