Replacing 16 mm Film Cameras with High Definition Digital Cameras

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ABSTRACT

For many years 16 mm film cameras have been used in severe environments. These film cameras are used on Hy-G automotive sleds, airborne gun cameras, range tracking and other hazardous environments. The companies and government agencies using these cameras are in need of replacing them with a more cost effective solution. Film-based cameras still produce the best resolving capability, however, film development time, chemical disposal, recurring media cost, and faster digital analysis are factors influencing the desire for a 16 mm film camera replacement. This paper will describe a new camera from Kodak that has been designed to replace 16 mm high speed film cameras.

OVERVIEW

Motion analyzers are high speed video systems. What distinguishes them from standard video systems are their record rate that is greater than 15x record rate and their capability to analyze motion. These motion analyzers are designed specifically to play captured images in slow motion. The motion analyzers use high speed electronic cameras. The cameras are tethered to the processor. The images are stored at very high bandwidths into the processor. After the images are captured [stored], frame-by-frame, they are reviewed in slow motion on the motion analyzer's display. Most applications need a quick look at the captured images. This is very easy with most motion analyzers. Others applications require measurements (i.e., displacements, velocities, areas). High speed subjects can be defined as anything that moves faster than the eye can perceive. Industrial imaging of high speed subjects can provide the understanding for improving quality, trouble-shooting a problem, increasing capacity, reducing set-up time, and advancing research. It is apparent why companies throughout the world are using motion analyzers to remain competitive.

Kodak started manufacturing motion analyzers in 1980. Many years of experience designing, manufacturing and supplying motion analyzers worldwide has resulted in the development of a one-piece Hy-G digital camera, the KODAK EKTAPRO RO Imager.

INTRODUCTION

The RO camera is a complete image capture system built into an thirteen pound, 4 x 5 x 11 inch housing designed specifically for replacement of high speed film cameras. It produces high-resolution digital color or monochrome images that provide the data required for replacing Hy-G film cameras. Image playback and analysis is on desktop computers. The RO camera complexity and cost was reduced by moving the playback function to a desktop computer. The camera still has the capability for displaying images LIVE at the record rate for ease of setup.

RO stands for record only. The camera records up to 1000 full frames per second. It features a high resolution, light-sensitive CCD sensor with an electronic shutter. This shutter provides blooming protection which prevents the "smearing" of bright light sources, e.g. camera looking into a flood lamp or a hot spot. The RO is a very rugged camera packaged in a highly integrated housing. This camera operates off +28 VDC. This camera has a redundant memory protection system that assures images are sustained in the camera absence of main power. The RO is the same size as the most widely used 16 mm film camera. Recorded digital images are read through a fast serial interface or a removable storage module. The RO is controlled through an RS-485 interface or a simple dedicated hardwired interface. The RO is a cost-effective replacement for high speed film cameras.

The RO design is based on the HRC sensor technology, a high resolution interline CCD sensor. The sensor resolution is 512 x 384. The pixels are 16 μm x 16 μm square. The pixel pitch is the same in both the horizontal and vertical directions, which is ideal for computer image analysis applications. The sensor has a Color Filter Array [CFA] deposited on the surface. This CFA is arranged in a Kodak proprietary matrix called a Bayer pattern. A Bayer pattern consists of a blue, green, red, green pixel arrangement in a 2 x 2 matrix. After capture, the images are processed through a Bayer Color Algorithm on a computer to produce 24-bit color images of superb quality. The RO is also available with a monochrome sensor for higher resolving power and light sensitivity.

RO fps	RO w/500 f	RO w/2000 f
1000	500 ms	2000 ms
500	1000 ms	4000 ms
250	2000 ms	8000 ms

The RO can capture up to 500 images currently and in the future, 2000 frames. The RO digitizes the captured image to 8 bits and stores the image data into internal DRAM memory. All RO cameras that have 500 frames can be upgraded to 2000 frames. The table to the right shows the record time for the RO. An RO with 500 frames uses about 100 Megabytes of memory. Whether the camera has 500 frames or 2000 frames, it fits the same form factor as standard Hy-G film cameras.

