DESIGN AND IMPLEMENTATION OF A 3-CCD, STATE OF THE ART, 750-LINE HDTV PROGRESSIVE SCAN BROADCAST CAMERA

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ABSTRACT

This paper describes an HDTV camera system implementing the 1280 x 720 image format supporting the 750/60/1:1 production standard. An interlaced HDTV camera has been adapted to meet the proposed US HDTV progressive standard. A new 1" video format, 16:9 aspect ratio progressive scan, frame-transfer (FT) CCD sensor with square pixels was designed, and sensor incorporation and camera adaptations were implemented. The new sensor is described and the impact of the 750-line standard is discussed. The first prototype of this camera will be demonstrated at the 1996 NAB show.

INTRODUCTION

The CCD image sensor was introduced into broadcast cameras around 1986. In 1992 the first HDTV CCD camera system to meet the proposed (European) EUREKA HDTV standard was introduced [1]. This LDK 9000 camera system, designed by Broadcast Television Systems (BTS), is based on a 1" frame-transfer sensor that was developed to support the 1250/50/2:1 interlaced European standard as well as the new American 1920 x 1280 format 1125/60/2:1 interlaced production standard. This camera has been used for the production of test material by the Advanced Television Test Center.

The Advisory Committee for Advanced Television Services (ACATS) recently released its proposal for a new U. S. television standard commonly referred to as HDTV [2]. The development of a progressive scan format for HDTV has been driven by concerns such as compatibility with computer systems, ease of compression, freedom from flicker (especially with graphics), and better temporal resolution. As discussed in the ACATS process, the interoperable and extensible HDTV system can serve not only entertainment and television, but can also offer economic and qualitative benefits to education, health care and human services, commercial enterprise, and the information infrastructure.

Several factors were considered critical to achieving interoperability [3]. One of these factors is the use of progressive scan square pixel image formats in capture, transmission, and display. Thereby, the television equipment can be extended to and stimulated by applications in computer communications, high quality imaging, synthetic imaging, animation, motion pictures, and so forth. The information infrastructure needs an image architecture that eases exchange between industries and applications.

Significant technical hurdles have acted as barriers to deploying a progressive scan HDTV system. Nonetheless, the Grand Alliance did incorporate progressive scan among their formats. Most experts agree that a progressive scan system is ultimately desirable and certainly inevitable in the proposed lifetime of HDTV, though the time frame is debated.

The major technical hurdle has been the difficulty in producing a progressive scan camera of comparable sensitivity and specifications to a studio quality interlace scan camera. Existing commercial and prototype cameras have been inadequate. Indeed, the existence of adequate component technology has been in doubt. Herein laid the motivation for our research and development efforts.

Through a cooperative effort between the Polaroid Image Sensor Technology Division and BTS the LDK 9000 HDTV CCD Camera system was recently adapted for the progressive 1280 x 720 standard (750/60/1:1). A new frame-transfer sensor meeting this standard was developed at Polaroid to be optically, electronically, and mechanically compatible with the previous interlaced sensor, although differing in image format and timing. The main adaptations of the camera system performed by BTS included the following elements:

- Camera/sensor pulse generator
- Camera Processing Unit pulse generation
- Vertical contour delay
- 7 inch view finder

Apart from the above-mentioned functions, minor adaptations were made in several areas to meet the timing specification and to optimize sensor performance.

Parameter	Value
Aspect Ratio	16:9
Interlace	1:1 (progressive)
Field frequency	60 Hz
Total number of lines	750
Number of active lines	720
Line frequency	45.000 Hz
Total line time	22.222 µsec (1650 samples)
Active line time	17.239 µsec (1280 samples)
Horizontal blanking	4.983 µsec (370 samples)
Sample frequency	74.25 MHz
Sync pulse	Tri-level

Table 1. Main characteristics of the 750/60/1:1 1280 x 720 production standard

PROPOSED 1280 X 720 PROGRESSIVE TELEVISION STANDARD

Interlace scanning has proven to be an efficient way of sampling pictures. The flicker perception of the human eye demands a refresh rate of the CRT of at least 50 times per second to prevent large area flicker. In order to save bandwidth, it was decided to refresh alternately the odd lines and even lines, thus doubling the vertical resolution for a given signal bandwidth. This means that for a given signal bandwidth the number of pixels in an interlace standard will be twice the number of pixels in a progressive system, resulting in a better static resolution.

