Critical technologies for electronic still imaging systems

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ABSTRACT

Electronic still camera systems are now in the consumer market place. The hard copy image quality of these systems is poor in comparison with the ever improving photographic film systems. However, the rate at which solid state image sensor technology, signal processing technology, mass storage technology, and non–photographic hard copy technology are advancing indicates that these electronic still camera imaging systems will someday find a place alongside traditional photographic systems. The current and future status of these critical technologies is the subject of this paper.

1. INTRODUCTION

On January 6, 1839, the Academie des Science in Paris announced that Louis Jacques Mande Daguerre had "discovered a method to fix the images which were represented at the back of a camera obscura; ...".[1] Since that eventful day photographic images have dominated how mankind has recorded history from world wars to family outings and documented new discoveries ranging from the exploration of the atom and the tombs of ancient Egypt to the natural habitats of the rain forests, jungles, and deserts around the world. Before World War II there were no serious challenges to the photographic method of image recording, but the commercial development of color television in the 1950's and the subsequent development of high quality magnetic recording and VLSI semi–conductor technology in the 1970's and 1980's has brought electronic image recording to the consumer in the form of home video systems. The new 8 mm video camcorders have replaced the Super 8 film systems as the choice for recording family events and travel. In the commercial area, Electronic News Gathering, ENG, has replaced 16 mm film for television news broadcasting. Attempts are being made to use High Definition Television Systems (HDTV) as a replacement for film in the motion picture industry. While HDTV systems have not replaced film for motion picture production, the introduction of the BETA and VHS VCR systems and the Laser Disc systems have brought film originated movies into the homes of millions.

During the same time span, conventional silver halide–based still photography has had strong, continuous growth. This growth has been spurred by improvements in film, cameras and ease of processing. Today a consumer can spend less than $100 for a high quality 35 mm camera with autofocus, automatic exposure control, automatic film advance, automatic film speed indexing, and built–in electronic flash. The resulting images are of very high quality. But while conventional photography continues to enjoy strong growth there is another electronic imaging system appearing on the horizon, one that may someday share the consumer market with the film–based systems of today. The electronic still camera, ESC, is a commercial reality today, and it and the technologies that make it possible are the subject of this paper.

1.1 Electronic still camera system concept

Figure 1 shows a conceptual ESC system that could be assembled from currently available products. The system and camera is built around the Still Video Floppy, SVF, which records the image as an analog video signal.[2] Figure 2 shows the original SVF standard along with the new High–Band standard. In both cases the camera records 50 single field images or 25 full frame images; a video frame is made up of two interlaced fields. In the case of the High–Band standard, the images are recorded using a higher carrier frequency thus providing more bandwidth for each scan line and yielding greater horizontal resolution; the vertical resolution remains the same– 242 lines for the field format and 484 lines for the frame format.

The player/recorder converts the SVF analog signal into a form suitable for display on a conventional television set or monitor and also allows one to capture images from broadcast television or from VCR's and record them on the SVF disks. By using an image transceiver with a modem and public or private telephone communication systems one can send images anywhere in the world. Hard copy can be obtained from images stored on the SVF disks. The prints can be made from any number of print engines including thermal printers, electrophotographic printers, ink jet printers, and raster printers exposing conventional or instant photographic materials.

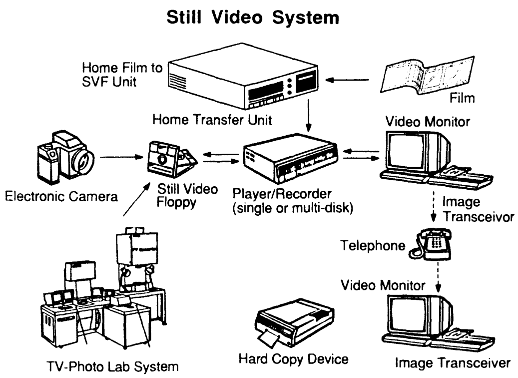

Figure 1. Conceptual diagram of a possible still video system based on the still video floppy, SVF, standard.

