White Paper

High Frame Rate Electronic Imaging

Key Words: motion analyzer, high speed video, 16 mm film camera, rugged camera, high resolution camera, fast frame CCD, digital camera, high resolution video, record only camera, hi-g camera, gun camera, high frame rate, HSV

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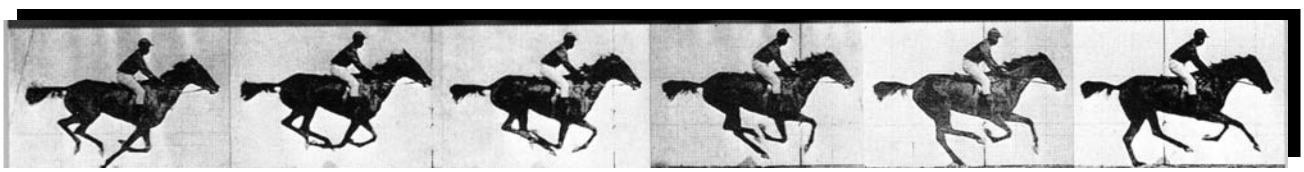
History of High Frame Rate Imaging

Introduction

High frame rate imaging origins began with the English photographer Eadweard Muybridge. He used a sequence of still cameras in the 1870s to photograph moving horses. Film became a means for capturing fast moving objects. Film processing had changed little over the years. It became more automated, the chemical solutions were more balanced, and the processing time had been somewhat reduced. However, special developing facilities were still required. So was time. Video changed that.



Up until the 1960's, film was the only medium available to record motion that was faster than the human eye could perceive. Video gave researchers and engineers a new tool for recording objects that move fast, random in nature, extreme in size or speed, or presenting challenging characteristics. New video technology was required to capture images of such demanding applications. The combinations of these new video technologies into a recording system are commonly referred to as a high-speed video system or a motion analyzer. Since the 1970s, when the first electronic motion analyzers became commercially available, the cost, capabilities and features of high-speed video and electronic cameras have improved dramatically. Today's high-speed video cameras offer far more capabilities and advantages than their forerunners. In addition, while film certainly continues to have important applications in high-speed photography, the increased sophistication of electronic motion analyzers ensures its place in solving future problems.

Origins/Classification

The evolution of motion analyzer technology can be delineated by frame rate and the sophistication of features. The first motion analyzers were an outgrowth of magnetic recording technology in the early 1960's, with the first generation motion analyzer commercially available in the 1970's. These video systems could only capture 120 frames per second (fps). Introduced by NAC Inc. in 1979, the second generation motion analyzer could capture 200 fps. This was a great step forward in technology since the HSV-200 captured images in color and could record for long duration. In 1980, Kodak introduced a third generation motion analyzer, the SP2000 motion analysis system. This revolutionary high-speed video device recorded monochrome images at 2,000 fps or 12,000 partial frames per second (pfps) onto half-inch instrumentation tape. Although the frame rate was unsurpassed for many years, the handling of images on magnetic tape was cumbersome.

The next significant technology advancement in motion analyzers came in 1986 with the announcement of the Kodak EktaPro 1000 motion analyzer, which operated at 1000 fps and 6000 pfps. Although it operated at a lower frame rate than the SP2000 motion analysis system, the EktaPro 1000 motion analyzer had many advanced features, including a low-cost, high-performance tape transport system, dual camera operation, GPIB control interface and IRIG timecode synchronization. The tape transport moved half-inch tape at 300 inches per second while the heads recorded 16 channels of image data. The dual camera operation allowed images from either camera or displayed them both in a split screen. The cameras could even operate at different frame rates. The two camera images could also be interleaved so that two 500 fps-cameras provided 1,000 fps. Magnetic recording technology has been used in the last three generations of motion analyzers. However, the technology suffered from the recording limitations inherent with magnetic tape-based motion analyzers. Such motion analyzers were not only limited by the amount of record time, but during a rewind cycle, the magnetic tape was not positioned for recording and an intermittent event at this time could not be captured.

Since these recorders were electro-mechanically intensive, there was a lag in recording images. The lag time encompassed the response time from the moment a recording was initiated to the actual recording of an image. There was a lag time associated with their ability to stop. The time required to start and stop made these motion analyzers inefficient for short recordings. Some applications require only a few images at any given time to be captured at a high frame rate. There may be long periods between capture. A magnetic tape-based motion analyzer would waste most of its recording media with start-stop sequences. These were but a few of the limitations. Moreover, with complex applications, the difficulties multiplied.

The fourth generation motion analyzer was an entirely new approach to high speed image capture by using solid state memory as the recording media. In 1990, Kodak introduced the EktaPro EM motion analyzer, which stored digital images in Dynamic Random Access Memory (DRAM). The use of DRAM was a departure from conventional wisdom that insisted an event must be captured by recording minutes of image data. However, the DRAM technology demonstrated that long record times were not necessary for most applications. Manipulating images with DRAM technology allows unique image capturing techniques that improve data quality and provides for continuous image recording. Over the last two decades, DRAM integrated circuits have been increasing in storage density and decreasing in storage cost per frame. Recently, DRAM architectures have been pushing the memory densities to a level where their use in high-speed motion analyzers is cost effective. Even higher densities are expected in the future.

The fifth generation motion analyzer advances the technology with higher resolution, faster frame rates and improved image quality for color and monochrome images. Three motion analyzers qualify as fifth generation machines. They are the Kodak EktaPro HS motion analyzer, model 4540, the Kodak EktaPro Hi-Spec motion analyzer, and the Kodak EktaPro motion analyzer, model 1000HRC. The HS 4540 records at 4,500 fps to 40,500 pictures per second. The HS4550 has four times the record rate over older motion analyzers at similar resolutions. The Hi-Spec is a more compact analyzer that records 1000 fps in rugged environments. The imager can withstand shock loading up to 40g. The HRC records up to 1,000 color or monochrome images per second at a resolution of 512x384 pixels—four times the resolution over older motion analyzers.

The sixth generation motion analyzers are self-contained and offer users increased flexibility and durability. The Kodak EktaPro RO imager, the NAC Memrecam Ci motion analyzer, the NAC Memrecam CCS motion analyzer, and the Kodak EktaPro MotionCorder 1000 qualify as sixth generation class analyzers.

The Kodak EktaPro RO imager is a stand-alone, self-contained camera specifically designed to replace film cameras in extreme environments. The RO is small in size and light weight. The imager accepts a removable PCMCIA hard drive or flash memory drive for archiving images from DRAM memory to these drives. The images are held until downloaded to a desktop computer. Previous motion analyzers were tethered to an image processor. The RO (record only) camera requires no such processor or tethering. Instead, any computer with appropriate software can convert the data to TIFF. Then the data can be analyzed.

The Memrecam provides similar stand-alone capabilities. It can deliver 500 color fps at a resolution of 580x434 pixels. By reducing the resolution, it can record up to 2,000 color pictures per second. The Memrecam Ci has a built-in control panel that is easy to use and simple. NTSC/PAL images can be viewed on a standard monitor as the user manipulates VCR like controls on the rear panel.

The Kodak EktaPro MotionCorder 1000 is a highly portable analyzer designed specifically for the Production Manufacturing environment. It is has a very small and highly sensitivity camera body for imaging in tight areas. It has an ASA equivalent of approximately 1600. It is a monochrome camera that has a resolution of 640 x 240. Combining the high sensitivity (extended depth-of-field) with this resolution, the MotionCorder produces superb images. The MotionCorder can image at 240 fps to 600 fps. It has different frame formats that provide more options for longer record time. It can record from a few seconds to over 40 seconds depending on the frame format.

The 6th generation motion analyzer's main advantages are size, cost, portability, ruggedness and ease of use. The RO is designed to capture images and have a limited playback. Images are intended to be playback on a computer. Since most companies already have a computer, and since most use specific analysis software anyway, their only additional cost is the camera. This kind of stand-alone image capture system is expected to represent the future of motion analysis systems. The new video systems could be compared to revolutionary technology found in personal computers, where customers combine different vendors' hardware and software to configure their machine to their specific applications.

Why Use High-Speed Video?

High-speed video cameras offer the advantages of ease of use, live picture set up, reusable recording media, and most importantly, immediate playback capabilities. The technology also offers specific cost benefits. There are no chemicals or film to buy. The high-speed electronic camera can be used repeatedly without concern of the cost of disposable media.

In the case of disadvantages, there are two: speed and resolution. Film still offers greater frame rates and resolution. Shown in Figure 1 is a plot of electronic resolution in pixels vs. film types.

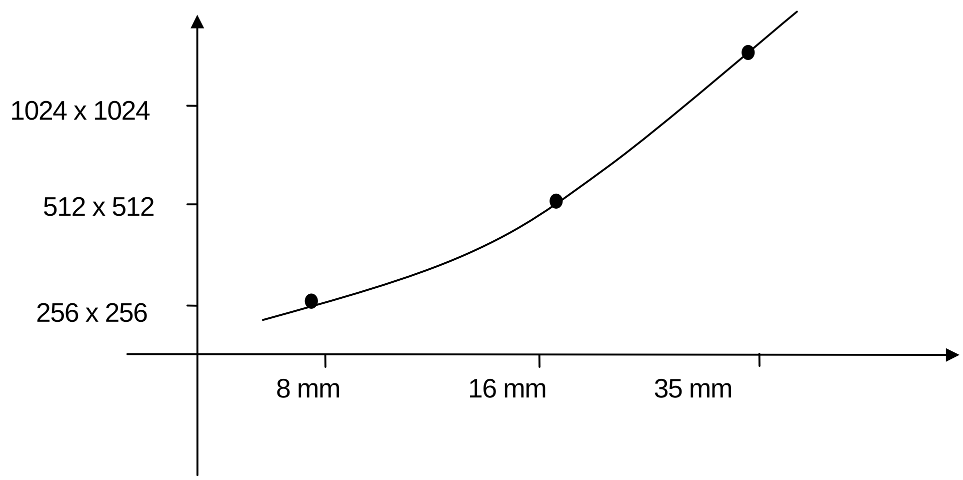


Figure 1 Resolution Vs. Film Type

Other applications currently using high-speed motion analysis, include: production line trouble shooting, machine diagnostics, destructive testing, automated assembly, packaging, paper manufacturing and converting, and a variety of impact, shock, and drop tests. Some research groups use the technology to study combustion, ballistics, aerodynamics, flow visualization and human performance.

Because film cameras require a “wind-up” time to get up to full speed, electronic imaging has distinct advantages when events are unpredictable or intermittent. Some examples include: lightning strikes, a jam in a production line, a blade failure in a turbine engine, or a vessel subjected to increasing pressure until it ruptures. Due to the unpredictable nature of such events it is hard to know in advance when to start the camera. Electronic cameras, on the other hand, can be triggered automatically by a variety of means; or they can record continuously in a loop until triggered to stop.

For example, in a canning operation, one out of every thousand cans jams up the production line. However, because the jam is completely unpredictable, there is no indication when a problem may occur. By the time an event occurs, recording is too late. To keep the camera running at high-speed while waiting for an event is extremely costly and impractical. Shown on the next page are several tables for various record lengths, record rate and playback times.