The RO is designed to operate similar to a film camera. Prior to recording, the RO camera is in sleep mode or Standby. A signal is sent to the camera to wake it up from a low power state to a ready-to-record state. The time from standby to ready mode is 2 seconds. This assures that the camera sensor, camera electronics and communication are all in sync. After the camera is in the Ready mode (hardwired ready status line is True), a Trigger signal from the user will start the camera recording. The first image recorded will be frame 0. The camera continues recording until the end of memory. At that time the camera will automatically download the images to the Memory Module (PCMCIA drive or Flash card) if programmed by the user. Otherwise, it will wait in a hold mode until instructed to download the images to the Memory Module.

The RO has three methods for communicating. The simplest is a four-wire interface shown below in a multiple camera configuration (Figure 1). This interface provides hardwired control of the camera without the use of a computer. Each of these lines can be bused together to other cameras in a wired-or network. In this networked configuration, all cameras can be initialized, triggered and status monitored from a common set of lines controlled by applying or sensing a DC voltage.

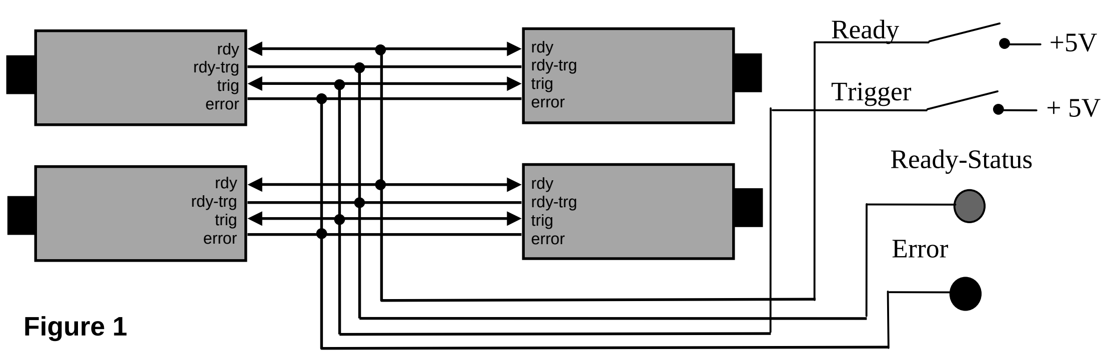

Figure 1

The second method of communicating with the camera is the RS-485 interface. The RS-485 serial communication interface is used to configure and control the camera. The RS-485 serial interface can be bused together for networking cameras. Certain commands sent over the RS-485 interface will be global, meaning all cameras recognize the command at the same time. Other commands will require addressing individual cameras through the RS-485 interface. A partial list of RS-485 commands are shown in the table below.

Command	Function	Command	Function
Attach	gains control of RO	**Download**	archives recorded images
Stop	aborts any command	**Rate**	sets the record frame rate
Live	RO displays Live images	**Exposure**	sets the exposure for Live/Rec
Ready	sets RO into Ready mode	**Adjust Offset**	starts a white/black balance
Record	RO starts recording	**Set Session ID**	test number
Set RO ID	sets camera ID	**Set Autosave**	enables auto save to disk
Get RO State	returns RO status	**Get Imager Type**	returns the type of camera
Get RO Temp	returns RO temperature	**Get Session Len**	returns the size of frame store
Get Batt Status	returns battery status	**Identify**	returns RO ID
Reset	resets to default values	**Reset**	erases all images in DRAM

The RS-485 interface when bused is shown in the figure below in Figure 2. Cameras are uniquely identified by the ID programmed by the user. The RS-485 interface can be driven from a PC using a National Instruments 485 card. The distance that can be driven is over 100 feet.

The RO Imager in the future will have a high-speed serial interface. This interface would allow networking of cameras together to a common cable. This common cable would attach to a computer. Images are transferred through the high-speed serial interface to the computer. No camera control is allowed through this interface.