But interlace scanning also shows some well-known artifacts, especially with moving pictures:

- It is impossible to combine two fields to one picture for moving objects, as each field comes from a different moment in time. This is a major drawback for creating still pictures from a moving scene, and for video to film transfer.
- While, with proper filtering, the frame can be nearly free of aliasing, each field may contain aliasing since it has only half of the samples in the vertical direction. The human eye has to integrate out aliasing effects per field, to see the full frame resolution of the picture. This results in small area flickering at field rate. The cancelling of aliasing between fields only holds for still pictures.
- Even at slow vertical movement of one line per field vertical aliasing is dramatically increased. This is especially visible on slowly moving almost horizontal lines in the picture.

With the move to digital television, the performance of the compression system becomes critical. Compression of interlaced signals is more complex and performs worse than compression of progressive scanned signals, where the entire image is sampled at the same time.

The 750-line 1280 x 720 format progressive scan standard provides a good, practical solution to the problems of interlacing while obtaining excellent compatibility with interlaced HDTV [4]. The key characteristics of this standard are given in Table 1 [5].

Several features of this standard greatly add to its practicality. Firstly, the picture format uses exactly 2/3's the horizontal and vertical pixel counts of the interlaced standard for ease in resampling. Next, the field and pixel frequencies are identical allowing the use of the same production equipment. In addition the line time is 3/4's that of interlaced potentially easing analog delay designs. Finally, adequate horizontal and vertical retrace intervals are allowed.

CCD SENSOR

The CCD sensor was designed specifically for progressive scan high definition video applications. With square pixels, an active array of 1280 x 720 pixels (1296 x 730 total pixels), a 16 mm diagonal for use with 1" format lenses, and with 60 frames/second operating speed, this sensor is ideal for the proposed 750/60/1:1 progressive-scan HDTV standard (Table 2). The frame-transfer architecture used provides high sensitivity, high fill-factor, no lag, and no smear when used with a mechanical shutter wheel as in the LDK 9000. The imager (shown in Figure 1) consists of the imaging array with both active and dark reference pixels, a full resolution storage section, a dual-channel horizontal register, and two output buffers.

The imaging pixel (Figure 2) is a 3-phase buried channel

Parameter	Value
CCD-type	FT
Optical format	1 inch
Image diagonal	16 mm
Image area width	14.00 mm
Image area height	7.88 mm
Number of lines	730
Pixels/line	1296
Pixel width	10.8 µm
Pixel height	10.8 µm
Chip width	15.29 mm
Chip height	15.25 mm
Chip area	233 sq. mm
Output registers	2
Pixel output rate	74.25 MHz
Frequency H-clocks	37.125 MHz
Swing H-clock	5 V
Frequency V-clocks	2.475 MHz
Swing V-clock	10 V