0.5	250	500	1000	2000	3000	4500
1	125.00	250.00	500.00	1000.00	1500.00	2250.00
5	25.00	50.00	100.00	200.00	300.00	450.00
10	12.50	25.00	50.00	100.00	150.00	225.00
15	8.33	16.67	33.33	66.67	100.00	150.00
30	4.17	8.33	16.67	33.33	50.00	75.00

Table 1 Playback Time (sec) vs. Record Frame Rate for 0.5 sec

5	250	500	1000	2000	3000	4500
1	20.83	41.67	83.33	166.67	250.00	375.00
5	4.17	8.33	16.67	33.33	50.00	75.00
10	2.08	4.17	8.33	16.67	25.00	37.50
15	1.39	2.78	5.56	11.11	16.67	25.00
30	0.69	1.39	2.78	5.56	8.33	12.50

Table 2 Playback Time (min) vs. Record Frame Rate for 5 sec

60	250	500	1000	2000	3000	4500
1	4.17	8.33	16.67	33.33	50.00	75.00
5	0.83	1.67	3.33	6.67	10.00	15.00
10	0.42	0.83	1.67	3.33	5.00	7.50
15	0.28	0.56	1.11	2.22	3.33	5.00
30	0.14	0.28	0.56	1.11	1.67	2.50

Table 3 Playback Time (hours) vs. Record Frame Rate for 60 sec

Electronic cameras offer another distinct advantage: synchronization. Multiple electronic cameras can be set up at different angles to record an event of series of events. The cameras can be triggered together or in any particular sequence. Most importantly, when any cameras are running at the same time, they capture data at exactly the same moment. Precise synchronization provides more complete data, better quantitative measurements and more accurate analysis. Such precise synchronization is not possible with high-speed film cameras.

In an airbag deployment for example, engineers would want to see a test from a variety of angles. The information is far more valuable if an exact moment can be viewed from different angles. Because such events are of extremely short duration, having cameras even slightly out of synchronization reduces their information value for 3-D analysis tremendously.

The electronic camera's immediate playback capabilities may be its greatest asset. The cost of film is miniscule when compared to the cost of an engineer's time. If a test can be reviewed immediately, engineers will know if they need to plan another test. It also speeds the entire process up in finding a problem and then correcting it. The lengthy delays between tests and the expensive set-up and tear down of test equipment are outdated.

Fundamental Technology

Sensor

There are three sensor[3] architectures most commonly found in high frame rate digital cameras: frame transfer, interline transfer and interline. A short description for each structure will be given along with their performance characteristics.

Charge Coupling with Pixels

A classical three-clock phase CCD gate structure will serve as the model for describing the charge transfer between pixels. A CCD sensor captures the optical image by tessellating the incident light into a two-dimensional array, X by Y picture elements (pixels). The light energy (photons) is converted into electrons. The electrons are collected as charge in a photosensing element. This element can be a photocapacitor, photodiode or photo-gate that is called a pixel. The control of the charge coupling within the sensor is illustrated in following figures.

A pixel consists of a photo-sense element formed under each gate, Figure 2(a). In the example, the gate with positive voltage forms a photosite for collecting charge. The gates with 0 voltage act as barriers. During charge accumulation, G1 is held at a positive voltage, which creates a potential well beneath the gate. Photons pass through the gate that is formed out of polysilicon material to create hole-electron pairs. The electrons are swept out of the region. he holes are captured in a depletion

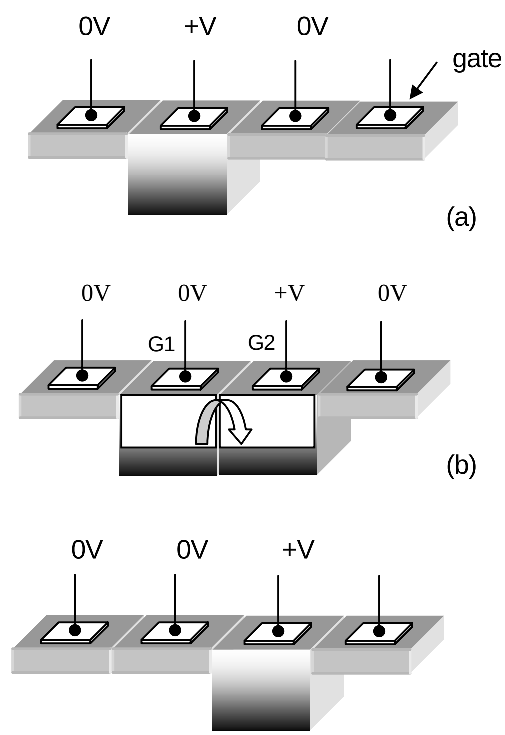


Figure 2 Charge Coupling with Pixels (c)

zone near the surface of the gate. The charge continues to accumulate (called integration) as photons create hole-electron pairs, until the cell's charge is read out.

The charge is read out by moving the charge from pixel to pixel, Figure 2(b). This is called charge coupling, hence the name charge coupled device (CCD). Charge is moved by clocking the adjacent gate (G2) to the same positive voltage as its neighbor. The charge flows into the newly formed well. To empty all the charge out of the previous well (G1), its gate voltage needs to be brought to 0 volts, Figure 2(c). This forces all the charge into the new well.

There is a last gate in this type of structure. It provides a node to dump the charge at the end of a column. It is biased to provide a DC potential barrier to isolate the photo-sense element from the output node. From this output node, the charge is moved to an amplifier that converts the charge into a voltage level. This is the clocking process in a 3-phase CCD structure.

Frame Transfer

In a frame transfer sensor, a high percentage of each pixel site is designed to capture and translate the incoming energy. Typically referred to as the "fill factor," this capturing and translating can approach 100%. However, a situation can occur, using our water bucket analogy, whereby the incoming light is so strong that the bucket fills and overflows (pixel blooming). Since the sensor is an array, adjacent buckets (pixels) are on the sides of the overflowing bucket (pixel). The only place for the excess overflow water to go is into the neighboring buckets. This overflow process, if excessive, can continue until all of the excess has been propagated to many adjacent pixels. This situation results from scenes that have bright, spectacular areas.

This is referred to as "blooming" of the sensor. The effect in an image is an area or vertical stripe, which saturates to full white level, indicating the pixels are saturated. An area of high illumination near an object of interest may be corrupted to the point that data cannot be accurately interpreted. Fortunately, if one is willing to give up some of the fill factor, some of the pixel site area can be configured to function as an overflow drain. This drain is able to bleed off the excess charge once the pixel's well (or bucket) is filled so as not to corrupt its neighbors. This overflow drain is an extremely important feature in preserving good data to interpret imaging information, or in an application where illumination cannot be totally controlled.

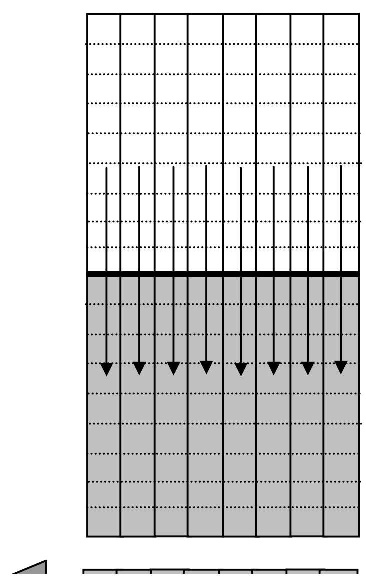


Figure 3 Frame Transfer Sensor Architecture

The process of imaging with a full-frame sensor can be related to that of film in a camera. Film has no ability to capture an image at one moment in time and stop the incoming light until the film is advanced. If no means is employed to stop the light before the film is advanced it will either be blurred or fully exposed. The same situation exists for a full-frame sensor. In this case, the sensor's charge must be read off all the pixel sites to be ready for the next image capture. The answer is similar to that of the film camera; that is, some form of shuttering system must be incorporated. The shutter is opened for a specified amount of time to let the image's light fall upon the sensor for recording and then closed while the readout takes place.

The second area has a mask on the pixel's surface that block any light from adding charge to the storage site. In the sensor's operation, the light builds up charge in the unmasked area for a given amount of exposure time.

Then, very rapidly, all the pixels have their collected charges transported to the corresponding pixel sites under the masked area. From that area, the charges can be read off the sensor to be translated into an image for viewing.

Before the next capture can begin, any accumulated charges in the unmasked pixel area must be drained off. The sensor is then ready to start the capture process again. Depending upon the specific architectural design of the sensor, smearing of the image can occur in this design because of the need to transfer the collected image rapidly to the masked portion. This can detract from the clarity of the final image and influence the ability to correctly interpret image

Reading or collecting the sensor's data is handled through one or more readout registers located at the edge of the sensor. While different conventions exist, one of the more common is to have the first edge row of pixels transfer their values into an associated position in the adjoining register. Once there the charges are cascaded off the register in a serial fashion from one end. Once the last row of pixels has had its charges moved into the register, a transfer is set up to move all of the next to last row's pixel charges into the associated last row positions. This process prepares for the next cycle of moving charges into the readout register. In a similar fashion this cascading row movement continues until each remaining row has been shifted one row closer to the readout register.

Interline Transfer

An interline transfer CCD, while sharing some common design features with the previous architectures, incorporates some significant differences. At the pixel site, part of the area is set aside with a mask to act as a local storage site at the end of an exposure. One of the performance trade-offs for this architecture is giving up some sensitivity because of smaller pixel area for the ability to perform electronic shuttering. Since the storage area is at the pixel site adjacent to the active area, the transfer of charge can be accomplished very fast, thereby stopping the exposure cycle. Because the transfer happens at the pixel site with a short transfer distance, little chance for smearing exists. With the charge stored safely at the pixel, a cascading movement of charge from one masked site to another is initiated to move these charges off the sensor, similar to the approach described for the full-frame architecture.

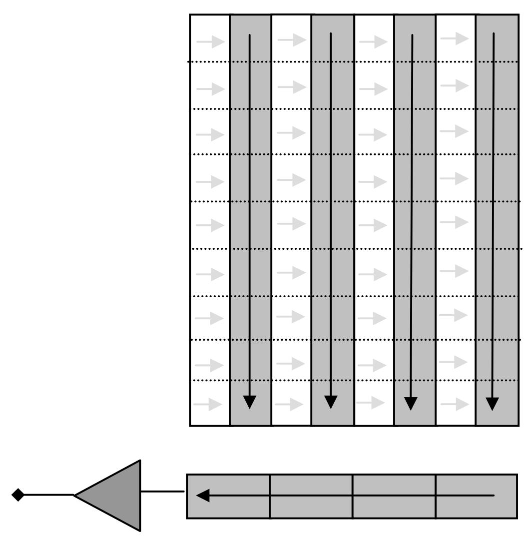


Figure 4 Interline Sensor Architecture

Additional area at the pixel site can be set aside to perform the blooming suppression, or overflow task, noted earlier. In an effort to make up for the loss of collection area, which impacts the sensitivity of the sensor, sensors from some foundries (i.e., Kodak) have processed a microlens on each pixel. A microlens can double or triple the amount of light directed onto the remaining active area. This compensates for much of the loss of pixel area. In terms of photographic measurement this can gain back almost one to one-and-a-half f-stops.

For our next discussion about pixels and their mechanism for moving charge, we will address a true two-clock phase CCD example. The *KODAK DIGITAL SCIENCE* KAF-1600 Image Sensor (full-frame CCD) is manufactured by Eastman Kodak Company, Microelectronics Technology Division.[4] The device is built with an advanced true two-phase, two-polysilicon, NMOS CCD technology. This type of technology aids in the reliable fabrication of small pixel sizes. It also contributes to a higher short-free yield and aids in lowering the dark current without compromising charge capacity. The extremely low dark current makes the device ideal for low light imaging applications. The on-chip output amplifiers have been specially designed to perform at a high-speed operation (45 MHz BW) at low noise levels (15 e- rms) to increase frame rate.

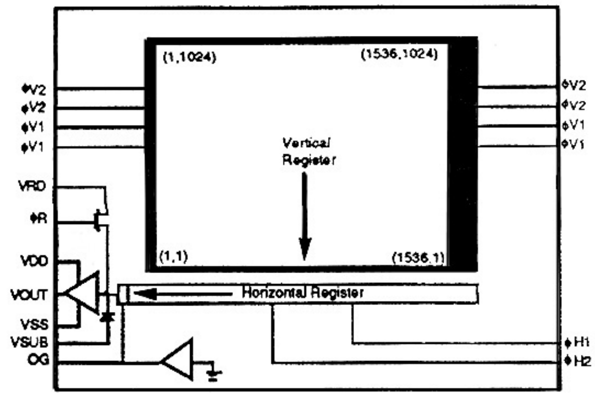


Figure 5 KAF-1600 Image Sensor Block Diagram

Referring to the full-frame block diagram the sensor consists of one vertical (parallel) register and one horizontal (serial) CCD shift registers and an output amplifier. All registers incorporate two-level polysilicon and true two-phase buried channel technology. The vertical register consists of 9.0 μm x 9.0 μm photocapacitor sensing elements (pixels), which also serves as the transport mechanism. T he pixels are arranged in a 1536(H) x 1024(V) array in which additional 16 columns and 8 rows of light shielded pixels are added as dark reference.