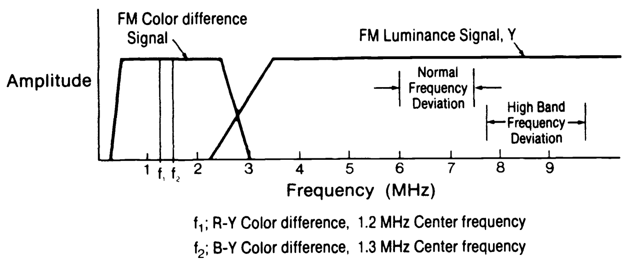

Figure 2. The image encoding standard for SVF systems.

An additional feature of the system is that a scanner can be used to convert existing images on negatives, transparencies, or paper into electronic signals for recording on the SVF disks. Image scanners/recorders can be installed either at photofinishers or in the home. Such a system provides complete flexibility to the consumer.

Figure 3 provides a more detailed look at the important parts of a ESC system; the system shown is just an abstraction of an ESC system and does not represent any particular product. One key aspect of such a system is that film–based images that are scanned into it can make use of the same system hardware and software that is used to transform the electronically captured image into a final hard copy print, soft display, or transmitted image.

In what follows, detailed discussions will be presented on the key ESC technologies: the solid state sensors that record the image, the in–camera signal processing that is required, the recording technology that stores the images, and the hard copy technology that produces prints. In far less detail, the technologies that deal with data compression and image manipulation will be discussed; the brevity of the discussions are not meant to imply that the technologies are not important, but that the detail required to fully understand the technologies falls beyond the scope of this paper.

As a final and very significant part of understanding an ESC system, the impact of international standards will be discussed. One of the key issues is the need for a world–wide, digital, non–broadcast television–based family of standards for future ESC systems.

In most of what follows, the emphasis will be directed toward systems that use hard copy output rather than soft display. The reason for this bias is based on the authors' feelings that an ESC system must produce hard copy images equivalent in quality to photographic prints. Many ESC images will be viewed via electronic displays, but current electronic display technology does not equal the photographic print or projected transparency for overall quality. Our crystal ball does not show us what display technology will hold sway in the future, so we, along with you, will have to watch the drama unfold before us.

1.2 Milestones in ESC systems [3,4,5]

Table 1 shows a complete list of ESCs that have been developed to date. A few of them rate special recognition from the historical point of view. In 1981 Sony demonstrated its Mavica color still camera and viewer, Mavipak transmitter, and Mavigraph video printer. The camera had a 280,000 pixel CCD sensor with red, green, and cyan stripes and the printer used thermal dye transfer technology with a 512–element heater. In 1986 Canon began marketing its RC 701 ESC system in the U.S. The camera used a CCD sensor with 380,000 pixels. In 1988 Canon introduced a high resolution version of its ESC, RC 760, with a CCD sensor that has 600,000 pixels. Also in 1988 Fuji Photo Ltd. demonstrated its 400,000 pixel ESC, DS–1P, that employed a removable static, random access memory, S–RAM card as the storage medium rather than the SVF disk. Polaroid demonstrated a monochrome ESC/motion camera which recorded still images on S–VHS–compact cassettes. The other ESC systems use the SVF disks for image storage. As can be seen from Table 1, the number of product entries are growing at a very rapid rate.

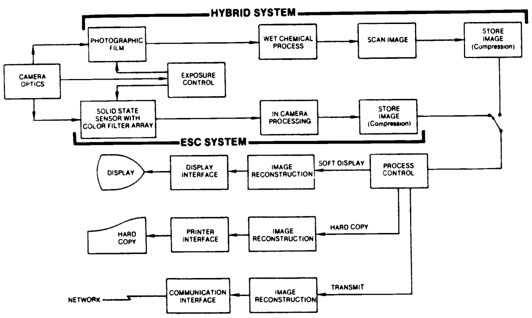

Figure 3. Functional outline of a hybrid imaging system and an electronic still camera system.

