They Said It Couldn't Be Done – System Design and Image Processing in the EFS-1 Electronic Film System

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Abstract

Digital still cameras (DSCs) have become a staple of consumer electronic products, joining the ranks of camcorders, cell phones and personal digital assistants (PDAs). For the majority of the image-capturing public, the transition to digital photography has been a positive experience, with the ability to instantly view and share photographs outweighing the tradeoffs in resolution and dynamic range. However, a significant population of high-end photographers (the so-called 'prosumer' category) have not embraced the digital camera revolution, as is evident from the continued sales of 35mm SLR cameras and accessories. One of the factors contributing to this reluctance is the investment in both money and time that many prosumers have made in their photographic equipment. Although digital SLR cameras are now commercially available, the cost of these is still somewhat prohibitive.

In an effort to address the desire for 35mm SLR users to 'go digital' with their own equipment in a cost effective way, SiliconFilm Technologies has developed a re-usable electronic film system (EFS) for film-based 35mm cameras. The core of this system is an electronic film cartridge, '(e)film' , that is compatible with the form factor of a roll of 35mm film and is capable of capturing and storing multiple digital images. This device enables a photographer to easily switch between film-based and digital image capture without modification to the camera body.

The electronic film system and in particular, the (e)film cartridge, presented technical challenges in almost every aspect of system design. The requirements and constraints of developing an electronic image capture device with form, fit and function compatible with 35mm film led more than one engineer associated with the project to conclude that, "It couldn't be done." In the following sections, we shall describe the system requirements for this product, the challenges presented by the requirements and how they were successfully overcome. Lastly, we shall discuss some of the image processing issues relevant to this design and to CMOS-imager based cameras.

System Design Goals-

The overall design goal of this product is to function with manual and automatic 35mm cameras with image quality, ease of use and product reliability comparable to that of professional digital cameras at a price affordable to the broad prosumer market. The system level functional requirements driving the design are as follows:

1. No modification to the target camera body.
2. No interference with the normal operating modes of the SLR camera.
3. Image capture should occur for all camera operating modes.
4. The (e)film cartridge should be capable of being left in the camera for extended periods of time with no negative consequences.
5. The EFS should give the user an unambiguous indication of its operating state.

In order to achieve these goals, the system design criteria are prioritized in the following order:

1. Size/Form Factor restrictions
2. Power Consumption
3. Data Throughput
4. Image Quality
5. Cost
6. Manufacturability

Challenges/Solutions-

The primary challenge in designing a drop-in electronic film module is to develop a system that enables the image capture front end electronics to physically fit within the available volume of a 35mm SLR camera body, while still providing convenient interface to a host PC for image transfer. The solution used at Silicon Film is to separate these functions into two pieces: (e)film for image capture and temporary storage and (e)port for image transfer to the host. These parts are shown in Fig.1.

Figure 1. EFS-1 components: (e)film and (e)port

In addition, the functional requirements of minimal impact and interference with camera operation implies that the (e)film cartridge should operate from a dedicated power source rather than use the batteries of the 35mm camera body. The (e)film power, therefore, is supplied by a pair of 1/3N batteries stacked within the film canister. The 1/3N batteries are the smallest size batteries readily available and consistent with the (e)film power requirements. Even these small form factor batteries occupy most of the available volume in the film canister section. As a result, the circuit board containing the electronic components necessary for image capture, storage, processing and control are contained on a rigid/flex PCB assembly that is wrapped and folded around the (e)film battery compartment and represents some fairly creative circuit board design and layout as well as clever mechanical engineering of the (e)film cartridge. A functional block diagram of the EFS (e)film/(e)port is shown in Figure 2.