An image is acquired when incident light, in the form of photons, falls on the array of pixels in the vertical CCD register and creates electron-hole pairs (or simply electrons) within the silicon substrate. This charge is collected locally by the formation of potential wells created at each pixel site by induced voltages on the vertical register clock lines (¢V1, ¢V2). These same clock lines are used to implement charge coupling for readout. The amount of charge collected at each pixel is linearly dependent on light level and exposure time and nonlinearly dependent on wavelength until the potential well capacity is exceeded. At this point, charge will 'bloom' into vertically adjacent pixels unless drained.

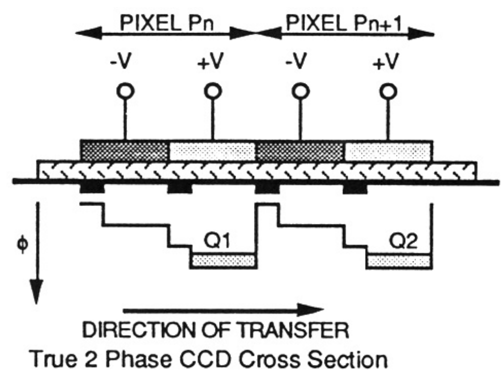


Figure 6 True 2-Phase CCD Cross Section

Integrated charge is transported to the output in a two-step process. Columns of charge are first shifted line-by-line into the horizontal CCD. Lines of charge are then shifted to the output pixel-by-pixel. Transfer to horizontal CCD begins when ¢V1 is brought high causing charge from the ¢V1 and ¢V2 gates to combine under the ¢V1 gate. ¢V1 and ¢V2 now reverse their polarity causing the charge packets to 'spill' forward under the ¢V2 gate of the next pixel. The rising edge of ¢V2 also transfers the first line of charge into the horizontal CCD. A second-phase transition places the charge packets under the ¢V1 electrode of the next pixel. The sequence completes when ¢V1 is brought low while the horizontal CCD reads out the first line of charge using complementary clocking of ¢H1 and ¢H2 as shown. Vertical register clocking in this way is known as accumulation mode. The falling edge of tH2 forces a charge packet over the output gate (OG) onto the output node (floating diffusion) and sensed off-chip. The cycle repeats until all lines are read.

Charge packets received from the horizontal register are dumped onto the floating diffusion output node, whose potential varies linearly with the quantity of charge in each packet. A two-stage source-follower amplifier is used to buffer this voltage change to the outside world. The translation from electrons to voltages is called the output sensitivity or charge-to-voltage conversion. After the charge has been sensed off-chip, the reset clock (¢R) removes the charge from the floating diffusion via the reset drain (VRD). This, in turn, returns the floating diffusion potential to the reference level determined by the reset drain voltage.

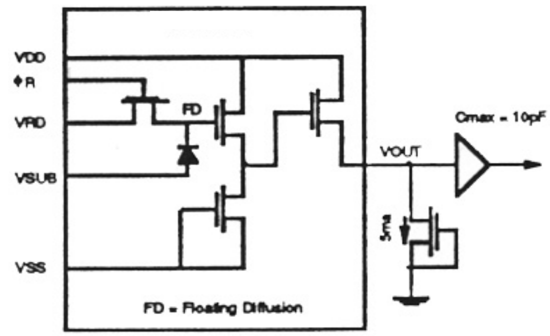


Figure 7 CCD Output Structure

User Interface

There are examples of well-designed user interfaces all around us, light switch, radios, automobile accessory controls. Most interfaces are easily distinguishable between simple, and complicated. What factors separate the interfaces from those that are complicated from the simplistic are physical complexity, evolution of a design, and the analog/digital nature of the controls.

One could think of a VCR controller and imagine a device with 50 or more keys. This would be overwhelming to most users. Some elegant designs have only the most essential controls on the keypad, with the more detailed operations dedicated through on-screen interfaces. Many user interfaces for digital cameras have gone this direction.

The evolution of a design depends largely on the longevity of the technology. The telephone is a great example of an evolving technology that has become simpler, yet more sophisticated. While digital is new, analog electronic cameras have been around for years. It is safe to say that many user interfaces are still evolving for digital cameras. What is normally being expected as part of the interface is still to be established by customer requirements in imaging standards.

Digital has brought new capability into our world that previously was unavailable with analog. However, a human has a simple mental understanding of turning a knob vs. typing in a number. More user interfaces that are implemented in software for cameras are starting to use the representation of analog controls in the interface. This takes advantage of association of the analog operation, but in digital terms.

Now that some design philosophy has been given concerning a user interface, we should explore what control features are important to operating a digital camera.

The user interface can be defined in terms of camera controls. These controls have varying degrees of importance depending on the application. However, there are some fundamental controls that should be found with all digital cameras. These controls are:

- setting the exposure time to control the light
- changing the gain to improve sensitivity
- setting the black level to make an offset adjustment
- configure the mode of operation to define how an image is to be captured

Other controls that are useful but not essential are:

- enabling defect correction to remove bad pixels
- changing strobe output polarity
- detecting camera status
- defining external trigger polarities

These controls can be in the form of physical interfaces with knobs or switches. Most advanced cameras today are using software interfaces for control. This approach allows, in many instances, a path for updating the controls, more flexibility in the range of the controls, and a larger variety of commands. In addition, the Frame Grabber will often provide additional control of the camera through its interface including timing, pixel depth, and frame size.

In considering all aspects of the user interface, one should pay attention to the ease of use. Even if the application is one that does not require constant adjustment of the camera, an end user needs to feel comfortable in setting up the camera. Therefore, adherence to good ergonomic design with intuitive controls should be found in any camera's User Interface.

Imaging Devices

Imaging devices are the detectors that convert light from photons to electrons. Typically, this sensor has a structure using MOS or CCD technology. The sensor captures the optical image by tessellating the incident light into a two-dimensional array representing the picture. The photosite is called a pixel. The light energy is converted into an electrical charge. Depending on the architecture of the sensor, these pixels are addressed to read the converted charge out of the sensor. Some sensors use a photo capacitor or a photo diode as the photosensitive element in the sensor. After conversion, some offsets and parasitic components must be removed from the signal. This is the process for converting light into an electrical charge.

Most imaging devices used in today's motion analyzers are solid-state sensors. There are a few motion analyzers still use tubes (i.e. vidicon, plumbicon). The main advantage using the tubes is the low cost. However, tubes will deteriorate over time, exhibit image lag from fast moving objects, are subject to damage easily and are non-linear in their photoelectric response. In contrast, the solid-state sensors characteristics include no deteriorating over time, no image lag, and they are linear. Some sensors are coupled with image intensifiers. An image intensifier is used to amplify light. Some intensifiers also have a shuttering capability. Some solid-state sensors have electronic shuttering that can be precise controlled. Today, tubes are not used for imaging but rather for light amplification.

Electronic sensors that operate at frame rates above 200 fps are multi-channel devices. Multi-channel means that the sensors read the imaging data out in parallel over multiple readout channels. The fundamental sensor architectures include interline, interline transfer, block, and frame transfer. The interline architecture is good for very fast frame rates but is limited in resolution due to the charge transfer over long busses. The interline transfer is usually made with a combination of a photo-detector that transfer it's charge to a CCD shift register. These sensors are good for higher resolution but typically have a limited frame rate not much over 1000 fps. The block type of architecture divides the sensor into sub-blocks. These blocks are readout in a predetermined order. This allows a very high readout rate (fps) but the resolution is limited due to the bus structure. The frame transfer type of sensors has to move all pixels to a shielded area on the sensor. From the shielded area, the pixels are read out of the sensor. This type of sensor is limited in the frame time but typically have higher resolutions than the MOS devices (interline).

The block, interline transfer and frame transfer are shown in Figure 8

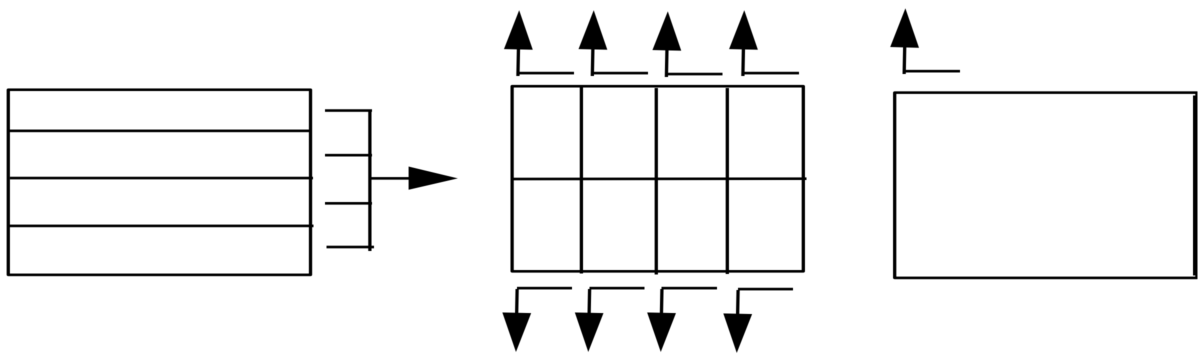


Figure 8 Block, interline & frame readout structure

Signal Processing

The signal-processing channel is very important for producing high-quality images from a motion analyzer that uses multi-channel sensors. The noise associated with one channel may be small when viewed as a single element. However, when multiplied by several adjacent signal-processing channels, the noise is very noticeable. This is why it is important for any multi-channel motion analyzer to have very low noise channels.

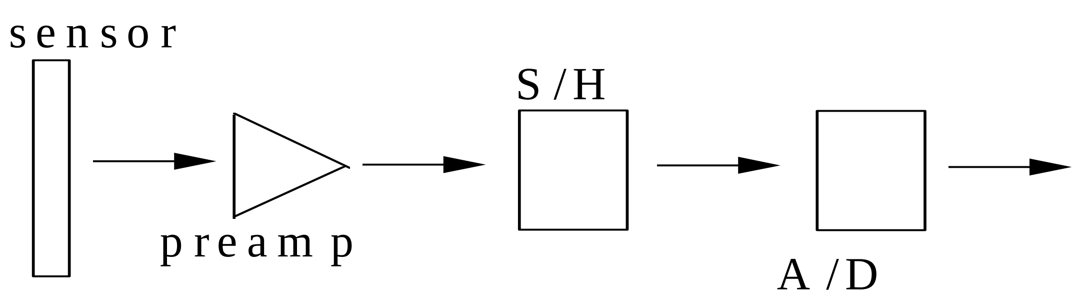


Figure 9 High Speed Video Channel

A typical signal-processing channel is shown in Figure 9. First, the video signal output from the sensor is amplified by a preamp. Next, the video signal passes through a sample-and-hold circuit. The purpose of the sample and hold is to capture the video signal and hold it for conversion. There are many forms of sample-and-hold circuits. One of the most commonly used designs is a correlated double sampler (CDS). This circuit, in addition to the sample-and-hold function, eliminates reset noise associated with the charge-to-voltage output structure of the CCD imager. The next step is to convert the analog video signal to a digital value. The analog-to-digital converter transforms a given voltage level to a digital code value. This code value will be as wide as the analog-to-digital converter's precision. Most high-speed video systems convert the pixel values to eight bits.