Table 2. CCD characteristics

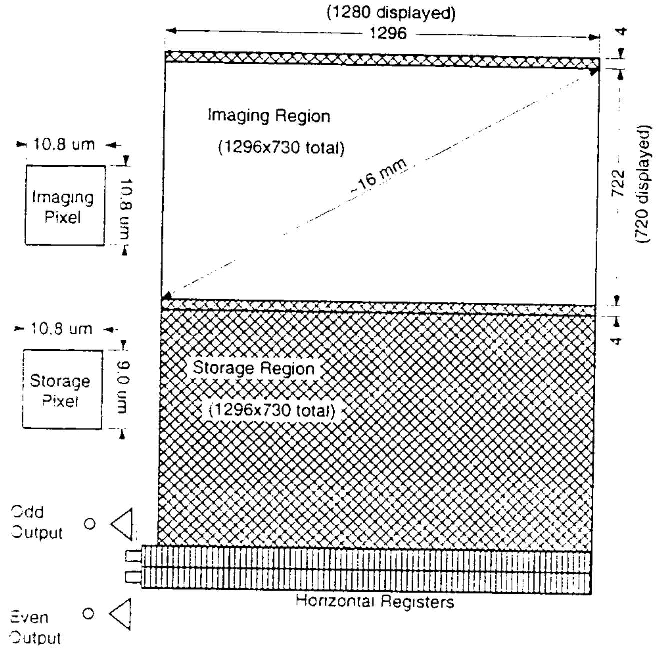

Figure 1. CCD Block Diagram

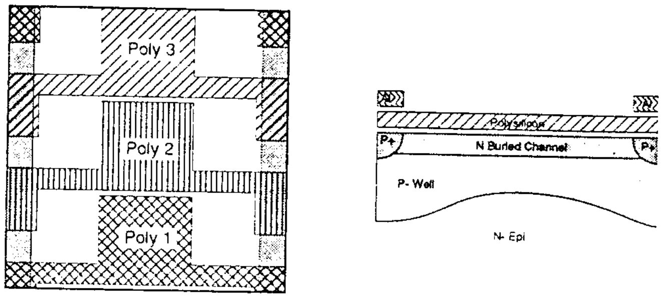

Figure 2. Imaging pixel top view (left) and cross-section (right).

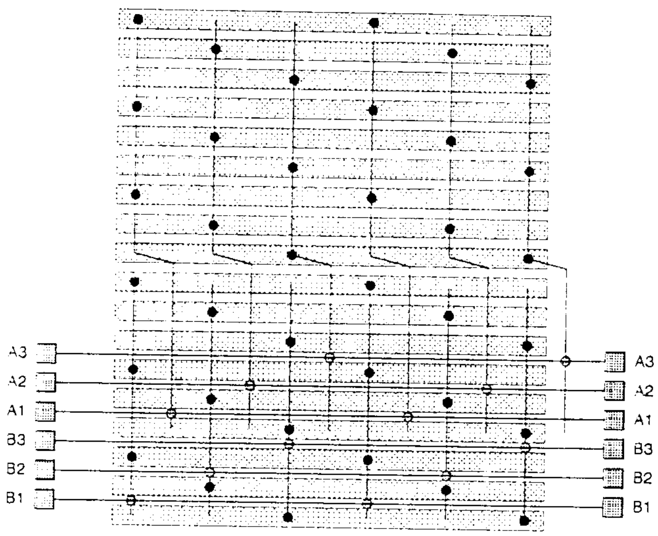

Figure 3. Double-level metal clock interconnect

device with integrated vertical anti-blooming protection. It is 10.8 x 10.8 microns square. The device is formed with three polysilicon layers, one for each phase, with large open areas (>33% of pixel) for enhanced blue light sensitivity. The vertical N-type buried channels are separated by P+ channel stops. The P-Well doping is modulated to form a weak spot in the center of the channel that acts as the anti-blooming barrier, which turns on when the pixel fills up to drain excess photocurrent down into the lightly N- doped epi layer. The storage pixel is configured similarly, although it uses wider poly gates for greater charge storage density. Thus the storage pixel could be made smaller (9.0x10.8 microns).

Since this sensor was designed to be compatible with the already existing camera, the process was carefully adjusted to give proper operation at the supplied clock voltages. This was complicated by the large number of functions that the pixel must implement: light absorption, charge collection, vertical overflow drain, charge transport, and charge reset (frame clear) for exposure control.

High vertical transport shift frequency (2.475 MHz) is required to move the charge from image to storage section during the brief optical blanking period provided by the shutter wheel. This frequency is by necessity higher than that used in the interlaced design because there are more lines to move (730/frame versus 576/field). Two-level aluminum wiring was used to shunt the polysilicon gate resistances resulting in less than 1 ohm equivalent series resistance. This allows the roughly 6 nf capacitive load to be driven at the required speed. Narrow aluminum straps connecting the poly gates run over the channel stops in the imaging section so that they have minimal impact on light sensitivity. Care was taken in their design to ensure that no fixed pattern artifact such as stripes was introduced by the straps. These are connected by busses on the second aluminum layer running across the storage section as shown in Figure 3. These busses are tied to package leads at each end to further lower series resistance.

During readout the charge is shifted one line at a time from the storage section into the horizontal registers. These charge packets are split up into the two registers on an even-odd column basis, using just a single transfer gate. The two registers operate in parallel at one-half the pixel frequency (37.125 MHz). The charge is transported along the 4-phase buried channel register to the matching sense nodes. The camera provides 4 phase clocking with 4-5 volt amplitudes, which posed a greater challenge in this design because the square pixels are wider and hence the horizontal gate length is greater reducing the fringing fields which assist charge movement. Extensive simulation was performed to ensure that excellent horizontal charge transfer would be achieved even at high clock frequencies.