Electronic Still Camera

DATE	MODEL	MEDIA	IMAGER	LENS	COMMENTS
Aug 1981	Sony Mavica	Mavica	2/3" 280K	16-64mm	First ESC demo
Dec 1983	Toshiba	disc	2/3" 200K		64mm disc
July 1984	Canon	SVF	2/3 " 400K	16-64mm	Demo Camera
Oct 1984	Copal CV-1	SVF	2/3 " 280K	9-27mm	Demo Camera
Nov 1984	Hitachi	SVF	2/3" 190K		Demo Camera
Nov 1984	Panasonic	SVG	2/3" 300K	14-24mm,f/2	Demo Camera
Oct 1985	Sanyo	SVF	2/3" 280K	9-27mm	Demo Camera
Oct 1985	Mitsubishi	SVF			Demo Camera
May 1986	Canon RC 701	SVF	2/3" 380K	11-66mm	First ESC sold in US
Sept 1986	Panosonic 3100	SVF	2/3" 300K	10&25mm, AF	
Nov 1986	Chinon	SVF	2/3" 250K	12-72mm,f/1.7	Demo Camera
Dec 1986	Casio VS-101	SVF	2/3" 280K	11mm f/2.8	
Feb 1987	Rollei	SVF			Camera back for 3001/3
May 1987	Sony MVC-A7AF	SVF	2/3" 380K	12-72mm	
June 1987	Konica KC 400	SVF	2/3" 300K	12-36mm,AF	
June 1987	Kodak	SVF	2/3" 280K		Demo Camera
Sept 1987	Fuji ES-1	SVF	2/3" 380K	x3 Zoom	
Nov 1987	Minolta SB-90	SVF	2/3" 380K		Maxxum camera back
Jan 1988	Konica KC 100	SVF	2/3" 300K	11mm f/2.8	Binocular style
Jan 1988	Chinon	SVF			CP-9AF Camera back
Mar 1988	Canon RC 760	SVF	2/3" 600K		
Sept 1988	Nikon QV-1000C	SVF	2/3" 380K	x4/x11 Zoom	B/W Photojournalism
Sept 1988	Fuji ES20	Hi-SVF	2/3" 400K	12-25mm, AF	$1400 list price
Sept 1988	Canon Q-PIC	Hi-SVF	1/2" 360K	11mm f/2.8	$700 list price
Sept 1988	Olympus V-100	Hi-SVF	1/2" 360K	x3 Zoom f/2.8	Binocular style
Oct 1988	Konica KC300	Hi-SVF	1/2" 300K	12mm f/2.8	$700 list price
Oct 1988	Matsushita ES10	Hi-SVF	1/2" 360K	tele-wide	Commercial use ($2050)
Oct 1988	Sony 2MVC-C1	Hi-SVF	1/2" 280K	auto focus	$650 list price
Oct 1988	Canon RC-470	Hi-SVF	1/2" 360K	9&16mm	Business use (1950)
Oct 1988	Fuji DS-1P	RAM	2/3" 400K	16mm	16 MByte RAM card
Oct 1988	Polaroid S/V-M	S-VHS	2/3" 550K	12mm f/1.3	B/W still & Motion
Nov 1988	Minolta	Hi-SVF	2/3" 380K		$1600 list price

Table 1. Electronic still camera systems that have been demonstrated or placed on the market.

2. SYSTEM ANALYSIS

The end user, the customer, of an ESC will measure the quality of the system by how well the images it produces compare to the images that he or she can currently obtain from a conventional 35 mm film–based system. In this section the foundation will be laid for how to analyze the ESC system, and the results will be used in subsequent sections to demonstrate the importance of the separate technologies to the final image.

Figure 4 shows an image quality polygon. It is an attempt to graphically show the magnitude of the quality of each of the major components of the ESC system. The radial, outward spokes indicate the level of quality of each of the components normalized by some convenient scaling factor.

A short definition of each term will now be given.

1. Resolution: for an ESC this is usually defined by the number of pixels per image sensor, but film systems usually use the modulation transfer function, MTF, to define image resolution and sharpness, which is more accurate.

2. Sensitivity: this is equivalent to film speed and can be expressed as an equivalent ISO speed or the minimum illumination (typically measured in lux) required to capture a high quality image.

3. Exposure Latitude: this is the range in exposure over which the ESC can record subjectively determined high quality images; the exposure latitude can be expressed in terms of a ratio, for example, 400:1, in terms of stops, about nine, or in absolute terms, 20 lux to 8000 lux.