One way to determine the performance of a video-signal processing channel is with an assessment of sources of noise within the channel as compared to the actual video level. This is called the signal-to-noise ratio (SNR). SNR is a common figure of merit used in video specifications and is given as follows:

Channel SNR is defined as:

SNR (db) = 20 log 10 [Channel Signal $_{max}$ /Channel Noise $_{sum}$]   Equation (1)

where:

- Channel Signal $_{max}$ is the full scale video level measured in millivolts
- Channel Noise $_{sum}$ is the square root of the sum of the squares of
- pre-amp, sample-and-hold noise sources, and analog-to-digital noise sources.

The sensor SNR is defined as:

SNR (db) = 20 log 10 [$S_{electrons, full well}$ /$N_{electrons, noise}$]   Equation (2)

where:

- $S_{electrons, full well}$ is the signal charge in electrons rms (root mean square) stored in the fully saturated well.
- $N_{electrons, noise}$ is the standard deviation of noise in electron rms.

Summing the noise for each element in the signal processing channel described in Figure 9 gives an accurate measurement of its performance as given in Equation 1. Noise from the sensor must also be added to get the complete estimate of channel noise.

When a specification sheet describing the digitization of an image to 8 or 10 bits, the true SNR should be examined. SNR values for a true 8-bit video signal are 48 dB and 60 dB for a 10-bit video signal. If the specification sheet claims a 10-bit pixel, the SNR must be 60 dB to have 10-bits. Simply using a 10-bit A/D on a signal that has an SNR of 8-bits will not give you the expected dynamic range or image quality.

Digital Image Storage

There are two types of image storage for a motion analyzer. The first type captures images at the frame rate of the camera. The second type archives images onto magnetic media after the images are captured. The difference between the two types of storage is not only the rate at which images can be written, but their permanence as well.

Capture Storage

Motion analyzers have used various types of electronic media to store images during capture. This includes magnetic longitudinal recording, helical scan recording, solid-state memory (DRAM), magnetic disk, optical disk and magneto-optical disk.

Magnetic media have been used because of a long history of storing recorded information. The first demonstration of magnetic recording for reproduction of information was by Valdemar Poulsen in 1898 (telegraphone). In 1920, the development of the vacuum tube amplifier made possible the reproduction of sound at a specified level from a steel wire. In 1947, the introduction of magnetic recording to radiobroadcasting started with The Bing Crosby Show. The art and science of magnetic recording have advanced significantly since that time.

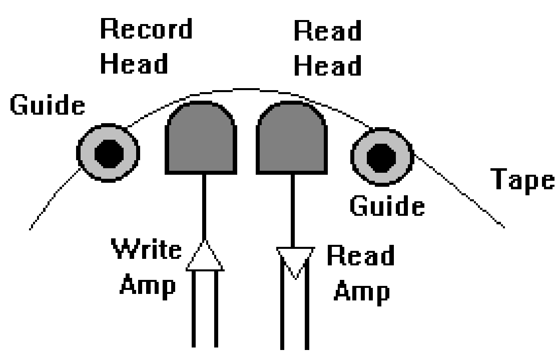


Figure 10 Magnetic Recording

A simplified process of magnetic recording is illustrated in Figure 10. An incoming electronic signal is amplified through the write amp, which excites the record head with a current. The record head produces a magnetic field. This field is contained within the head except at the point where the tape makes contact with the head. At this point, the head has a separation called the head gap. The magnetic field diverges from the head and penetrates the magnetic tape, which "copies" the information onto the tape. The tape moves by the transport at a constant velocity while the magnetic head's field changes according to the next signal to be recorded.

The reproduction of the original information requires rewinding the tape and passing the area, which was recorded over, reproduce heads. The magnetized area on the tape induces a magnetic field onto the reproduce heads. This field is converted into a current by the heads and is then amplified and restored. Restoring the signal means that it must be corrected for distortions introduced by the magnetic recording/reproduction process. These are the basic record and reproduce process.

There are several recording limitations inherent with magnetic-tape-based motion analyzers. One of its biggest handicaps is handling the complexities surrounding record time. During a rewind cycle, the magnetic tape is not positioned for recording and an intermittent event at this time cannot be captured. Since these recorders are electro-mechanically intensive, there is a lag in response time from the moment a recording is initiated to the actual recording of an image. This lag time is also present in their ability to stop. The time required to start and stop make these motion analyzers inefficient for short recordings. Some applications require only a few images at any given time to be captured at a high frame rate. There may be long periods of time between capture. A magnetic-tape-based motion analyzer would waste most of its recording media with start-and-stop sequences.

Most modern motion analyzers are using solid-state memory (DRAM) storage for image capture. The advantages of manipulating images with DRAM technology allows for unique image capturing techniques. In addition, storing digital images in DRAM provides substantially better image quality. Images can be continuously recorded, like an endless loop tape recorder, which helps in capturing elusive intermittent events. Images can be recorded instantly on command, which allows users to capture a multiple series of "snap shots." Playback rates can be adjusted in a variety of speeds both forward and reverse for in-depth analysis. Undoubtedly, it is DRAM-based memory that has increased the popularity of motion analyzers as problem-solving devices.

Resolution	3000 FPS	1000 FPS	500 FPS	30 FPS
256 x 256	197 MB/s	66 MB/s	33MB/s	2MB/s
512 x 512	786 MB/s	262 MB/s	131 MB/s	8 MB/s
1024 x 1024	3.2 GB/s	1 GB/s	524 MB/s	32 MB/s

Table 4 : Sensor Bandwidths

Writing into multiple DRAM memories in a highly parallel architecture allows for extremely high frame-rates capture. Table 4 illustrates the bandwidth requirements for different sensor resolutions. For example, to capture images that have a 512 x 512-pixel resolution at 1,000 fps, requires a DRAM bus width of 128 bits. DRAMs can be adapted to match the capture bandwidth by simply changing the width of their bus. This flexibility is one of the attributes that make DRAMs widely used in motion analyzers.

Capture Storage

The next stage of image storage calls for downloading the DRAM data to a more permanent archival source. In most instances the medium of choice is magnetic tape, the capture media was the same as the archiving media. However, with DRAM base storage, images must be saved since the DRAM is volatile. If power is removed, the images are erased. Both magnetic and optical storage are used to archive images. The choice is usually dependent on the capacity required and the transfer rate. The tradeoffs are cost of the media, the transfer rate, the access time to images and the storage capacity. An additional factor may be the method of image distribution once they are stored. Each of these factors needs to be weighted by the user to select the archiving media that suits the application. Table XXXX shows a variety of archiving devices. Most of these storage devices are widely used in the computer industry.

Storage Type	Capacity (Bytes, Frames)	Xfer Rate (B/sec, Frames)	Media ($)	Hardware ($)	Size
8mm Drive	40GB, 200k	6MB, 30	25	3,000	5 1/4 hh
8mm Library	400GB, 2M	2MB, 10	25	50k - 100k	7.6 cu ft
CDR Write	680MB, 3.4k	0.6MB, 3	5	5,000	5 1/4 hh
CDR jutebox	62.5GB, 310k	0.2MB, 1	5	14,000	1.3 cu ft
5 1/4 Optical	1.2GB, 6k	0.5MB, 2.5	110	3,000	5 1/4 fh
5 1/4 Optical Jutebox	18GB, 90k	0.4MB, 2	110	13,000	3.1 cu ft
Disk RAID-5	30GB, 150k	20MB, 100	2500	25,000	1.8 cu ft
D1 Video	152GB,762k	27MB, 1350	468	138,000	2 cu ft
Comp. Dig Video	201GB, 1M	27MB, 1350	248	46,000	1.8 cu ft
PCMCIA	340MB, 1700	0.75MB, 3.75	700	125	2.5 ff

Table 5 Storage Capacities for a 512 x 384 Pixel Image

The 8mm tapes drives are slow for archiving. However, they are cost effective and have a large storage capacity. CD writable discs are improving on their write times. The CD writable discs have the advantage that their storage life is over 100 years. This media is relatively inexpensive. Their access times are also improving. Also, CDs can be put into a jukebox, which is particularly advantageous for libraries where cost is a factor. Optical drives are somewhat better than CDs for archiving. Their transfer rates are higher and the capacity per disk is slightly higher. Multiple hard drives (RAID) are good for fast archiving, medium cost range but have a limited capacity. Digital videotape transports offer very good transfer rates, very large storage capacity but suffer in access time. Also, these tape units do need an extensive library jukebox for multiple tape access. The PCMCIA drives are not very good archiving due to their limited storage capacity. However, they are a very good medium for intermediate storage of images before archiving. This is because of their rugged design; it can withstand tough environments that motion analyzers endure. Ranking by capacity, performance and cost, tape has the advantage for archiving images.

Display/Playback

Traditionally, the displays used for motion analyzers are video monitors that conform to NTSC, PAL and SECAM standards. NTSC is widely used in the United States, Canada and Japan. PAL is used mostly in Europe. SECAM is the standard used in France. Some of the newer motion analyzers used computer monitors (SVGA). Some video monitors have an RGB input, however, most of these are at a low bandwidth (CGA resolution).

The display performance of each standard is listed in Table 6

Display Type	Line/Frame	Pixels/Frame	Field Rate (Hz)
NTSC	525	--------	60
PAL	625	--------	50
SECAM	625	--------	50
HDTV	+1000	--------	60
VGA	--------	640 x 480	72
SVGA	--------	1024 x 768	75
XVGA	--------	1280 x 1024	86

Table 6 Display Performances

Although video monitors are widely used, in the future, these monitors will limit the performance of the higher resolution motion analyzers. RGB (red, green, blue) monitors are used in some motion analyzers. These monitors do not limit the resolution as compared to the video monitors. Also, they are better suited for non-interlaced CCD sensor formats.

Analysis

After the images are captured then displayed for a quick look at the motion, the user may need to make some measurements. Measurements can be made in a variety of methods. The simplest method involves laying a ruler onto the video monitor, marking points with a grease pencil and measuring the movement of an object from frame to frame. Often, a reference object of a known dimension is placed in the plane of view. Then the object is measured and a conversion factor is determined for correcting any magnification due to the lens. Velocities may be calculated by determining the distance an object moves between a frame interval and multiplying the time interval between the measured frames. This is a fundamental approach to do simple measurements.

The digital motion analyzers make measurements easier for the user. Most of these analyzers have an x-y reticle. The reticle can be moved in increments of pixels. Therefore, the actual distance can be measured in a given image plane by simply noting the initial x-y pixel coordinate to the ending x-y pixel coordinate. The accuracy is much higher due to the exactness of pixel position as compared to resample video that may have less predictable boundaries.

A more sophisticated method of analyzing motion is with a dedicated workstation or software program designed for this purpose. Motion Analysis Workstations are used to read an analyzer’s images, play the images, provide software tools for marking objects, tracking the marked objects from frame to frame and storing the data in files. There are different levels of sophistication in these workstations. Some measure motion through manual tracking methods while others are automatic. The manual tracking analyzers are simple to use but, they are labor intensive.   The automatic analyzers require some operator setup and monitoring, however, the level of involvement is far less.

Auto tracking is very important when many images are being analyzed.   Auto tracking removes the tedium and errors that happen when operator fatigue sets in.   It also reduces the processing time compared to manual moving markers, stepping to the next frame and moving the markers again.   An auto-tracking algorithm is designed to locate the centroid (center) of an object.   This may be accomplished by a computer algorithm by looking for image threshold boundaries within a given search area, pattern recognition, or some other type of predictor.   The operator usually needs to monitor or check occasionally the tracking process. Most analyzers will stop on the frame that an object is lost. There may have been some obscured or erratic movement that exceeds the tracking boundaries of the predictor. When this happens, the operator edits the marker's position and starts the tracker back up. All the previous data is still valid. The automatic tracking capability of a motion analyzer is important when thousands of images need to be analyzed.

Motion images often are captured in less than ideal conditions. The images may be darker than desired or in need of some modification. Motion analysis workstations usually have the capability to adjust brightness

Determining What is Required

To obtain satisfactory motion analysis results from a high-speed video camera, a number of factors have to be resolved. Issues such as frame rate, image resolution and methods of recording determine the imagery that will result from a given test. How much light is available? How much light is needed? What are the sensitivity and resolution capabilities of the imager? The answers to these questions determine not only the test's equipment requirements, but obviously influence the test's results.