Parameter	Value
Sensitivity (at sense node)	14 uv/e-
Amplifier gain	0.4
Noise after DLP in 30 MHz	33 e-
Bandwidth output	150 MHz
Quantum efficiency (peak)	26%
Sensitivity with BG40	2150 e-/lux
Overexposure	100,000 X
Full well capacity	40K e-
Dynamic range	62 db
Sampling frequency vertical	92.6 line-pairs/mm
Sampling frequency horiz.	92.6 line-pairs/mm
Image lag	none
Smear (incl. camera)	none

Table 3. CCD Performance

The output buffers are fairly conventional three-stage source-follower design. All three drive transistors are surface channel, giving high transconductance for low noise operation. The bandwidth (>120 MHz) is high enough to ensure accurate signal transmission. The layout of the two buffers was arranged to ensure they would match even with layer-to-layer misalignment during fabrication. The two video output signals are combined in the video pre-processor using the delay line principle (DLP).

Measured performance of the initial samples of the CCD sensor is summarized in Table 3.

OPTO-MECHANICAL DESIGN

The opto-mechanical system of the 1" CCD HDTV camera is designed to use lenses with a maximum aperture of f/1.2. The system consists of (from front to back): seal glass, IR-filter, retardation plate, shutter wheel, two 4 position filter wheels (for effect and ND filters), beam-splitter, optical low pass filters and sensors. In the adaptation of the optical system to the progressive format, in addition to the sensors only the optical low pass filter was changed.

Modulation Transfer Function

The modulation transfer function (MTF) of the camera is determined by the lens, optical low-pass filter, aperture of the image cell, and the electrical sample-and-hold. The MTF of the lens at f/4 is mainly diffraction limited. The MTF of the optical low pass filter is cosine shaped. The aperture of the image cell and the sample and hold both have sin(x)/x characteristics. Based on this model one expects a MTF of 47% for a sine wave at 27 MHz, versus a measured value of 50% (Figure 4).

Aliasing

A CCD-camera is a two-dimensional spatial sampler. The kings of fashion do not care about Nyquist nor does Nature! Therefore in everyday life the Nyquist condition - that the

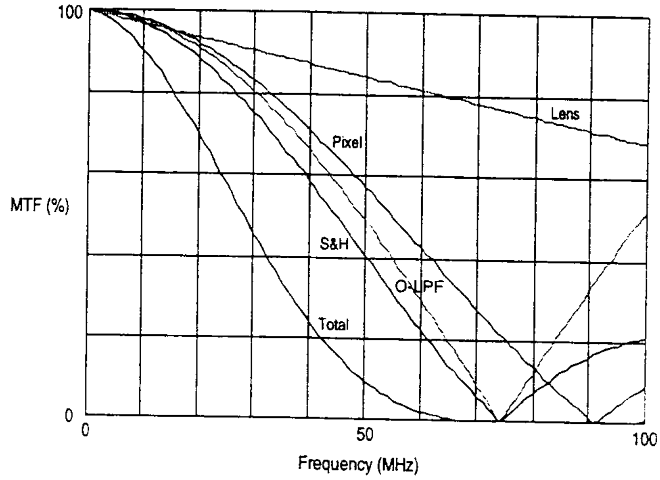

Figure 4. The modulation transfer function (MTF) of the camera. Shown are the separate contributions of lens, optical low-pass filter (O-LPF), aperature of the pixel, and the sample-and-hold.

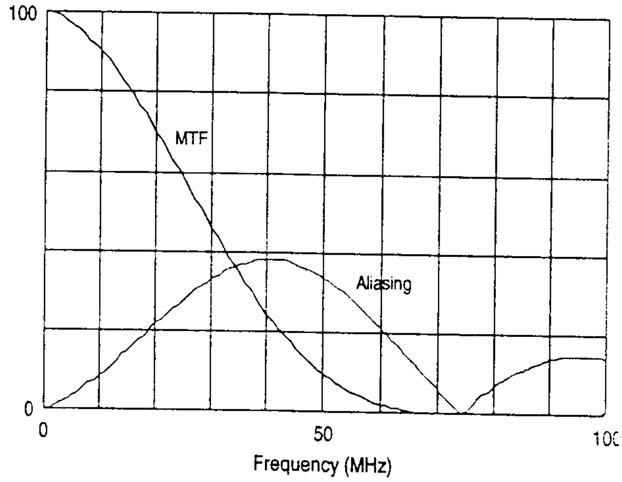

Figure 5. Shown are the MTF of the camera-head and the residual aliasing due to folds at the pixel sample frequency of 74.25 MHz

maximum frequency of the optical signal must be below half the sampling frequency - will be violated. This will cause Moire, or aliasing, patterns, which will create low-frequency patterns the eye is very sensitive to.