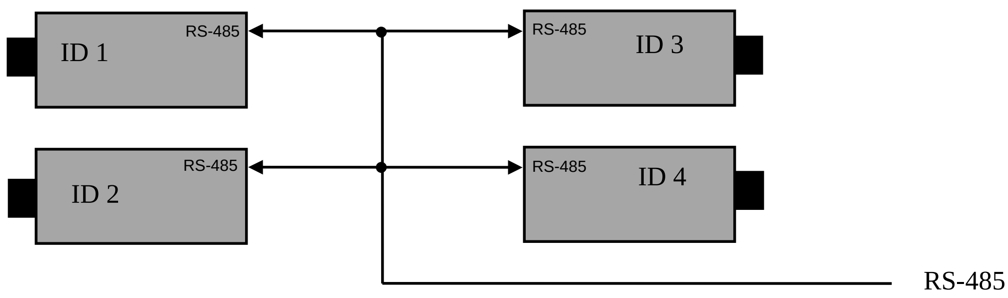

Figure 2

The RO block diagram is shown in the figure below (Figure 3). The RO has one main connector. All system power, hardwired signals (Ready, Trigger, Ready Status, Fault), RS-485, HS Serial and wired-or fault indicators are through this connector. It is a round military type of connector.

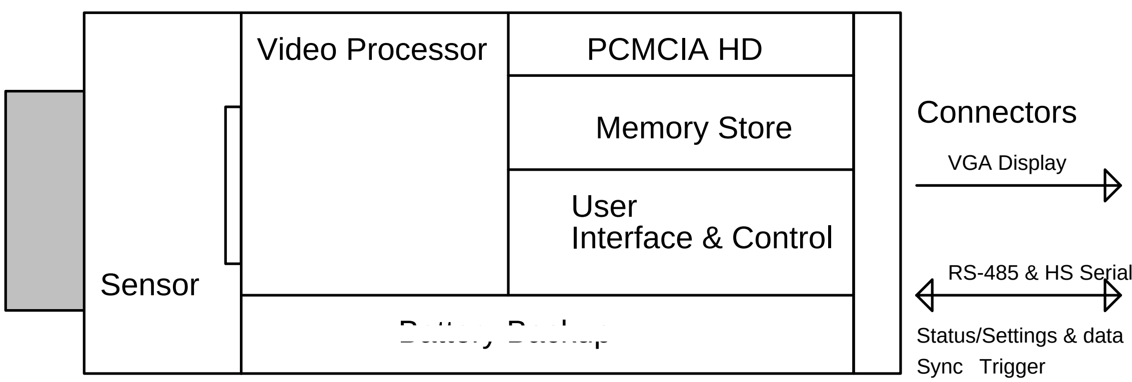

Figure 3 RO Block Diagram

CAMERA TECHNICAL DESCRIPTION

The camera has an electronic shutter built into the 512 x 384 CCD sensor. Operating at 1000 fps the sensor provides excellent subject detail. The electronic shutter operates as fast as 50us exposure. The camera supports a monochrome or color sensor. The color sensor has a Color Filter Array (CFA) deposited on its surface. This CFA sensor produces accurate 24-bit color. The color processing is done outside the camera when the images are transferred to a computer. This simplifies the amount of hardware in the camera, lowers cost and reduces the necessary data to transfer by one third. The color processing will be discussed later in this paper. Within the camera body is all the signal processing electronics for the CCD. This camera digitizes the image data and stores it into a large memory store. Images are then transferred to the Memory Module or through the HS Serial interface to an image server. Shown in Figure 4 is a simplified block diagram of the camera. The CCD sensor will be discussed later.

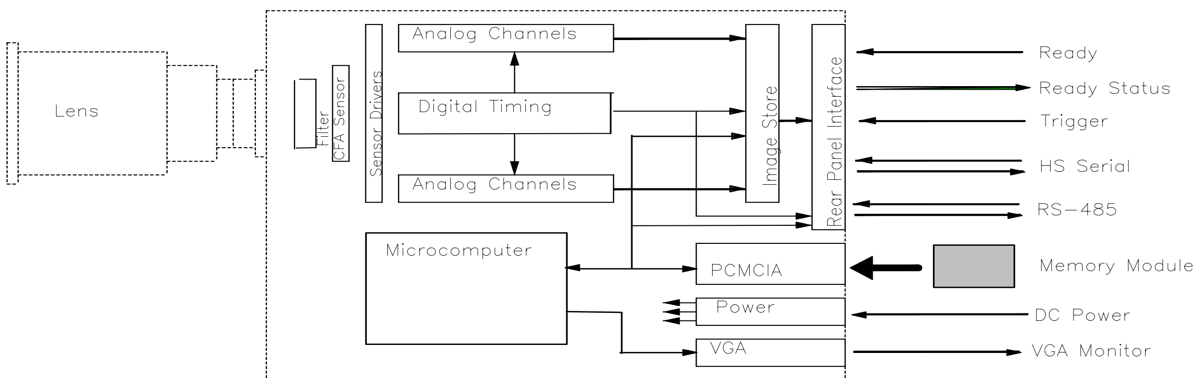

Figure 4 KODAK EKTAPRO RO Imager

Sensor Driver

The sensor driver assembly provides the sensor bias voltages, and translates the pixel-level timing generated on the camera controller into the precise timing and voltage drive signals necessary to drive video signals from the sensor.