The first question that must be asked is: What do I want to be able to see and/or measure from the motion analysis test? That answer determines everything else. But because of the technology's flexibility, the questions don't have to be answered perfectly. One of high-speed videographiers greatest assets is immediate playback. If in the first test the frame rate is too slow, the frame is simply increased. If more light is needed to get a sharper image, another lamp can be added, the lens aperture may be opened or a light amplifier (intensifier) could be used. Engineers can also experiment with various settings to find the optimal parameters.

The following section describes the various parameters that determine the end result. In any motion analysis test, all of these factors must be determined to some degree, even if the experimenter must guess through trial and error.

Frame Rate

Frame rate, sample rate, capture rate and imager (or camera) speed are interchangeable terms. Measured in frames per second, the imager's speed is one of the most important considerations in motion analysis. The frame rate is determined after considering the event's speed, the size of the area under study, the number of images needed to obtain all the event's essential information, and the frame rates available from the particular motion analyzer. For example, at 1,000 fps a picture is taken once every millisecond. If an event takes place in 15 milliseconds, the imager will capture 15 frames of that event. If the frame rate is set too low, the imager will capture not enough images. If the frame rate is set higher than necessary, the analyzer's limited storage may not be able to store all the necessary frames. In other instances, too high of a frame rate sacrifices the area of coverage. This happens when an imager's frame rate is set higher than it's ability to provide a full-frame coverage. In most of the new generation of motion analyzers, the imagers have an option that provide "partial frames per second." At this rate, the height of the image is sacrificed but in return, the frame rate can be as much as twelve times the imager's full-frames-per-second rate. When considering the performance some of the lower frame rate motion analyzer's specifically will increase their frame rate by recording partial frames but use line doubling during display. Line doubling is a technique for restoring the partial frame image to a full frame image. Currently, the fastest motion analyzer provides 4,500 full fps and up to 40,500 partial fps.

When considering the frame rate performance of a motion analyzer be specific about your requirements. Look closely at a manufacture's specification sheet to see what the true resolution is at any given frame rate. Some lower frame rate motion analyzers are using a technique called line doubling to increase their full frame rate performance. However, the true resolution at the stated frame rate is actually lower and upon display, the lines are doubled to fill out the image (4:3 aspect ratio). If no analysis is intended for the images this presents no problems. However, if measurements are to be made, it is important to know the true frame size (resolution) during record such that measurements in the direction that lines are doubled can be corrected in the calculations. Typically, for this type of motion analyzer's the imaging sensor was designed for standard video. By using this type of sensor the cost is less than a sensor designed for high frame rates. The sensor is being pushed to a higher frame rate. To achieve a higher frame rate beyond it's original specification, the amount of image data read out of the sensor must be reduced (lower resolution). Therefore, make sure the frame rate performance matches the motion analyzer's capability.

Record Time

The recording time of a high-speed video system is dependent on the frame rate selected and the amount of storage medium available. The continuing technological advances in DRAM cards make higher storage levels affordable, but DRAM is still a limiting factor. However, as the following chart shows, most high-speed events occur in such short durations that a 1,600-frame DRAM card is usually more than enough to capture the event. Those seeking higher storage capacity can get at least 19.7 seconds of record time on the Kodak EktaPro EM motion analyzer running at 1,000 fps. Another choice would be the NAC Memrecam C2S that has 24 seconds of record time at 200 fps. This motion analyzer makes use of image compression technology to gain a longer record time with limited DRAM memory.

As memory chips get denser, that capacity will increase, as it will for similar motion analyzers. Table 7 provides average event times for various applications. The event time was measured from actual imaging data. The definition of an event time is the duration of event that produced significant information for motion analysis.

SUBJECT	EVENT TIME (seconds)	FRAMES (1,000/sec)
Money sorting machine (single bill time)	1.2 sec.	1,200
Flame pattern test (fuel combustion)	0.7 sec	700
Wire bonding (one cycle)	0.8 sec	800
Surface mount (one placement cycle, no pickup)	0.3 sec	300
Food—crackers on process line (three samples)	0.3 sec.	300
Potato chips being bagged (one cycle)	1.1 sec.	1,100
Tire testing, front and rear over glass plate	0.4 sec.	400
Hot glue applied to film box flap	0.2 sec.	200
Blood stream (one cell motion across screen)	0.8 sec.	800
High voltage circuit breaker (one cycle)	0.2 sec.	200
Label pickup (one label)	0.6 sec	600
Golf ball impact and flight (club)	0.6 sec.	600
Composite material fracture	0.1 sec.	100
Car crash test (impact)	0.3 sec.	300
Air Bag Inflation	0.035 sec.	35

Table 7 Average time of event duration

Time Magnification

The goal in using a high-speed camera is to obtain a slow motion display of a high-speed event. Time magnification describes the degree of "slowing down" of motion that occurs during the playback of an event. To determine the amount of time magnification, divided the recording rate by the replay rate. For example, a recording made at 1,000 fps and replayed at 30 fps will show a time magnification of 33:1. One second of real time will last for 30 seconds on the television or computer monitor. If the same recording were replayed at only 1 fps, that one-second event would take more than 16 minutes to play back. Most systems allow replay in forward or reverse with variable playback speeds. Therefore, it is important to capture only the information that is necessary otherwise; long recordings can take hours to playback. Some examples are shown in the Table 8.

Record Rate	Time (sec)	Frames Recorded	Playback @ 30 fps	Playback @ 1 fps
250	20	5000	167 sec	83 min
500	50	30000	1000 sec	500 min
1000	2	1500	50 sec	25 min
4500	0.11	500	17 sec	8 min

Table 8 Recording played back in slow motion

Exposure

Many factors influence the amount of light required to produce the best image possible. Without sufficient light, the image may be;

- under-exposed, detail is lost in dark regions
- unbalanced, poor color reproduction,
- blurred, due to the lack of depth-of-field

The time that light is exposed to the imaging sensor depends on several factors. These factors include, lens f-stop, frame rate, shutter time, light levels, reflectance of surrounding material, imaging sensor's well capacity, and the sensor's signal-to-noise (SNR) ratio. All of these factors can significantly impact the image quality. An often over looked factor is the exposure time.

Exposure Time

The exposure time, shutter rate, shutter angle are interchangeable terms. The exposure time for mechanical shutters is set in terms of number of degrees that it is open. The exposure time for electronic sensors are either the inverse of the frame rate if no electronic shutter exists or the time that an electronic shuttered sensor is exposed in microseconds. Shown below are the relationships for defining the exposure time.

- mechanical shutter = (shutter's revolutions per second x shutter angle)/ 360
- no shutter = 1/frame rate
- electronic shutter = period of time that the sensor is exposed

The exposure time determines how sharp or blur free an image is—regardless of the frame rate. The exposure time needed to avoid blur depends on the subject's velocity and direction, the amount of lens magnification, the shutter speed or frame rate (which ever is faster) and the resolution of the imaging system.

A high velocity subject may be blurred in an image if the velocity is to high during the integration of light on the sensor. If a sharp edge of an object is imaged, and the object moves within one frame more than 2 pixels or a line pair, the object may be blurred. This is due to the fact that multiple pixels are imaging an averaged value of the edge. This will create a smear or blur effect on the edge. To get good picture quality, the shutter rate should be 10x that of the subject's velocity.

The lens magnification can influence the relative velocity of the subject being image. The velocity of an object moving across a magnified field-of-view (FOV) increased linearly according to the magnification level. Instantly, if an object is viewed far away, the relative velocity in the FOV is less than that viewed next to the object.

Motion analyzers use electronic or mechanical shutters that operate as fast as 10 microseconds (1/100,000 of a second), which is fast enough to provide blur-free images of high-speed events. The shutter controls the amount of light that is exposed to the sensor by the cycle rate of the shutter and the time that the shutter is open. The cycle time is set by the frame rate. The shutter then determines the exposure time. If no shutter capability exists for the imaging sensor, then the frame rate will be the effective exposure time. Therefore, for a high velocity object, higher frame rates are required. The shutter is synchronized to the sensor timing. Multiple cameras can be synchronized if the shutters can be controlled in unison. Shown in Table 9 are subjects that their velocities have been averaged and converted to frame rate/exposures.

SUBJECT	Minimum Frame Rate	Minimum Exposure (uS)
Money sorting machine (single bill time)	500	100
Flame pattern test (fuel combustion)	3000	20
Wire bonding (one cycle)	1000	50
Surface mount (one placement cycle, no pickup)	1000	100
Food—crackers on process line (three samples)	250	1000
Potato chips being bagged (one cycle)	250.	1000
Tire testing, front and rear over glass plate	500	100
Hot glue applied to film box flap	500	500
Blood stream (one cell motion across screen)	1000	20
High voltage circuit breaker (one cycle)	1000	1000
Label pickup (one label)	250	1000
Golf ball impact and flight (club)	1000	20
Composite material fracture	1000	100
Car crash test (impact)	1000	100
Air Bag Inflation	3000	70

Table 9 Typical Frame Rates & Exposure Times by Application

A proper shutter speed may be calculated as shown in Figure 11. If the object's velocity, the field-of-view, the imaging sensor's dimensions and pixel count are known, the shutter speed required to produce a sharp image can be calculated. The relative velocity (Vr) at the sensor can be calculated by reducing the subject's velocity by the optical reduction at the sensor. The pixel size must be calculated by dividing the sensor size in the dimension of interest (x or y). Knowing that a relative velocity at the sensor plane that is less than 2 pixels or a line pair will produce a good image, we multiply the pixel size by two. Therefore, the shutter speed is calculated by dividing the 2X pixel size by the relative velocity (Vr). The inverse yields the minimum shutter speed or in the case of an imaging system without a shutter, it is the minimum frame rate for sharp images.

$$\text{Exposure (shutter rate)} \leq 2\text{X Pixel Size} / \text{Vr} \qquad \text{Equation (3)}$$

where:

Vr = sensor dimension x (field-of-view / object's velocity)

Pixel Size = pixel dimension / total pixels

Note: pixel dimension should correspond to the dimension used for the total pixel count.

Let's look at an example of this calculation. Our subject is moving at 35 mph or 616 in/sec. The camera is perpendicular to the object and looking at a view 10 feet (120 in.) wide. The camera's sensor is 0.5 inches wide and has a resolution of 200 pixels. The cameras view of 10 feet is optically reduced onto the 0.5-inch sensor. This also optically reduces the velocity from 616 in/sec in the object space to 2.6 in/sec at the sensor. The sensor resolution of 200 pixels per 0.5 inches means that each pixel is 0.0025 inches wide. As a rule-of-thumb, an acceptable amount of blur is less than two pixels, in this case 0.005 inches. Therefore, the object will move the width of two pixels in 0.0019 seconds. Taking the inverse of 0.0019 seconds is 520 or a shutter time of 1/520 of a second or less will provide a sharp image of the object. Shown in Figure 11 is this example.