The frame-transfer image cell has a large aperture and therefore has intrinsically good horizontal and vertical aliasing behavior for higher spatial frequencies (greater than the Nyquist frequency). An optical low-pass filter helps to reduce aliasing further, especially at lower frequencies, by introducing dips (or notches) in the MTF. These dips must be at the vertical sampling frequency (92.6 line-pairs/mm) and at the horizontal sampling frequency (74.25 MHz, or 92.6 l-p/mm) for maximum effect (Figure 5). The need for a vertical anti-alias filter is unique to this progressive scan camera, since interlaced CCD sensors typically have considerable overlap in the even and odd scanning apertures that performs a similar function at the cost of vertical resolution.

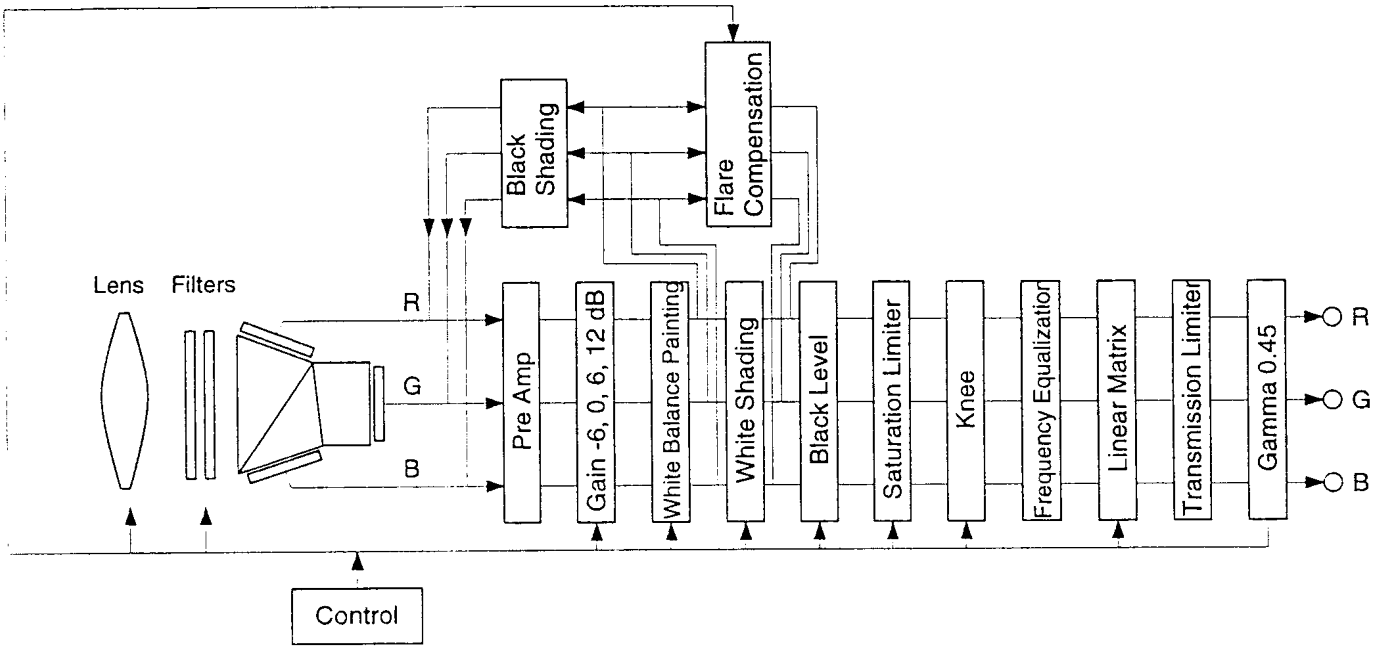

Figure 6. Camera head video processing.

VIDEO PROCESSING INCLUDING CONTOURS

Video processing in a progressive scan camera is not very different from the processing in an interlaced camera. The processing of the LDK 9000 camera has already been described in an earlier paper [1]. It consists of a part in the camera head (Figure 6), and further processing in the camera processing unit (CPU) (Figure 7).