Signal Processors & Data Conversion

Signal processors are responsible for conditioning the sensor signals for digital conversion. Analog control and setup of these functions are programmable, and controlled via a serial communication scheme. The sensor output channels are connected to pre-amps. The pre-amp amplifies the signal off the sensor to a level sufficient for processing. Next are the Gain & Offset electronics. Gain & Offset is used to amplify the signal and remove unwanted noise. Next is a Sample & Hold that retains an averaged sample of the video. An A/D converter then digitizes this video. Next is the Channel Formatter block that converts and buffers the digital signals for transmission to the Processor. This channel architecture is replicated for all of the outputs on the sensor.

Memory Store

The Memory Store is where images are stored. There is approximately 100 MB of storage for 500 RO images. This architecture is highly parallel to absorb the high bandwidth from the Signal Processing Channels.

Micro Computer

The Micro Computer controls the communication between the camera and the external interfaces. It transforms images into MSDOS readable files. It monitors the camera status and reports the information through the RS-485 interface. It transmits images through the HS Serial interface as well. All camera configurations is set with the Micro Computer into non-volatile memory.

Rear Panel

The Rear Panel contains all the connectors and external interface connections. There is a main connector through which all control signals are routed. It also has the HS Serial interface, the hardwired control/status lines and power. Through the RS-485 interface, the camera can be addressed and configured. The RS-485 is designed for multiple camera communication. There is a termination switch at the edge of the main connector. This is a slide switch.

On the Rear Panel there is a VGA Monitor interface. This is the display interface for setting field-of-view, focus and aperture settings. There is a lockable door that opens for insertion of a Memory Module. There will be two types of Memory Modules; a flash type and a hard drive type. The flash type is (Memory Module - FM) for on-board Hy-G use. The hard drive type (Memory Module - HD) is for off-board use. There are indicators that specify the camera's state of operation. Also, there are three pushbuttons that enable live, low light live, and manual download of images to the Memory Module. After a recording is made, these buttons when pressed control the direction of play in the camera. Press the button again and the play stops.

Power Conversion

All special voltages necessary for the camera is derived from a single-voltage DC source. The Power Conversion Assembly contains all necessary conversion circuitry and filtering.

Memory Module

The Memory Module interface conforms to a PCMCIA Type 3 standard. Either flash memory cards or magnetic disk drives can be inserted as a non-volatile backup for the RO memory. The Memory Module could be thought as a film cartridge. It is inserted into the camera to hold images. After the recording, images are downloaded to the Memory Module. These images must, then be interpolated for the 24-bit color images.

CCD Technical Description

CCD Sensor

The video format used by the EktaPro motion analyzer, model HRC and the RO camera are based on a 512 x 384 Kodak CCD sensor. The video format breaks the single wideband video channel into many parallel channels, each of moderate bandwidths. This approach simplifies the signal processing functions compared to handling one very complex channel. Each pixel is a photodiode. The charge on the photodiode is transferred to a shielded vertical CCD register. The charge is then transferred, line-by-line, to a horizontal register. The horizontal registers are then read as a block through a parallel channel. Each block must be balanced and maintained at precise black/white reference levels to produce its outstanding image uniformity. Shown below is a block diagram of the sensor (Figure 5).

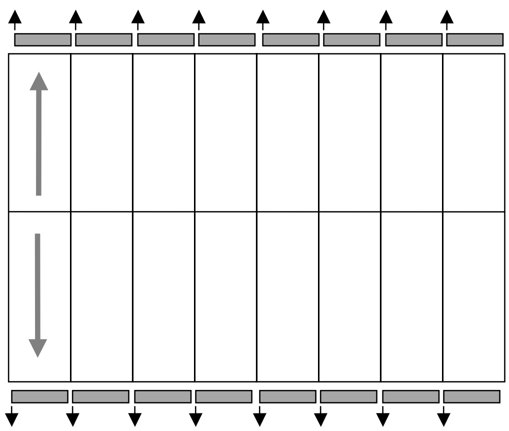

Figure 5

This sensor has an anti-blooming structure designed to handle large amounts of light. This anti-blooming works so well that the sensor can face directly into flood lamps and still capture the surrounding scene. This sensor also has an electronic shutter that can operate at a 50 usec exposure per frame. The shutter can be positioned at any point within the frame. This provides a method to synchronize the frame to subject at a precise time interval.