4. Dynamic range: this refers to the effective exposure range of the image on the sensor that the ESC system can reproduce. If the exposure control mechanism of the ESC sets the operational point in the middle of the possible exposure latitude, 4010 lux in the example above, the dynamic range would be plus–or–minus 3900 lux, or a sensor dynamic range of 400:1, or a little less than nine stops. However, the best CRT displays can properly display little more than a 40:1 contrast ratio. This then limits the dynamic range of the ESC system to a little more than five stops. There is a direct parallel in the photographic system; while a color negative may have over ten stops in usable latitude, the system, including the limiting paper exposure latitude, may have a net dynamic range between four and five stops.

5. Tone Reproduction: this is a measure of how well the final image gives the same appearance of the original scene in terms of overall contrast, shadow detail, and highlights. The physically measurable tone scale which produces the best subjective tone scale will vary depending on the viewing conditions; thus what is best for a soft display will not be the same as what is best for a reflection print, which is in turn different from what is best for a projected transparency.

6. Color reproduction: this refers to accurate reproduction of perceived color. While it is ideal to reproduce exactly the perceived color of the original scene, this is neither feasible nor required. The most important aspects are to have good flesh–to–neutral balance, proper hue and good saturation for the basic memory colors, such as grass, blue sky, etc., no obvious color shifts, and no pronounced holes in the color reproduction space.

7. Artifacts: these are unnatural occurrences in the image introduced by the various components of the ESC system. Two of the most obvious are due to the aliasing introduced by the low spatial sampling of the image resulting in too few pixels and quantization distortions which can occur if the the amplitude of the signal is recorded with too few bits; the resulting contours are easily seen and very displeasing.

8. Noise: in solid state image sensors this is usually quantified by the non–image electrons associated with the sensor, output of the sensor, and its support electronics. The noise will appear as random noise or grain in the final print. From the point of view of a television engineer noise is measured as the ratio of the peak amplitude level, in volts, of the desired signal to the root–mean–square (RMS) average of the noise. This ratio is often expressed in decibels which is 20 times the log to the base ten of the ratio.

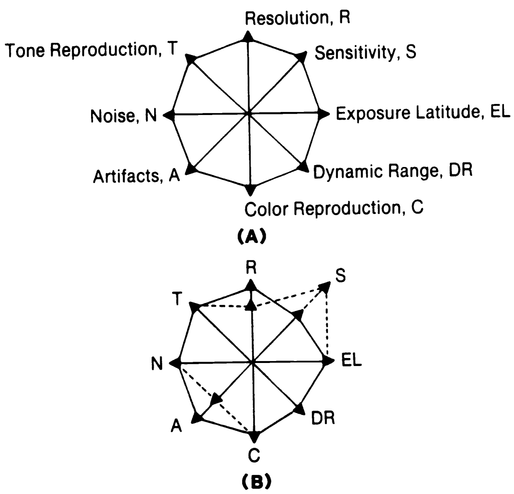

Figure 4. The quality polygon. A. The length of the radial arm is proportional to the quality of the designated characteristic. B. The quality characteristics are not independent and if the sensitivity is increased there may be a drop in resolution (sharpness) and an increase in visual artifacts.

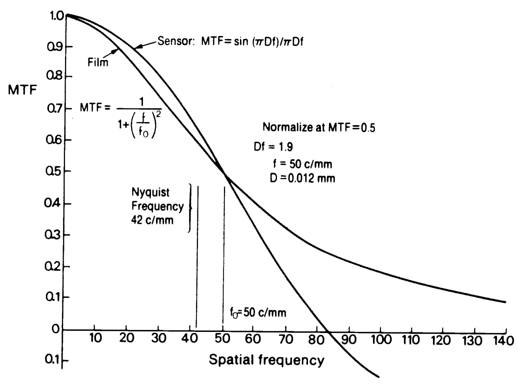

Figure 5. A method to calculate the effective pixel size that can be associated with photographic film when a frame transfer device with square pixels is assumed as the sensor model. The curve shown for the film is based on a theoretical model and does not represent a particular film.