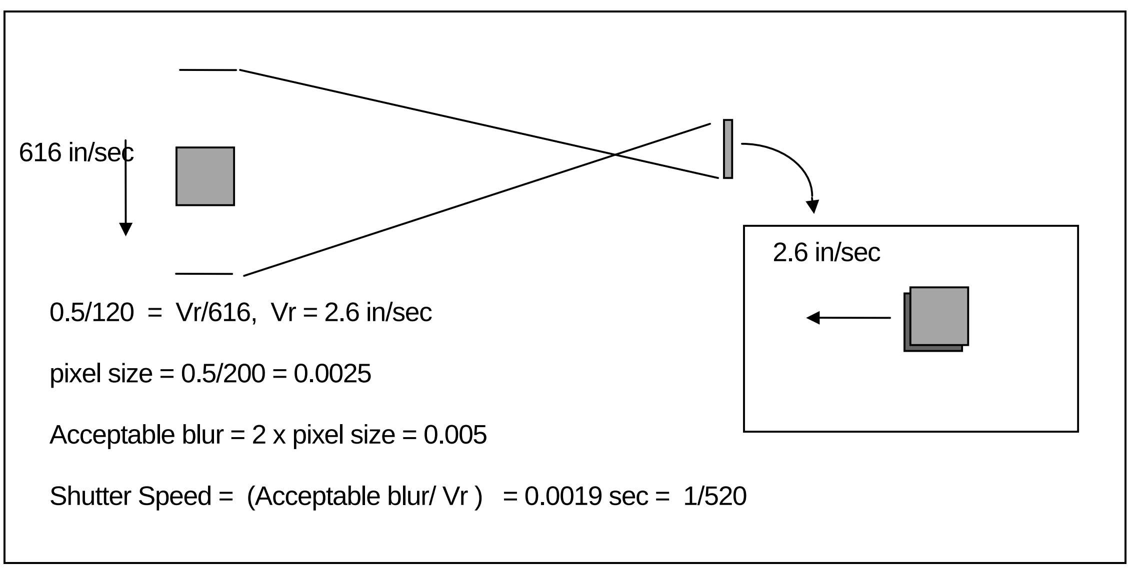


Figure 11 Calculating the correct shutter speed or frame rate

Resolution

There are many ways to express the resolution of a camera system. It is important to determine what factors must be taken into consideration to determine the resolution of a camera system. Shown below are the basic building blocks of a camera system that contributes to the system's overall resolution. The overall system and individual blocks can be expressed in terms of the capability to resolve a given object in the field-of-view as transfer function. A transfer function is simply the means of relating the output response to that of the input excitation.

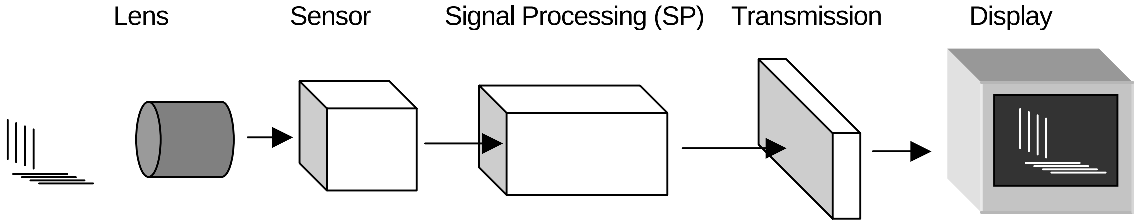


Figure 12 Elements of Resolution within the Imaging

There are several common methods of expressing this transfer function. Two of the most widely used expressions are MTF (Modulation Transfer Function), and CTF (Contrast Transfer Function). MTF is used more often in describing a lens behavior since it is a continuous expression relating the modulation of a sinusoidal variation of light. CTF is used more extensively in describing digital cameras behavior since it is an expression of a transfer function response to a step in contrast difference. An explanation of the two needs to be given.

Modulation Transfer Function

The Modulation Transfer Function (MTF) was derived from an information theory as a mathematical principle describing the ratio of signal-to-noise. MTF is usually expressed as a graphical curve (Figure 13) showing the ability of an imaging sensor to spatially reproduce the scene consisting of a black and white bar pattern incident on the surface of sensor. The black and white bar pattern is used to measure the MTF, since it has a sinusoidal contrast function varying at different spatial frequency as shown below.[5]

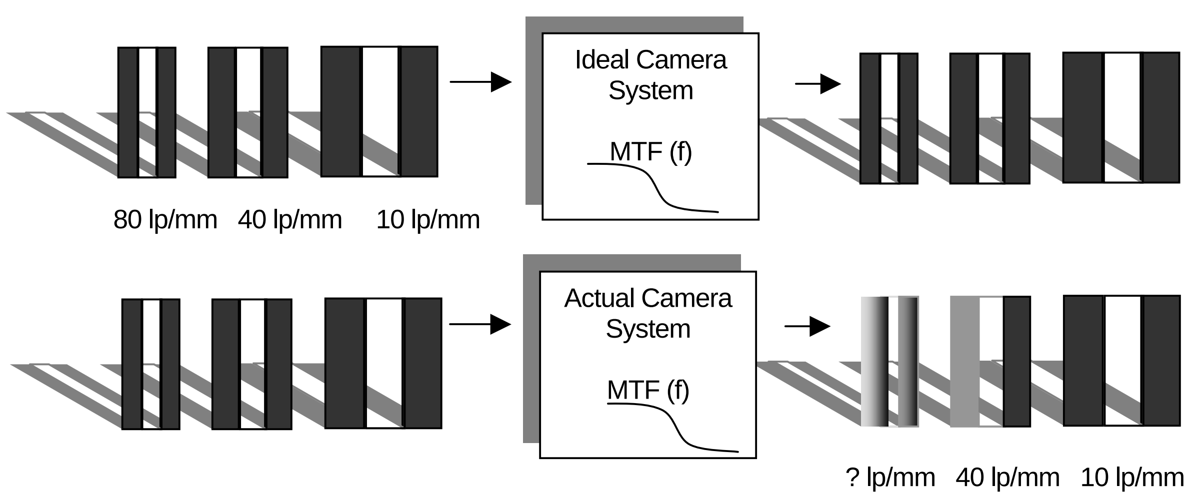


Figure 13 Modulation Transfer

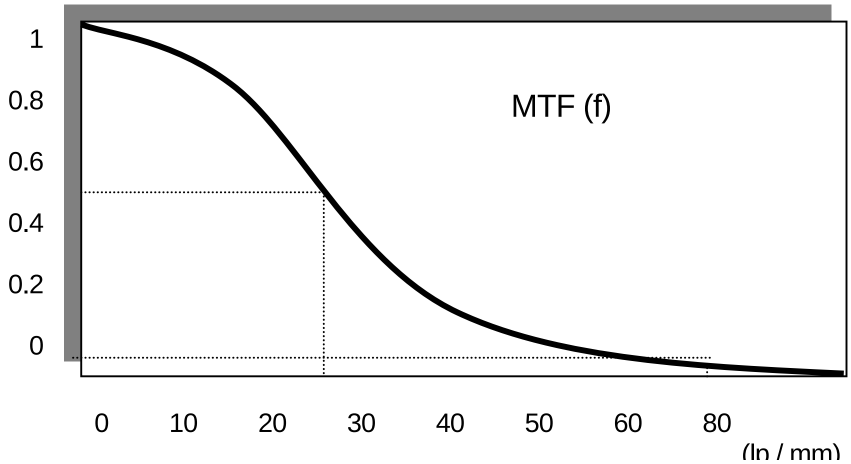


Figure 13 Normalized MTF Response

The ideal camera system can resolve every frequency pattern of the black and white transitions. If the imaging system was sampling at a continuous rate, its transfer function would have a MTF (f) = 1. However, an actual camera system is a sampling system and it may not be capable of resolving certain spatial frequencies as shown above. In this case, the edge of the black-to-white-to-black transition of the 80 lp/mm target can't be accurately determined. Therefore, the edge of the transition is indeterminate.

The MTF is expressed as a spatial frequency for a sinusoidal varying light stimulus as shown below;[6]

$$S(f)_{max} - S(f)_{min} = \frac{MTF(f)}{S(f)_{max} + S(f)_{min}} \quad X\ 100$$

$S(f)_{max}$ = maximum height of the sinusoidal signal

$S(f)_{min}$ = minimum height of the sinusoidal signal

Each element in the system (Figure 12) can be expressed in terms of MTF as shown below.

Sys MTF(f) = Lens MTF(f) x Sensor MTF(f) x SP MTF(f) x FG MTF (f) x Display MTF (f)

Attempting to image a scene with spatial frequencies near the pixel's theoretical limit will cause aliasing, moiré patterns, or beating frequencies within the image. Aliasing occurs when sampled data at frequencies above one half the sampling frequency (Nyquist) can't be distinguished as lower frequency signals. In addition, the highest spatial frequency imaged is restricted by the diffraction limit of the optics.

Contrast Transfer Function

The Contrast Transfer Function (CTF) is similar to MTF except the scene imaged is not sinusoidal, but that of a square-wave function. CTF is more widely used with CCDs since it is easier to implement.

$$B(f)_{max} - B(f)_{min} = \frac{CTF(f)}{B(f)_{max} + B(f)_{min}} \quad X\ 100$$

$B(f)_{max}$ = maximum output an adjacent pixel

$B(f)_{min}$ = minimum output an adjacent pixel

Each element in the system (Figure 12) can be expressed in terms of CTF as shown below.

Sys CTF(f) = Lens CTF(f) x Sen CTF(f) x SP CTF(f) x Tran CTF (f) x Display CTF (f)

An approximate relationship between MTF(f) and CTF(f) with the following equation:[7]

$$MTF\ (f) = \underline{\Pi}\left[CTF(f) + \frac{CTF(3f)}{3} - \frac{CTF(5f)}{5} + \frac{CTF\ (7f)}{7} \ldots\ldots\right] \times 100$$

Array Size

The resolution of a camera is largely influenced by the architecture of the sensor and the light-sensing element called a pixel. Pixels can vary in size from 5 microns to as large as 70 microns. However, most CCDs will have a pixel range from 6 micron to 24 micron. The construction of a CCD can be expressed as (X) pixels in the horizontal direction by (Y) pixels in the vertical direction. The number of pixels in the horizontal and vertical directions determines the resolving capability in the field-of-view. In addition, the size of an individual pixel determines the physical size of the sensor array. Designing larger pixels will result in larger arrays. There are economical limitations in the fabrication of large sensor arrays. Therefore, most CCDs will tend towards a smaller pixel that allows for more devices per wafer. In addition, the smaller the pixels the smaller the process design rule, which means the device can move charge faster.

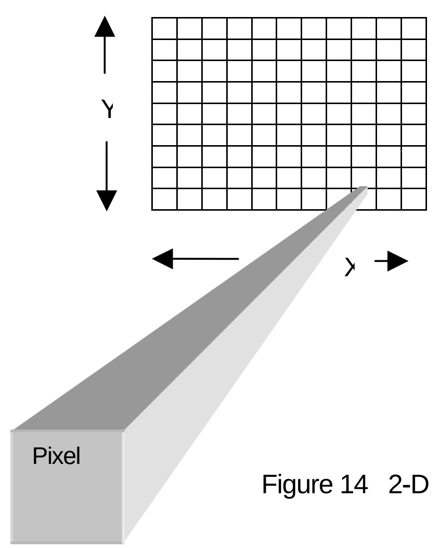


Figure 14 2-D Sensor Array

Pixel Theoretical Limiting Resolution

In principle, the pixel has a theoretical limiting resolution of 1/ [2 x pixel size] in units of line pairs per millimeter. As an example, a 9 microns square pixel will have a theoretical limiting resolution of 55 lp/mm. However, the use of the theoretical resolution would assume an ideal imaging system that has a unity transfer function. This assumption means literally, what you put in is exactly what you get out. In practice, an ideal imaging system is not possible. Therefore, to determine the actual resolution of a camera one must examine the elements that contribute to the reduction of the theoretical resolution.

A rule of thumb for capturing high-speed events is that the smallest object or displacement to be detected by the camera should not be less than 2 pixels within the camera's horizontal field of view.