Important design objectives for the LDK 9000 video processing were:

- Gain control over full temperature range.
- High dynamic range.
- Headroom before highlight compression of more than 14 dB.
- Signal/Noise deterioration due to video processing less than 1 dB.
- High quality, reliability and operational flexibility.
- Low power consumption.

Operation following the 1280 x 720 progressive standard calls for some specific adaptations as compared to the 1920 x 1080 interlaced standard:

- Line time is changed from 29.6 usec. to 22.2 usec. This calls for different line delays in the contour delay unit.
- Active line time is changed from 25.8 usec. to 17.2 usec. This calls for a more accurate timing in the video processing as timing errors will be more visible on the display.

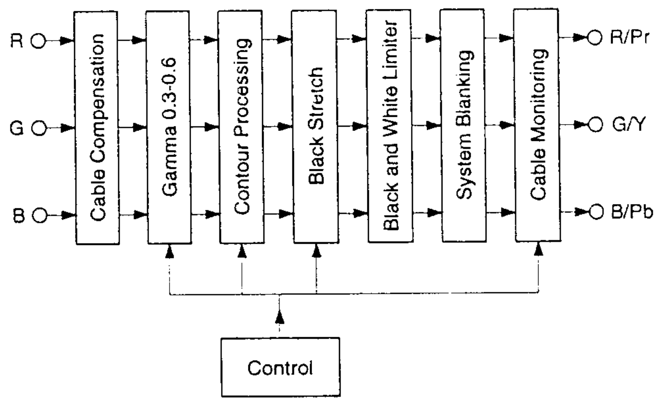

Figure 7. Video Processing CPU

- Vertical contours will look different -- the vertical contour generation in a 1080 line system is field based, with the 0T, 1T and 2T lines 1/540 picture height apart. In a 720 line progressive system vertical contours are generated from lines with a spacing of 1/720 picture height. This results in a higher vertical peaking frequency for vertical contours in a 720 progressive system.
- Horizontal contours will have a lower spatial frequency peak in the 1280 x 720 progressive scan system. This can be changed by shortening the delay lines in the contour processor, but there are practical limitations imposed by the lower Nyquist frequency of the 1280 x 720 system.

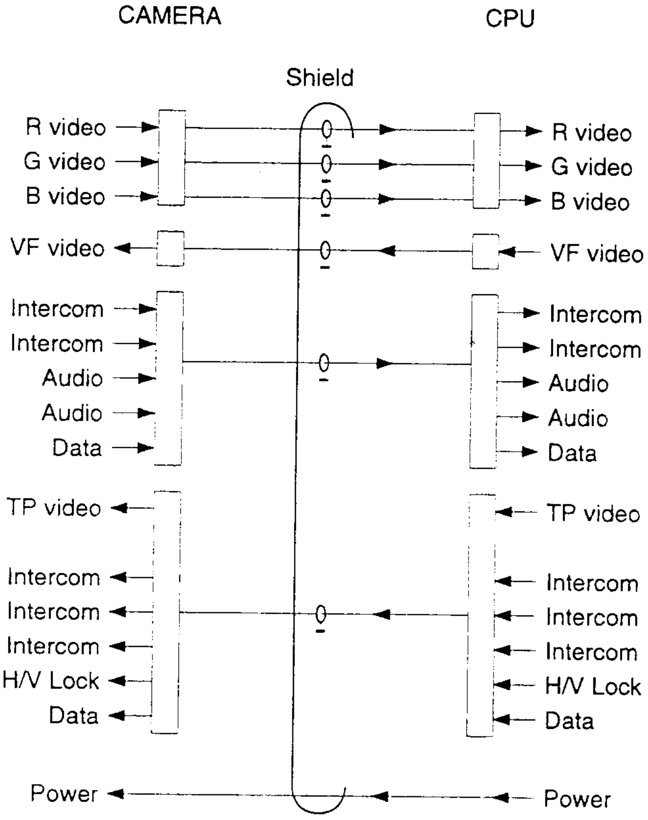

Figure 8. Multicore Transmission system

SIGNAL TRANSMISSION

The connection between camera and processing unit is formed by an interconnection system of cable and electronics specifically designed to maintain signal quality. A multicore cable can be used for short distances up to 300 meters. For longer distances, the multicore cable can be extended with a fiber optic system. Four coaxial cables are required for the R, G, B and view finder video signals. The remaining signals (figure 8) could be multiplexed into a single bidirectional coaxial cable, or into two separate single directional cables. This latter approach is used to achieve a simple interface with an optical fiber. Additionally, power wires are added, yielding a custom-made circular cross-section multicore cable.