To produce color, the sensor has a proprietary Color Filter Array [CFA]. This CFA will filter light into red, green and blue wavelengths for certain pixels. The filtered pixels are later interpolated into a full 24 bit color space. The color interpolation is accomplished by in a Kodak custom color co-processor designed for this array. This color processing will be covered in later sections.

The sensor has excellent sensitivity. In the camera, the ASA speed is 480 for color and 2100 for monochrome. The sensor's spectral response is between 400nm to 1000nm.

Color Filter Array

A Color Filter Array (CFA) on the sensor produces full-frame, accurate-color images. Kodak was granted a U.S. Patent for this CFA called a Bayer pattern. It is designed for progressive scan sensors. The array is composed of a kernel of 4 pixels. The filters are deposited during fabrication of the sensor. Two corner pixels are green while the opposite corners are blue and red. A custom IC was designed to calculate in real-time 24-bit color [RGB] by reading the Bayer pattern and interpolating the two missing color pixels. Three color values per pixel must be calculated, red-green (rmg), green (g), and blue-green (bmg). All of the green pixels, rmg and bmg must be calculated. At the red pixels, bmg must be calculated. At the blue pixels, rmg must be calculated. Color difference values are obtained from either horizontal, vertical or bilinear interpolation of the color difference values at the chroma pixels. Solving for the missing green pixel, g' in the array is as follows:

line 1	B1	G1	B2	G2	B3
line 2	G4	R1	G5	**R2**	G6
line 3	B4	G7	B5	G8	B6
line 4	G10	R3	G11	R4	G12
line 5	B7	G12	B8	G13	B9

At a horizontal edge: missing green pixel (g') = 1/2(G5+G6) [1]

At a vertical edge: missing green pixel (g') = 1/2(G2+G8) [2]

Both edges or no edges: missing green pixel (g') = 1/4(G5+G6+G2+G8) [3]

Using the missing green pixel (g'), the rmg and bmg values are calculated as follows for a red line:

line 1	B1-g'	G1	B2-g'	G2	B3-g'
line 2	G4	R1-g'	**G5**	R2-g'	G6
line 3	B4-g'	G7	B5-g'	G8	B6-g'
line 4	G10	R3-g'	G11	R4-g'	G12
line 5	B7-g'	G12	B8-g'	G13	B9-g'

examples:

horizontal interpolation rmg @ G5 green pixel = 1/2 [(R1-g') + (R2-g')] [4]

vertical interpolation bmg @ G5 green pixel = 1/2 [(B2-g') + (B5-g')] [5]

bilinear interpolation rmg @ B5 blue pixel = 1/4 [(R1-g') + (R3-g')+ (R2-g') + (R4-g')] [6]

bilinear interpolation bmg @ R2 red pixel = 1/4 [(B2-g') + (B5-g')+ (B3-g') + (B6-g')] [7]

Prior to these calculations, the pixels must have all offsets removed and be white balanced to achieve proper neutral tones. Other signal processing is done on the pixels after interpolation. Edges are enhanced to bring out fine detail by extracting the high frequency terms from the green field. These high frequency terms are scaled to ignore large edges. The pixels are next passed through a color correction & space conversion matrix for the RED, GREEN and BLUE color. These colors should correspond to the SMPTE XA/11 standard referenced in the CCIR, 709.

Sensitivity

The photometric sensitivity for the Color Camera at 1000 fps [no shutter] is 480 ASA and 2100 ASA for the Monochrome Camera. These numbers are with an IR Blocking filter at 670 nm. The lighting source was xenon. This ASA calculation is not straightforward due to the differences in spectral response, radiometric for the sensor visa versa the photometric response for film. Film's spectral response beyond the fog level (30% above background noise) is between 300 nm to 700 nm. The sensor's spectral response is between 400nm to 1000nm. Figure 6 shows the spectral sensitivity curves for each type of sensor.