The sensor resolution may be expressed also in terms of line pairs per millimeter (lp/mm). The meaning of line pairs per millimeter is an expression of how many transitions from black to white (lines) can be resolved in one millimeter. To calculate a sensor's theoretical limiting resolution in lp/mm, take the inverse of two times the pixel size. Shown below is the limiting resolution of a sensor with a 16-micron pixel. Typical sensor resolutions are shown in Table 10.

$$\text{Theoretical Limiting Resolution} = (1/(2 \times \text{pixel size})) \times 1000$$

$$= 1/(2 \times 16) \times 1000 = 31.25 \text{ lp/mm}$$

Frame Rate	Sensor Size (pixels)	Rate (MB/sec)	Resolution (pixels)	Frame Rate	Sensor Size (pixels)	Rate (MB/sec)	Resolution (pixels)
200	256 x 256	13	65536	200	256 x 512	26	131072
400		26		400		52	
500		33		500		66	
1000		66		1000		131	
2000		131		2000		262	
3000		197		3000		393	
4500		295		4500		590	
200	512 x 512	52	262144	200	1024 x 1024	210	1048576
400		105		400		419	
500		131		500		524	
1000		262		1000		1049	
2000		524		2000		2097	
3000		786		3000		3146	
4500		1180		4500		4719	

Table 10 Typical Sensor Resolutions and Bandwidths

Sensitivity

Most modern image sensors have a sensitivity that is equivalent to a film Exposure Index value of between 125 ISO and 480 ISO in color and up to 3200 ISO in monochrome. The sensitivity is a very important factor for obtaining clear images. An inexperience user may confuse motion blur with a poor depth-of-field. If the sensitivity of the camera is not high enough for a imaging an object for a given scene, the lens aperture must be opened up. This reduces the depth-of-field for the object to remain in focus. As the object moves, it could take a path outside the area that is in focus. The object would then give the appearance motion blur where it is only out of focus.

In practice, a single 600-watt incandescent lamp placed four feet from a typical subject provides sufficient illumination to make recordings at 1,000 fps with an exposure of one millisecond (1/1,000 of a second) a f/4. This level of performance is fine for many applications, although some demanding high-speed events have characteristics where greater light sensitivity may be preferred.

Sensitivity[(8)] for a camera may be defined as the minimum light level that an image sensor gives useful output. For analog video cameras, sensitivity is usually defined as the required illumination in lux incident to the camera that creates a mean video output level. It is commonly accepted that 30 video IRE units in amplitude, or 0.210 video volts for PAL, is the mean level with black being represented as 7 IRE units. An IRE unit is a scale for measuring full video output that is normalized to 100 units. Therefore, if 1 volt was your full scale video out, 1 IRE unit would equal 0.01 volt. Another way of expressing sensitivity for a digital camera is the normal response, often expressed as a digital number (dn) that corresponds to light illuminating the sensor (lux-sec). The sensitivity for a camera will be determined by the optical responsivity, the charge integration time and the signal-to-noise (SNR) ratio.

A digital camera's sensitivity can be compared to that of an analog camera by converting the dn/lux-sec to equivalent video IRE units/lux-sec. A method of comparing the two can be computed as equivalent ISO speed or comparing the ratio of equivalent faceplate illumination, for a given output. However, both should be compared under the same exposure time (i.e., 1/30 sec or 1/60 sec) and the lens needs to be operated at infinity. Close-up lens conjugates will not work for the following equation.

The following equation for converting a scene illuminance level to faceplate luminous exposure for a typical photographic scene (lens focused at infinity) is given as:

$$E_{g \text{ for 23 IRE units}} = \frac{8(C\text{x}T)}{(K \text{ x f-stop}^2)}$$

where: Eg = minimum luminous exposure in lux-sec for 23 IRE units

C = scene illuminance in lux

T = exposure time

K = specific lens constant (i.e., 3.3 to 4.0), use 3.4 nominal

f-stop = lens setting @ for Eg

H_{sat} = Eg x 4 (quarter well illumination at 23 IRE units)

Eg/T = faceplate illuminance for 23 IRE units

Sx = equivalent ISO speed = $78/H_{sat}$

A dn-to-IRE unit conversion factor is needed for digital cameras as follows:

8-bit cameras = 256 counts,   1 IRE = 2.56 counts or   1 count = 0.391 IRE units

10-bit cameras = 1024 counts, 1 IRE = 10.24 counts or 1 count = 0.0976 IRE units

Therefore, let's compare a given analog camera sensitivity to that of a digital camera. The following information is taken off two manufactures actual data sheets:

Camera Type	Sensitivity	Settings
Analog (NTSC)	20.0 Lux @ 23 IRE units	AGC = on
		Shutter = none
		Gamma = 0.45
		Gain = normal
		F# = 1.4
		Exposure = 1/60
		Color Temp= 2856 Kelvin
Digital, 8-bit	720 dn/ Lux –second at faceplate	AGC = none
		Shutter = 1/60
		Gamma = 1.0
		Gain = 0 dB
		F# = Not Applicable,
		Exposure = Not Applicable
		Color Temp= 6400 Kelvin

$$E_{g\ (\text{analog camera})} = \frac{8(20x\ 1/60)}{(3.4 \times 1.4 \times 1.4)} = 0.390156 \text{ lux-seconds}$$

and the faceplate illuminance level = $E_{g\ (\text{analog camera})}$ /T = 0.390156/1.0166 = 23.5 ≈ 24

We must convert the 8 bit digital camera's counts/lux-sec faceplate sensitivity to equivalent video IRE units/Lux-seconds given at 23 IRE units

0.391 x 720 = 282 IRE units/lux-second

Eg (digital camera) = 23/282 = 0.0816 lux-seconds

Next, we must compute the digital camera's faceplate illumination level for 0.0816 luminous exposure, for the same exposure time (i.e., 1/60 second).

1/60 = 0.0166, therefore 0.0816/0.0166 = 4.897 lux faceplate illumination for equivalent 23 IRE units

Comparing equivalent sensitivity levels:

Analog Camera = 24 = 4.9

Digital Camera 4.897

Depth of Field

Depth-of-field (DOF) is the range in which an object would be in focus within a scene. The DOF is the greatest when a lens is set to infinity. As the f-stop becomes smaller on the lens setting, the DOF also decreases. If the object is move closer to the lens, the DOF also decreases. Lenses of different focal lengths will not have the same DOF for a given f-stop.

Image Sensor Dimensions

The size of the image sensor within a camera is important to know. Some common size sensors include 1/2 inch, 2/3 inch and one inch. The one-inch sensor has an effective width of 12.8 millimeters, while the 2/3-inch sensor has an effective width of 8.8 millimeters. A lens that works properly on a camera having a small sensor may not produce a large enough image to work correctly on a camera having a large sensor. This is due to the distortion in the fringe areas of the lens. Knowing the width of a sensor prevents image blur because users can calculate parameters such as the required exposure time. The sensor's width also allows users to calculate the depth of field for a given aperture.

Record Modes

The motion analyzer's various methods of recording is one of the most distinguishing features of high-speed videography. t is also a feature that high-speed film cameras cannot match. The motion analyzer's greatest asset is it's continuous record mode where the camera runs and runs, replacing it's oldest images with the newest until an event occurs and triggers the camera to stop. Further flexibility allows the operator to program exactly how many images before and after the event are to be saved. For engineers and technicians trying to record unpredictable or intermittent events, the continuous-record, trigger or ROC mode is the only feasible options (see Figure 15

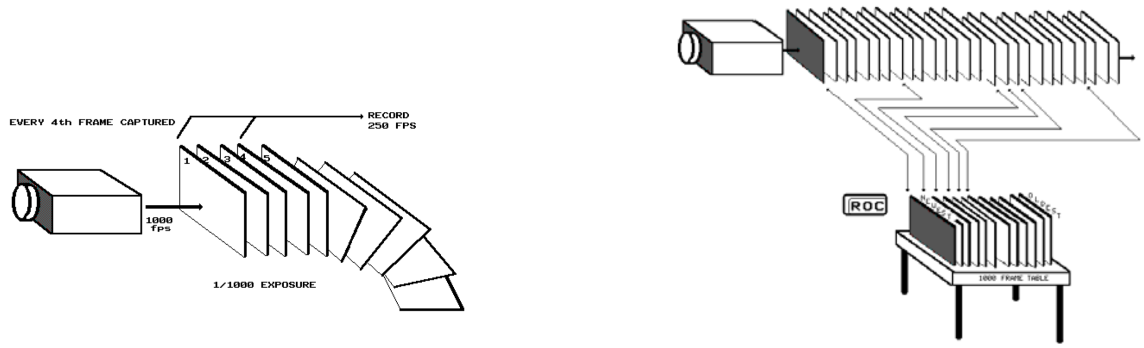


Figure 15 Continuous Record and ROC Modes

There are several other record modes that need to be discussed. One of the most powerful but, the least understood, hence least used, is Record-On-Command (ROC). ROC is powerful because images may be selected according to a user-supplied signal. An example of this is illustrated in Figure 16.

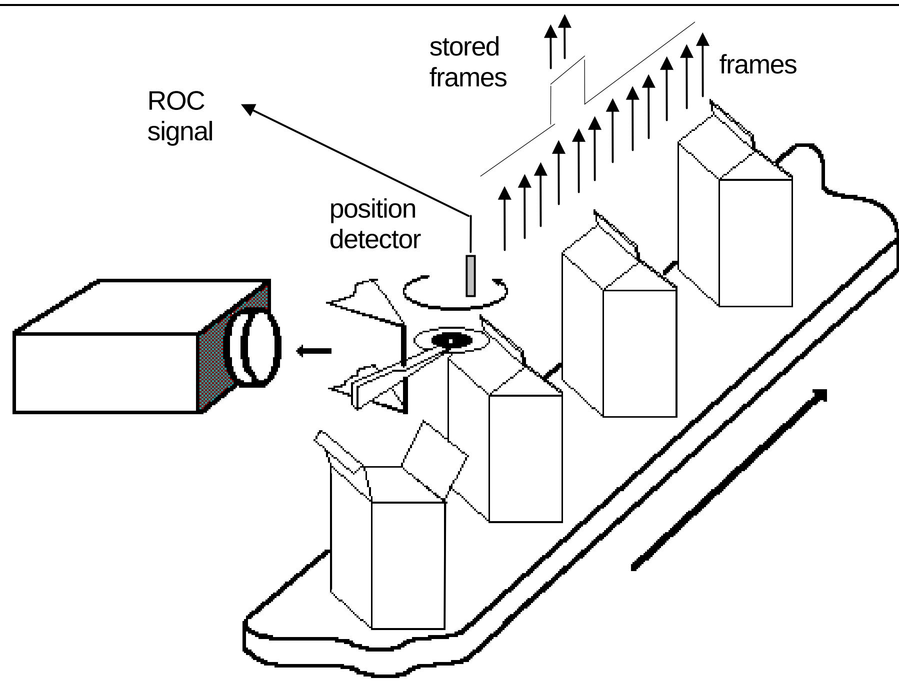


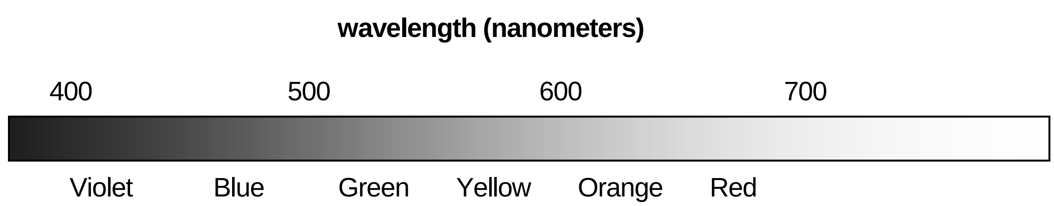
Figure 16 Imaging a Lid Closing

The end user's objective is to capture over a thousand images sequences of the box lid being closed. There is an error in how the lid is closed but it is intermittent and difficult to trigger. By using a tachometer pulse off the shaft driving the closing mechanism, precise timing can be derived for indicating the exact position when the lid is being closed. This timing pulse is used to qualify the image to the motion analyzer memory. If the pulse exists, images are written into the motion analyzer's memory. With no pulse, no images are recorded. Therefore, only images of the lid in an exact position will be recorded until the motion analyzer's memory is full. Additional, a range of motion may be recorded if the pulse is longer than a single frame period. In other words, if the motion analyzer is operating at 1000 fps and the pulse into ROC is 5.5 milliseconds long, 5 images per pulse will be stored. The use of this recording technique is only limited by the user's imagination. Indeed, it is one of the most powerful but least understood recording techniques.