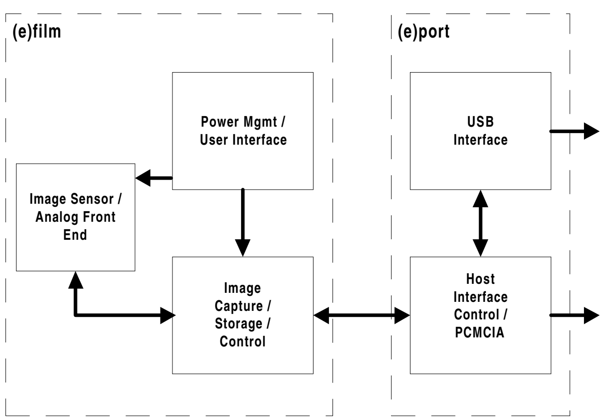

Figure 2. Functional Block Diagram of (e)film and (e)port

The image sensor/analog front end block consists of a 1.3Mpixel color CMOS image sensor (VVL6801) and a 12-bit analog-to-digital converter. The choice of this image sensor is critical to the system design for several reasons. First, as a CMOS sensor it has a distinct advantage over equivalent resolution CCDs in power consumption for the image sensing array. Since CMOS sensors are TTL-compatible devices, there is no need for vertical and horizontal clock driver interface chips, thus reducing both chip count and power requirements for the (e)film cartridge. This image sensor design implements a parallel-integration or "global-reset" mode in which all of the pixels in the array can be simultaneously reset and released from reset. This is ideally suited for use in mechanical shutter-based image capture systems. Lastly, the pixel dimensions (8.4um X 8.4um) provide an optical resolution and MTF that are well matched to the requirements of 35mm photography.[1] One of the primary drawbacks to the use of this image sensor in this application is the limited field of view it provides with 35mm optics. The imaging array dimensions for the VVL6801 are 8.6mm x 10.8mm compared to ~23mm x 35mm for standard 35mm film. This implies an image magnification factor of 2.8 that needs to be accounted for in composing shots. This is similar to the magnification factor of early digital SLR cameras from Kodak, Nikon, and Canon with similar sized imaging arrays.[2]

One of the more interesting design challenges in this device is that of ensuring that the image sensor array is aligned with the focal plane of the camera body. Standard image sensor packaging methods position the imaging die with respect to reference points on the package body, but once the chip package is attached to a PCB or flex circuit, it is difficult to determine if the imaging die is aligned with the focal plane of the camera optics. It is especially difficult to obtain precise Z-axis alignment using standard imager packaging techniques, since the mechanical tolerance stack of the imager die in the chip package, the chip package attachment to the PCB and the placement of the PCB in the optical path is generally greater than the depth of focus for 35mm camera optics. An additional complication for (e)film is the use of a focal plane shutter in most 35mm SLR cameras. The proximity of the shutter to the focal plane limits the allowable thickness of an imager package as well as the separation between the glass cover plate and the imaging array surface.

To solve this problem for EFS, a novel image sensor package was developed in which the image sensor die is mechanically indexed to precision molded rails on the outside of the imager package.[3] These rails are designed to mate with the film rails in a 35mm camera body so that when the (e)film cartridge is inserted into a camera, the rails on the imager package contact the film rails in the camera and insure proper alignment of the imaging array. This alignment takes into account the focal plane shift induced by the presence of the glass window/ IR-blocking filter incorporated into the imager package.

Image capture, storage and control functions are implemented in (e)film by two separate devices. A DSP (Analog Devices ADSP-2186) generates imager timing signals and manages storage and retrieval of image data to and from either SDRAM or NAND-Flash memory. An FPGA performs timing synchronization and data buffering to/from memory devices. One of the primary differences between CMOS-sensor and CCD-sensor based digital cameras is the necessity in CMOS-sensor based systems to account for fixed pattern noise (FPN) at an early stage in the image processing chain. This is particularly problematic in this design because of the use of a global-reset method of image capture. Releasing all pixels simultaneously from reset and then sequentially reading out rows causes the last rows to be read out to have an additional component of 'dark-current' noise compared to the first rows. This component of 'dark-current' noise is temperature dependent, increasing by a factor of 2 for every 7°C temperature rise.

Thus, a raw captured image in (e)film must be corrected for both FPN and dark current noise. The current design does this by capturing a dark reference frame immediately after capturing a raw image frame. Both images are stored temporarily in SDRAM and the resultant FPN and dark frame subtracted image is transferred to banked Flash memory that is capable of storing 30 captured images. This method of acquiring a corresponding dark frame for each raw frame limits the image throughput or frame rate to 1-2 frames per second but ensures a higher signal-to-noise-ratio (SNR) (typically 58dB) and better image quality in the stored image.

The power management and user interface functions are controlled by an ATMEL AVR 8-bit microcontroller. These functions are the most critical for the ability of the (e)film to operate in a 35mm camera body. Because the cartridge is expected to remain in a camera for weeks at a time without draining the battery power, aggressive power management practices are implemented in the design. The additional requirement that the (e)film should sense a picture-taking event with sufficient warning to power up the necessary components and ensure stable operating conditions for the image sensor presents a significant challenge for system design. A traditional approach based on sensing an open shutter using the image sensor is not viable since this would require the image sensor to be operating constantly and thereby drain battery power.