Sony, Ex. 1016, p.4

The image quality polygon can be used to compare systems as shown in Figure 4. Here system A has higher sensitivity than system B, but the price paid for the increased sensitivity is that the resolution is lower and there are more artifacts. As will be demonstrated in the following sections, these image quality parameters are not independent. Within any given set of technologies there are trade–offs to be made in the system design.

2.1. Resolution and aliasing [6,7,8,9]

A frequently asked question about electronic sensors is how many pixels are required to produce the equivalent image quality of film. In this section a systematic approach is used to address this question in a system context. However, before the system approach is used it is instructive to look at film and the imaging sensor as individual components in order to understand some basic differences. Also, it will be assumed that the sensor is a CCD.

Film's sharpness characteristics are usually quantified by its MTF which is obtained by exposing the film with sine wave targets of increasing frequency. The resulting sine wave response curve, as shown in Figure 5, is called the MTF and is treated as if it came from a normal linear system. In fact film is not a linear system, but no loss of understanding will ensue by making this approximation. Also, all color films have at least three different color layers, usually sensitive to blue, green, and red light. Due to increased optical scattering as the light travels deeper into the film, the bottom layer has a lower MTF than the top layer. For these discussions it will be assumed that a visual average of the three MTFs is being used; the observer views only the final print, but since the print image is a product of the dyes in the negative, the dyes in the print material, and the spectral sensitivities in the print material, all three must be taken into consideration in determining the visual average. An imaging site, or pixel, on a solid state sensor can have any shape, but here it will be assumed that it is square. The MTF of a square, ideal pixel is given by

$$MTF_{sensor}(f) = \sin(\pi D f)/(\pi D f), \qquad (1)$$

where D is the the pixel width and f is the spatial frequency. One obvious criteria would be to demand that the sensor pixel have about the same MTF as the film.[10] Figure 5 shows one such way to equate the film and pixel by normalizing the two curves at the 50% response frequency, f_0. This leads to the following relationship:

$$D = 1.9/(\pi f_0). \qquad (2)$$

Thus, if $f_0 = 50$ cycles per millimeter, c/mm, then D = 0.012 mm. If one assumes that the the sensor is a frame transfer device where the pixels cover the entire surface of the sensor and that the sensor has the same aspect ratio as the 35 mm frame, 2:3, then the sensor must have 2000 by 3000 pixels. To date, sensors with six million pixels have not been reported.

The above analysis is not complete, however. The CCD is a sampling image sensor while film is a continuous sensor. The nature of sampling introduces aliasing. Aliasing is the generation of false signals or, in the case of image sensors, false images. Figures 6, 7, and 8 demonstrate this property of sampled systems. If the sine waves in Figure 6 are sampled at a rate less than twice the frequency of the sine wave, the resulting signal will appear as a lower frequency or aliased signal. Figure 7 shows the spectra of the four sine waves. Note that the fourth and seventh harmonics are aliased to lower frequencies. Figure 8 shows the case of a simple image spectrum. When the sampling is high enough, above the Nyquist frequency which is equal to twice the highest frequency one wishes to record faithfully, no aliasing takes place but, as shown in part b of Figure 8, when the sampling frequency is below the Nyquist frequency, the spectra will overlap, giving rise to many artifacts. Figure 9 shows what happens when an image with strong vertical lines is sampled with an imager that does not meet the Nyquist sampling criteria; note the strong low frequency banding. This problem becomes acute in sensors that have color filter arrays on them, for then the banding can become a rainbow due to the different relative phases of the colored pixels on the sensor.

Thus in designing a system that samples an image, one must try to avoid or minimize the problems introduced by aliasing. In theory, the simplest method is to sample at twice the frequency of the zero, or near zero, response of the film. In the example shown in Figure 5 this means that we should sample the image, relative to the image plane, at about 300 times per millimeter since the MTF at 150 c/mm is 10%. This would require a format of 7,200 by 10,800 pixels or 77.6 million pixels. Clearly, while this solves the aliasing problem, it is an unacceptable, if not impossible, solution. As will be discussed in the next section, aliasing can be reduced but at the price of sharpness.

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