The electronics provides automatic compensation for all multicore cable lengths between 0 and 300 meters. This is realized by dividing the total compensation into a fixed part and an adaptive part. The fixed part can compensate any cable length within an increment of 12.5 m. The compensation determined at power-up, by means of a successive approximation measurement. The adaptive part, which is independent in each channel and continuously active, has two functions:

- It has to compensate the last residual cable length within the resolution of the fixed part,
- It has to compensate (the frequency dependant) loss differences as caused by such things as temperature changes of the multicore cable and differences between the individual coaxial lines.

Delay differences between the coaxial lines is kept small by using high quality coax: maximum 1.5 ns between R, G, and B video signals at 300 meter cable length.

7 INCH VIEW FINDER

The main challenge in adapting the view finder to the progressive scan 1280 x 720 format was operating at much higher line frequency (45 KHz) given limitations on power dissipation and demands for high brightness and contrast. A stable high voltage source is required to prevent "breathing" at high beam currents and to secure high resolution performance.

Although spatial frequencies are lower for 1280 x 720 than for the 1920 x 1080 system (27 MHz bandwidth gives 780 TVL for 1920 x 1080 versus 520 TVL for 1280 x 720), focus assist is still a valuable tool for the camera operator. Apart from peaking in the view finder, the HDTV camera system is provided with two focus assisting tools:

- Magnifier: Momentary activation of this function enlarges the center part of the image by approximately 1.6 times, filling the whole screen.
- Crawler: Small details in the picture are converted to a more coarse structure, which gives edges and other fine details a highly visible crawling pattern. Optimum focus is obtained when this crawling serration reaches the maximum intensity. It acts more or less like "peaking" and can be used continuously.

CAMERA SYSTEM

The camera being presented is part of a complete system configured for broadcast applications. The system, as modified for the progressive standard, consists of the following system components:

Camera head
7-inch view finder
Camera Processing Unit (CPU)
Multicore cable
Master Control Panel (MCP)
Operational Control Panel (OCP)
Lens
Accessories

The camera head has been designed as a compact, lightweight, modular unit (Figure 9). The camera features two four-position filter wheels with three neutral density filters and two special effect filters.

The 7-inch view finder can be mounted on a optional specially-designed support above the camera. The support is designed to accept the lightweight camera combination. The camera, with an optional 1.5-inch view finder, can be