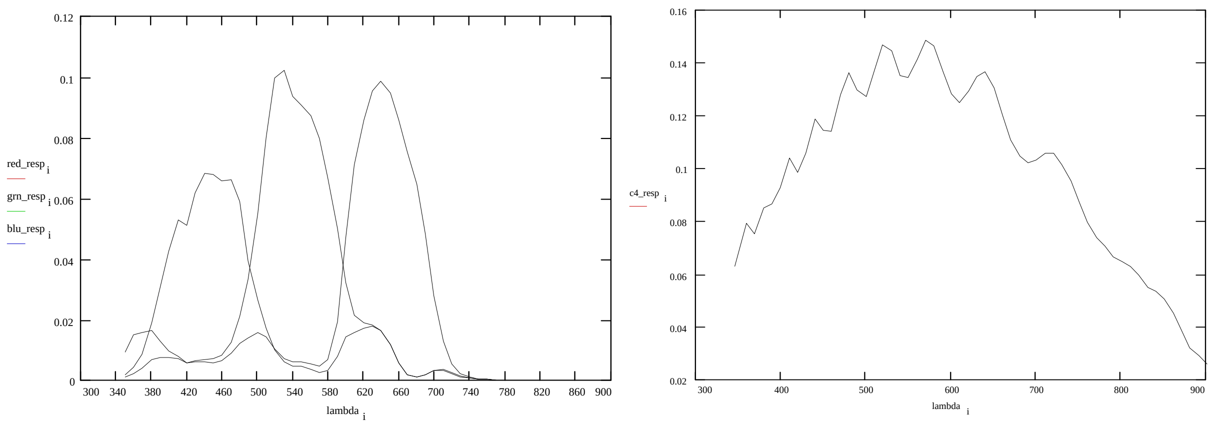

Figure 6 Color and Monochrome Sensor Spectral Sensitivity

Anti-Blooming

The camera can accept light overload levels many times that of full white, localizing the peak to only the saturated pixels. The sensor has specifically been designed to operate at high speeds with anti-blooming control. This is unique for high-speed sensors. This anti-blooming works so well that the camera can face directly into flood lamps that saturate a portion of the image and still capture the surrounding scene. Most CCDs and video tubes will bloom the entire image resulting in no information content for the scene. Capturing an event at high speed will often result in lost images due to a bright light washing out the scene. Most often, these images are the most critical ones since the cause of the unpredictable event can only be found in the images. This is why anti-blooming for high speed video imaging is so critical.

Shutter

An electronic shutter is essential for providing the stopping power. The shutter is disabled at 1/frame rate to allow the exposure period to be equal to the framing period. Periods of 50 uS, to 100 uS for 1000 fps, 50 us to 2100 us for 500 fps and 50 us to 3100 us for 250 fps are the shutter rates.

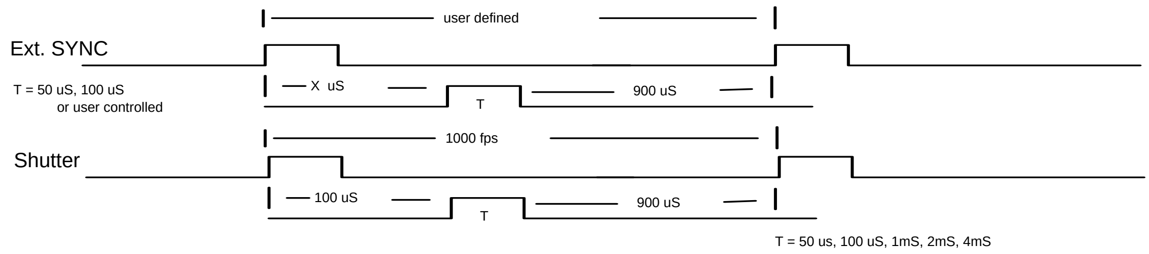

Figure 7 Shutter Timing

Resolution

The theoretical limiting resolution is 31.3 lp/mm.   Figure 8 shows the CTF curve monochrome sensor.   Figure 9 shows the CTF curve (lens not subtracted out) of a monochrome sensor and a color sensor operated in a monochrome mode. These show a reduction in the spatial resolution of 25%. This spatial reduction is expected with any sensor using a CFA to produce color images. As would be expected, the green channel is limited in spatial response due to the CFA kernel configuration and size.