The novel approach taken in this design is to employ non-optical signals in the camera body to determine a picture-taking event.[4] Many common SLR cameras use a "through the lens" focusing system in which a tilted mirror in the optical path reflects the image from the lens into the eyepiece. When the button on the camera body is depressed to capture an image, this mirror is quickly rotated out of the optical path and the shutter is opened to expose the film. Because the mirror rotation is a mechanical event it has two characteristics that recommend it for use as an image capture trigger event. First, it occurs on a time scale of milliseconds before the shutter opens and second it generates an acoustic signature within the camera body. By incorporating a low power acoustic detect/discriminator circuit into (e)film, a digital signal can be generated when the 'mirror-flip' occurs with sufficient lead time to power up the image capture components and stabilize the image sensor. An additional pushbutton switch is used in the (e)film to activate the acoustic sensor only when the unit is inside a camera and the camera back is closed.

Information about the operating state of the (e)film is transmitted to the user in two ways. An LCD is incorporated into the film canister and is positioned to coincide with the film information window on many SLR camera backs. This displays to the user the number of shots taken, battery charge condition, image transfer activity and error conditions. Additionally, a piezo-electric element is included that is capable of emitting audible tones to indicate insertion/removal from the camera (pushbutton state) and successful /unsuccessful image capture. Figure 3 shows a detailed block diagram of the (e)film cartridge components and their respective functions.

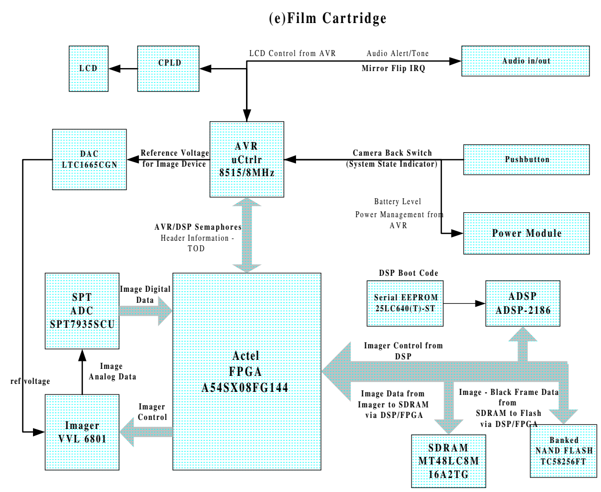

Figure 3. – (e)film detailed block/functional diagram

The (e)port module is designed to perform two functions. First, it is the means by which images stored in the (e)film Flash memory are transferred to a host computer, and second, it provides a convenient protective carrying case for the (e)film out of the camera. Image files are stored in the (e)film Flash memory in raw 12-bit compacted form and can be uploaded to a PC through either a USB1.1 or a PCMCIA interface on the (e)port. Communication between the (e)film and the (e)port is achieved through a high speed serial interface connecting the DSP on the (e)film to an AVR micro-controller on the (e)port.

Image Processing in EFS-1

The goal of image processing in EFS-1 is to produce excellent quality electronic and print images over a wide range of exposure and lighting conditions with minimal user interaction. To a large extent, image processing is somewhat easier in EFS-1 than with conventional digital cameras, because there is currently no provision for in-camera image preview. Although this may be viewed as a system deficiency, it also eliminates the necessity for a complete in-camera image processing chain, and thereby eliminates the image processing trade-offs inherent in generating a preview image. All image processing operations occur on the host PC within the TWAIN-compliant application that is an integral component of EFS.

As stated previously, images are stored in the (e)film cartridge in raw format, with dark frame subtraction as the only image processing step executed. Although this requires some front end image processing as the images are transferred to the host, there are distinct advantages offered to a 'serious' photographer in having access to the raw image data or 'digital negative' before look-up tables, color-space conversions or compression algorithms have been applied. In this section, we will not present a detailed discussion of the image processing chain, but rather highlight image processing issues relevant to the (e)film product. The critical image processing steps to be considered here are interpolation, auto white balance and sharpening.

Interpolation of the raw Bayer pattern data into separate, complete R-G-B color planes is implemented using an adaptive FIR-filter approach similar to that described by Parulski, et al.[5] However, prior to applying the full interpolation algorithm, pixel defects are corrected using a proprietary interpolation scheme. In addition to correcting for "binary-mode" pixel failures (either 'hot' or 'cold'), this scheme applies a stored gain map correction for each pixel to reduce speckle in flat areas (PRNU) of a captured image.

The problem of automatic-white balance (AWB) in digital imaging systems without a standard white reference is one that has not yet been completely solved. There are many approaches (most of them proprietary) and each of which exhibits some deficiency under some illuminant conditions. The goal of the AWB algorithm in the EFS system is to provide *reasonable* colorimetric accuracy under 4 illuminant conditions common to 35mm photography: sunlight, strobe flash, cool white fluorescent, and incandescent. This is done by defining a colorimetric figure of merit for each captured image and performing statistical calculations on the RGB content of candidate neutral pixels to determine an appropriate set of RGB gain coefficients. If the captured image doesn't meet the statistical requirements for neutral pixels or for figure of merit, no white balance adjustment is made. This is done based on the assumption that an incorrectly applied white balance algorithm is usually worse than none at all. In this case, the user has the option in the EFS application software to 'turn off' the white balance algorithm and apply the appropriate RGB gain corrections using any TWAIN-compliant image processing application.