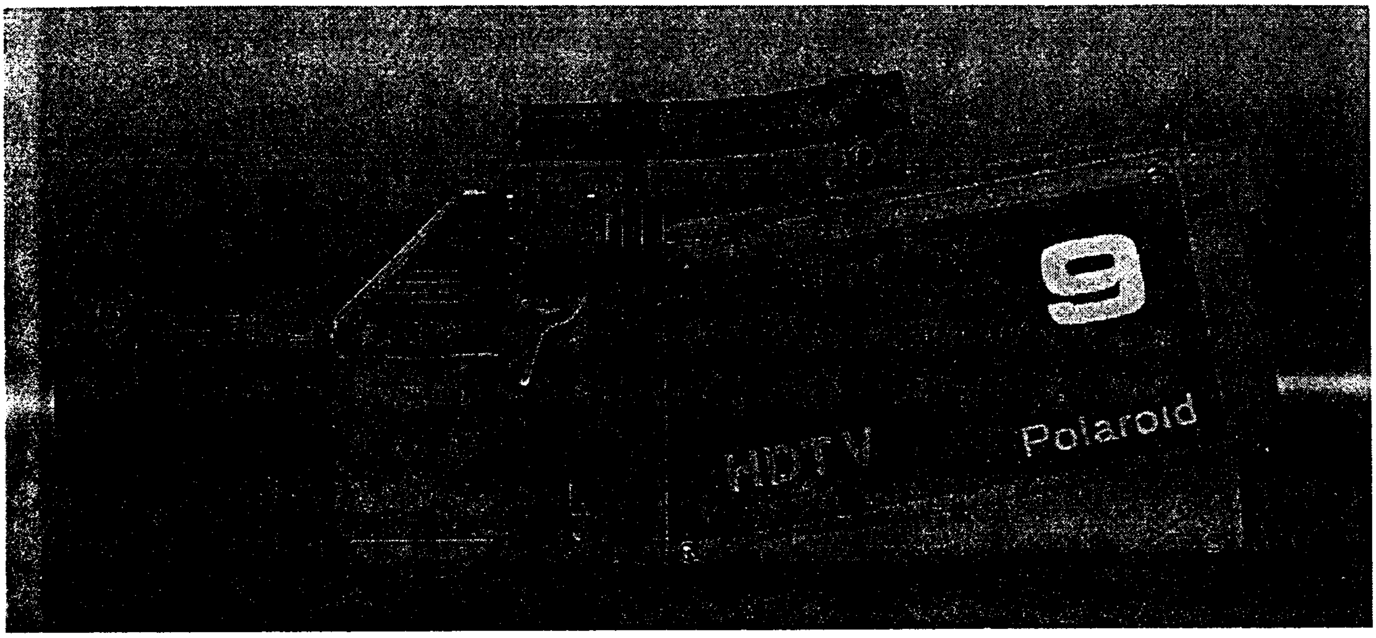

Figure 9 Camera head

easily placed upon or taken out of this support, leaving the support and 7-inch view finder on the tripod.

The CPU is a 19 inch rack mountable component which is 3 standard units high. The device is constructed using standard Eurocard PC boards and a rear connector panel with all signal interconnection options commonly used in broadcast studios.

The control panels follow the Series 9000 control philosophy, as used with all BTS standard TV cameras. The Master Control Panel gives access to most of the set-up controls via menus. The Operational Control Panel (OCP) provides all the operational control functions of the HDTV camera. The OCP is arranged with user-friendly directly accessible controls.

The camera can be used with a wide range of lenses built with internationally standardized interfaces. The camera presented is equipped with an 11 x 11 barrel-type lens from Fujinon. This heavier barrel-type zoom lens is supported by standard film-style accessories: a bridge plate underneath the camera accepts support rods, lens supports, matte boxes, etc.

The main camera system characteristics are summarized in Table 4. Performance specifications are summarized in Table 5.

For picture evaluation during the development period a Barco color monitor, Reference Calibrator model 121, was used. This monitor is capable of displaying 1280 x 720 progressive signals without effecting picture quality. Noise measurements were done on the Rohde & Schwarz VNA (Video Noise Analyzer). The Tektronix 1730HD Waveform monitor was used.

- An electronic white balance range from 2500K to 15000K.
- Highlight compression in automatic and manual mode.
- Black stretch in Y and R,G,B.
- Colorimetry according to EUREKA/EBU standard.
- 2-Dimensional contours.
- Electronic shutter with 5 and 2 msec exposure time. Also 50 Hz and 60 Hz lighting positions are available.
- Camera power consumption approximately 22 W.

Table 4. Main camera system characteristics

- Modulation Transfer Function of over 40% at 520 TVL (27 MHz) without contours.
- Limiting horizontal resolution of 700 TVL.
- Sensitivity of 1200 Lux at F/4.
- S/N ratio of 50 dB at a bandwidth of 30 MHz.
- The max. lens aperture is F/1.2.
- Dimensions approx. 140 x 210 x 350 mm.

Table 5. Camera system specifications

CONCLUSION

We report here on the first CCD HDTV broadcast camera to demonstrate the newly recommended 1280 x 720 progressive standard (750/60/1:1). A frame-transfer CCD was custom-designed, and a broadcast-quality interlaced HDTV camera was modified to meet the progressive standard.

A prototype camera has been built and is demonstrated at the 1996 NAB Exhibition. This camera meets all specifications as presented in this paper, and meets all goals toward proving the feasibility of the 750-line progressive HDTV standard.

The LDK 9000 system, with the 1250/50/2:1 standard, has already been in use for 4 years in Europe. During this time these systems have been used, to complete satisfaction, at a wide variety of events. A modified system for the new American 1920 x 1080 production standard (1125/60/2:1) was used for the production of test material by the Advanced Television Test Center. It is anticipated that this proven record of reliability and success will carry over to the progressive scan camera.

This project represents a successful embodiment of collaboration between industry, university, and research laboratory to accomplish more in a shorter period of time than any one could do alone.

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