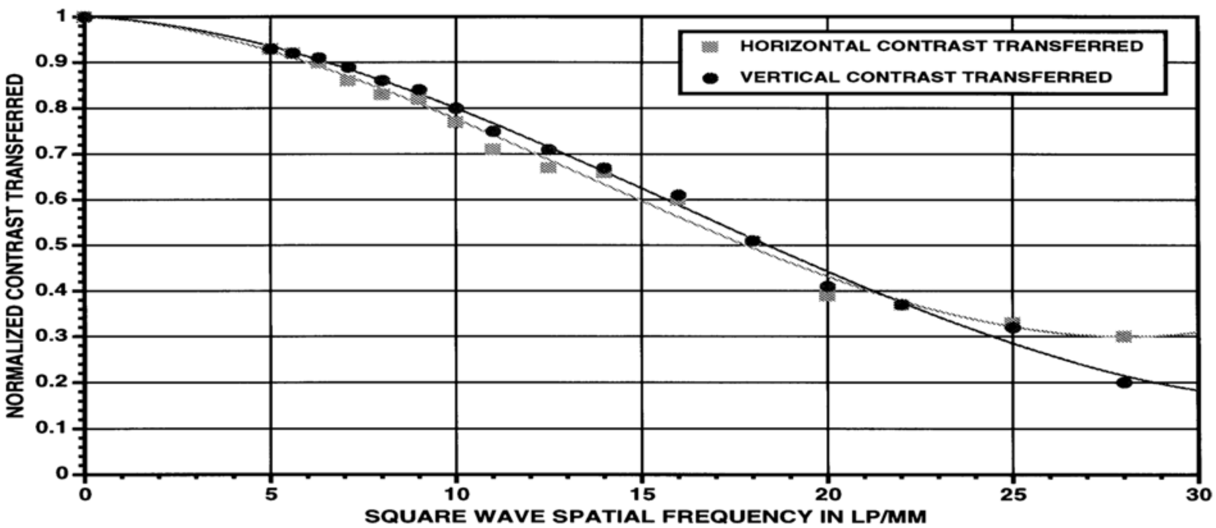

Figure 8 Monochrome sensor CTF Curve

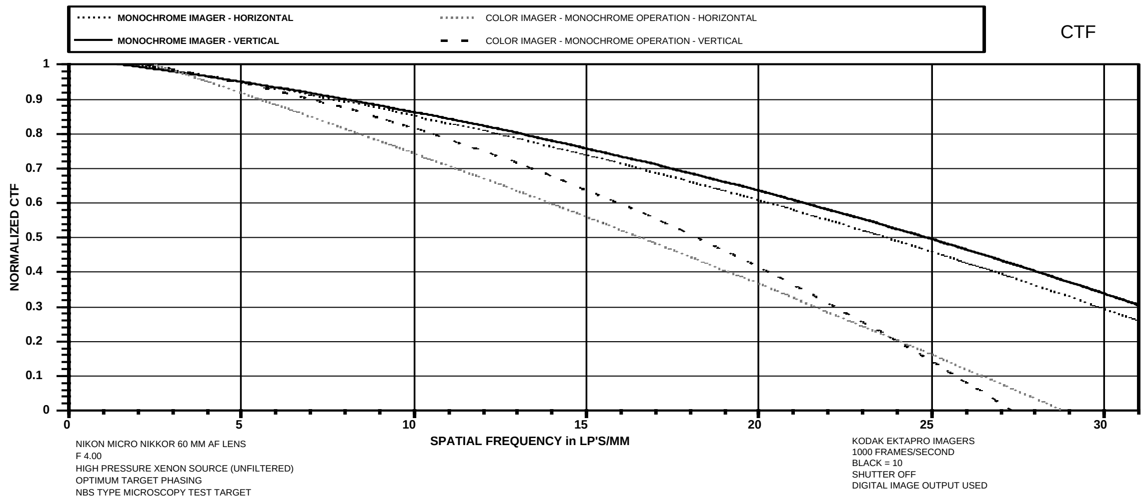

Figure 9 CTF Curve comparing a monochrome sensor vs. a color sensor in monochrome mode