The application of sharpening algorithms in EFS images addresses a fundamental difference between film-based and digital cameras. Because electronic image sensors consist of discrete uniform arrays of sensing elements, sampling theory predicts that there may be content in a captured image at spatial frequencies that produce aliasing artifacts in the output image. This is not the case for silver halide based film due to the random orientations and statistical distribution of grain sizes. Consequently, most digital camera designs include a blur (or optical low pass) filter in the optical system to eliminate the high spatial frequencies that cause aliasing, while film based cameras do not.

In the EFS, three possibilities were considered for dealing with aliasing. First, addition of a polarization-shifting optical element between the camera lens and the focal plane shutter. This violated one of the design principles of the (e)film product (modification of the camera body) and was ruled out. Second, inclusion of a thin-film blur filter as a top layer of the glass window on the imager package. This would have made the imager package prohibitively expensive and intolerant to normal handling and cleaning. Third, operate without a blur filter and mitigate aliasing artifacts in the image processing chain.

The EFS sharpening algorithm, therefore, combines an adaptive gaussian blur function with an adaptive Laplacian-based sharpening function to initially attenuate aliasing artifacts and then sharpen the resulting image. An example of the results of this approach is shown Figure 4. Additionally, in a similar fashion to white balance, if the results of the default sharpening operation are unsatisfactory, the user has the option of disabling this feature and applying a different sharpening method.

The absence of a blur filter in this system produces a beneficial side-effect with respect to image quality. In digital camera systems using anti-aliasing filters, there is a well known tradeoff between image sharpness and aliasing artifacts.[6] Furthermore, an improperly designed combination of image sensor pixel size and blur filter spot separation can have a detrimental effect on overall system MTF.[7] For the EFS, operating without a blur filter insures that the advantages of high quality lens design and fabrication for 35mm SLR cameras will not be compromised, producing images that reflect these qualities in crispness and detail.

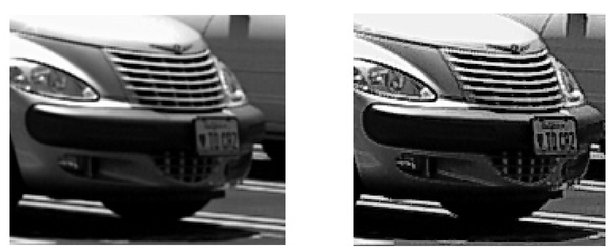

Figure 4. Left image: anti-aliasing & sharpening disabled; Right image: anti-aliasing and sharpening enabled

Conclusions

It was the intent of the design team of EFS to create a product that is a bridge between film-based and digital photography. In successfully developing EFS-1, the first generation of (e)film products, two concepts relevant to digital camera design in general were demonstrated. First, that it is possible to fit the '10 pounds' of image capture, storage and retrieval necessary for a digital imaging product into the proverbial '5 pound bag' of space available in the back of a 35mm camera. The design and fabrication of the (e)film cartridge represents a tight integration of optical design, mechanical design, printed circuit board layout and fabrication, and component packaging technology that required both creative and practical problem-solving.

The second principle that EFS demonstrates is that image quality in digital capture systems is about more than the number of pixels in an image sensor. It is commonly believed that an image sensor with less than 2MPixels cannot produce acceptable 8' x 10' prints.[1] However, at the PMA 2001 show, an 8' x 10' print from an (e)film prototype was matched in a blind comparison against equivalent prints from 3 different digital cameras having between 2 and 4MPixel image sensors. In all but one case, the (e)film print was judged to be of equal or superior image quality. This underscores the fact that a meaningful figure of merit for a digital capture system must take into account pixel size, sensor dynamic range, and system optical design as well as number of pixels.

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Biography

Matthew Whalen received a BS degree in Physics from Rutgers University in 1974 and an MS in Physics from Rutgers in 1983. As a Member of the Technical Staff at Bell Laboratories in Holmdel,NJ from 1980-1993, he was involved in optical fiber device research. From 1993 - 96, he led a digital camera development team for the AT&T Videophone product. Since 1996, he has been actively involved in CMOS image sensor design, characterization and color science development. He has published papers and holds several patents in the fields of optical communcations and digital cameras. He is a member of IS&T.