APPLICATIONS & TOOLS

An application that is very demanding for image analysis is automotive crash tests. There are two main types of automotive crash test, barrier and sled. Sleds are used to work out the design issues before the more expensive barrier crash is tested. The sled is on a rail that is propelled from standstill to 30 MPH by a hydraulic piston. On the sled are replicas of human anatomies called hybrid dummies. These dummies are accelerated in the sled in the reverse direction. Since the dummies are facing in the opposite direction of movement, the motion simulates a deceleration experienced in a crash. The sled does not sustain any crash damage in this process, but the dummies receive the full G force of a crash. The test engineers need to measure the displacements of objects in relationship to the crash dummies. Much of this empirical test data will eventually lead to wire frame models that can predict the displacement. In addition to the sled test, car manufacturers must perform actual head-on crashes called Barrier Tests. Barrier tests are very expensive and the geometry of the test should be worked out before a car is committed. Sled tests are often repeated many times before the full-scale crash. At the start of acceleration a signal called Time Zero marks the beginning of the test. This signal can be used as a Trigger to the motion analyzer. Once the user starts the motion analyzer recording, the test can begin. As the sled is fired from standstill to full acceleration, the Time Zero signal will trigger the motion analyzer. Frames before the trigger and those after the trigger are saved in memory. In this application, the test normally captures about 300 significant frames. The trigger mode of image capture is ideal for this application.

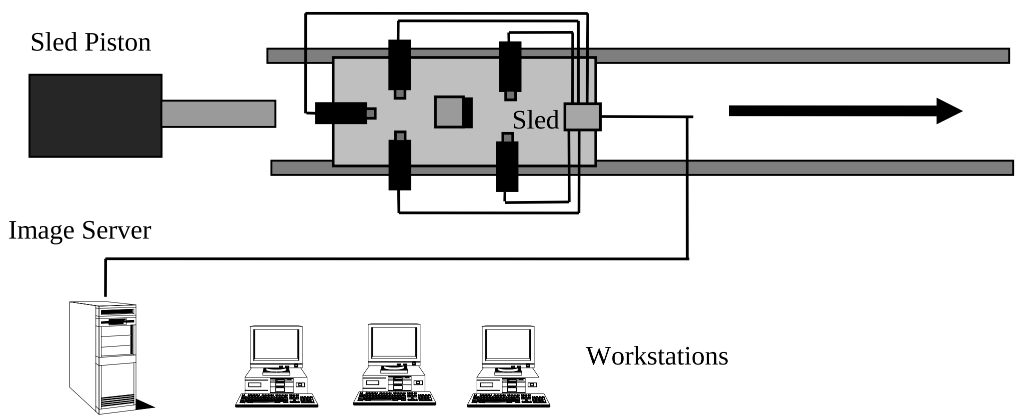

Figure 10

Shown in Figure 10 is a block diagram of a sled instrumented with RO cameras, an Image Server and workstations. In this example, there are 5 cameras mounted on the sled. These cameras are interconnected through a junction box that has a single output. This output can be connected to a control computer or an Image Server. The RO cameras can transfer images out of the camera through two interfaces, the Memory Module and the High Speed Serial interface. These images can be transferred to an Image Server for distribution or to a Workstation for analysis. An Image Server is a computer (PC) that is designed to network cameras together, convert the raw “Bayer” image format to 24-bit color images, provide a “quick look” at images, and hold the images for distribution over another network. A Workstation is a computer designed for analyzing images for motion.

The Memory Module when used to transfer images is often described as a “sneaker net”. Once the images are stored on the Memory Module, it must be removed from each camera. This is very easy to do and is the same as removing the film pack from a Hi-G film camera. Once the Memory Module is removed the next step is to insert it into an Image Server. The Image Server reads each Memory Module, converts the images into a format for display, and archives the images. The Memory Modules would then be available for the next test.

The second method of image transfer is through the High Speed Serial interface to the Image Server. Again, these images may be displayed for “quick look” or archived. Once the images are archived, they are available for analysis on workstations.

CONCLUSION

The KODAK EKTAPRO RO Imager is the first Hy-G electronic camera for replacing HS film cameras. Eastman Kodak Company, Motion Analysis Systems Division, has designed the camera. The RO's image quality, color accuracy at high speed and the compatibility of images with 3rd party software will increase the spectrum of new applications for motion analysis. The RO was specifically designed to take full advantage of Kodak's color technology to produce the highest quality high speed video images in our industry.

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