Another obscure recording technique for motion analyzers with DRAM memory is Slip Sync. This recording technique is used to operate the motion analyzer at a frame rate that is defined by a user's signal. Again, we will look at the application in Figure 13 to explain this operation. The principle of operation of slip sync is very similar to the use of a strobe when it is operating synchrounsly with an object that has a repetitious movement. Therefore, in our example, the user would input a frequency that was synchronized to the tachometer. As the frequency is varied, the images captured will be sync with the tachometer in a positive or negative direction. This allows any position of the lid movement to be observed and captured. Another example would be that of an accelerometer voltage that is feed to a voltage-to-frequency converter. As the acceleration changes, so does the frequency out of the converter. This frequency then drives the frame rate of the motion analyzer. Why should this interest us? Objects that move faster need a higher frame rate for recording than objects that move slower. Therefore, the rate of change is directly proportional to the rate of recording. Application examples include a crush test for materials using a strain gauge, a flame propagation study in a combustion engine using a pressure sensor, a automotive car crash using an accelerometer or an explosion that has a light sensor detecting the detonation. This mode of recording is uniquely possible with DRAM based motion analyzers.

Color

Understanding color is difficult but necessary even for monochrome imaging. The color of light is determined by its wavelength. The longer wavelengths are hotter in color (red). The shorter wavelengths are cooler (blue).



Color	Wavelength (nm)
Ultraviolet	390 - below
Violet	390 - 430
Blue	460 - 480
Green	490 - 530
Yellow	550 - 580
Orange	590 - 640
Red	650 - 850
Infrared	650 - above

Source	Color Temperature
candle	2000 K
sunlight, daybreak	+ 2000 K
tungsten	2900 K
sunlight, noon	4400 K
sunlight, afternoon	5400 K
HMI	5800 K
sunlight, evening	6500 K
sunlight, cloudy	6800 K
sunlight, cloudless	+10,000 K

Table 12

Color perception is a function of the human eye. The surface of an object either reflects or absorbs different light wavelengths. The light that the human eye perceives is unique in that it produces a physiological effect in our brain. What is red to one person may have a slight difference of perception by another person. Terms that further describe the color of an object is hue, saturation and brightness. Hue is the base color such as red, blue violet, yellow and others. Saturation is the shades that vary from a basic color to that of a different shade. An example of a hue would be green and a saturated color would be lime (light green). Brightness also known as luminance is the intensity of the light. The subject of color would take an entire book to fully explain the science. However, studying a color chart can give the user some insight into the composition a color scene.

Color temperature is a common way of describing a light source. Color temperature originally derived it's meaning from the heating of a theoretical black body to a temperature that caused the body to give off varying colors that ranged from red hot to white hot. Lord Kelvin developed this term and his name was associated with the unit measure. Listed in Table 12 are the values for common lighting sources.

Color versus Monochrome

Most of the early high-speed film was black-and-white. Once color film became available, the use of black and white declined. The use of high-speed color film set the format standard that video has attempted to meet. Over the years, monochrome images have been all that could be recorded on most motion analyzers. Today's motion analyzers can produce images that replace color film for some high-speed applications. Full 30-bit color images are now possible from motion analyzers such as the Photron Ultima APX-RS cameras. To understand the strengths and weaknesses of both color and monochrome in varying high-speed video applications, some background must be discussed.

There are various methods of producing color in high-speed video. Figure 14 shows three of the most widely used techniques. The color wheel is used in still imaging where the subject does not move during the imaging with the three color filters. This technique is not suitable for high-speed video due to the motion differences between each successive image. Using three imaging sensors with different color filters and a beam splitter, true color reproduction is possible. True color means that the primary colors and all the saturations are possible. This technique is costly since all the electronics is tripled in order for the three imaging sensors to be supported. The alignment of the three sensors must be very precise. Otherwise, misregistration will occur on the colors. The last technique is a cost saving compromise. Color Filter Arrays (CFA) provide a more cost affective means for producing color (only one imaging device). There are individual color filters deposited on the surface of each pixel. There is some combination of Red, Blue and Green or complimentary color scheme. Each pixel is isolated to a certain color spectrum. Although the pixels are filtered, the raw data must be interpolated for solving the missing pixels in each color plane.

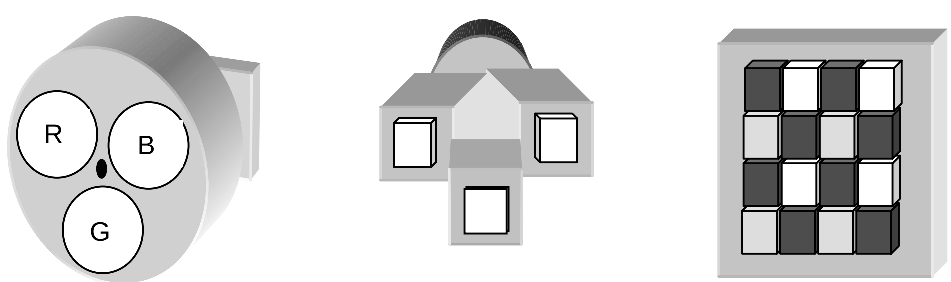


Figure 17 Methods for Producing Color Video

Now that the main methods for producing color have been discussed, we need to review why color and not monochrome.   Generally, monochrome images are better in image quality. Monochrome cameras are more sensitive due to the lack of color filtering. The resolving capability is better than CFA imaging sensors. This is due to the fact that there is no interpolation involved. The disadvantage of a monochrome image is the loss of color differential. Small changes in gray levels is harder to observe than a change in hue or saturation. Color is valuable for differentiating shades. It also produces a bridge from color film to color video.

Lighting

Fundamental Lighting Techniques

Lighting an application properly can produce dynamic results over poor light management.   There are four fundamental directions for lighting high-speed video subjects, front, side, fill and backlight.   Placing a light behind or adjacent to a lens is the most common method of illuminating a subject.   However, some fill lighting or side lighting may be needed to eliminate the shadows produced by the front lighting.   It is advisable to have the light behind the lens to avoid specular reflections off the lens. Side lighting is the next most common lighting technique. As the name implies, the light is at an angle from the side.   This can produce a very pleasing illumination. In fact, for low contrast subjects, a low incident lighting angle from the side can enhance detail. Fill lighting may be used to remove shadows or other dark areas. Fill lighting may also be used to lessen the flicker from lamps that have poor uniformity. Fill typically, is from the side or top of a scene.   Backlighting may be used to illuminate a translucent subject from behind. It is not used that frequently in high-speed video.   However, certain applications such as microscopy, web analysis or flow visualization will make use of backlighting.   All of these techniques are important for getting a high quality image.

Lighting Sources

There are a number of lighting sources available for high speed video. Some care must be taken in lighting selection due to the several factors. The areas that need to be considered included the type of light, the unfoimity of the light source, the intensity of the light, the color temperature, the amount of flicter, the size of the light, the beam focus and the handling requirements. All of these factors are important in matching the light to the application.

Lighting Estimate

The approach for estimating the amount of light required for fast moving subjects is often a trial-and-error. However, a calculated estimate can be made before starting a trial-and-error test. To calculate illumination required to light a subject, the following equations are used:

$$\text{foot candles} = \frac{25 \times (\text{f-stop})^2}{\text{Imager ASA} \times \text{exposure time in seconds}}$$

total lumens = subject's area to be illuminated x foot candles

$$\text{number of lamps required} = \frac{\text{total lumens}}{\text{beam lumen output of selected lamp}}$$

$$\text{exposure time (no shutter)} = \frac{1}{\text{Imager's frame per seconds}}$$

$$\text{exposure time (mech shutter)} = \frac{\text{shutter opening in degrees}}{360 \times \text{Imager's frame per seconds}}$$

exposure time (electronic shutter) = shutter width in microseconds

Types of Lighting

Lighting types can be identified by two characteristics, physical design and the method of producing the light. The physical characteristics include lens, the reflector, packaging and the bulb design. The method of producing light includes tungsten, carbon arc, fluorescent and HMI.

Tungsten

Tungsten lighting is also referred to as incandescent lamps. Tungsten color temperature is 3200K. A type of tungsten lamp is called halogen. Halogen is a hotter lamp since the bulb must heat the regenerative tungsten. The tungsten lamps are efficient in their light output.

Carbon Arcs

This type of lamp forms an arc between two carbon electrodes. The arc produces a gas that fuels a bright flame that burns from one electrode to the other. In time, this consumes the carbon.

Gas Discharge

Fluorescent tubes are one type of gas discharge lamp. At the end of each tube are electrodes. The tube is normally filled with argon and some mercury. As current is applied at the electrodes, the argon gas vaporizes the mercury. The mercury emits an ultraviolet emission. This then strikes the side of the tube that is coated with a phosphor. The phosphor then transforms the ultraviolet to visible light. Most fluorescent lamps emit a dominant green hue, which is not very suitable for a balanced light source. Additional, the discharge produces a non-uniform light that is easily detected as a 60-cycle flicker when playing images back from a high-speed motion analyzer.

Arc Discharge

HMI (mercury medium-arc iodide) is the most common lamp in this class of lighting. As current is passed through the HMI electrodes, an arc is generated and the gas in the lamp is excited to a light emitting state. The spectrum of light emitted includes visible as well as ultraviolet. This light source typically has a UV filter to block the harmful emissions. The HMI light is a balance light source. It generates an intense white light. If switching ballast is used with the HMI, it produces a uniform light with very low flicker. Other types of ballast are not as well regulated.

Synchronization

Applications requiring multiple cameras often need the images correlated in time. This means that the cameras need to run in sync. Each image needs to be precisely exposed. Clocking the shutter in unison can do this or operating the cameras off a common frame rate that is sync'd. With each camera in sync, the images can then be analyzed off a common time base. This allows 3-D views to be built off actual images for producing computer models of the motion. This area of image study is very important in automotive crash safety, airborne ordinance certification, and sports medicine studies. Shown in Figure 14 is an example of synchronous timing

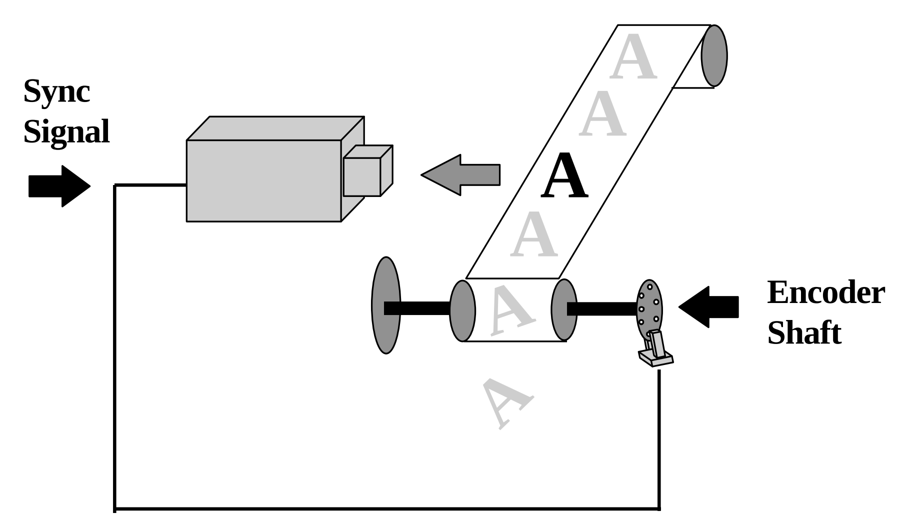


Figure 18 Synchronous recording

Field of View

Field-of-View (FOV) is a term given to the area that is imaged through the lens. The lens type and the distance to the subject determine the FOV. If the distance to the subject remains constant, the lens focal length will then determine the FOV. Shown in Table 13 are the FOV for several lenses used on a Photron Ultima APX-RS for a given working distance of 20 feet and a resolution of 1024 x 1024.

25 mm lens =	167.12 inches =	4.24 m
50 mm lens =	83.56 inches =	2.12 m
60 mm lens =	69.63 inches =	1.77 m
75 mm lens =	55.71 inches =	1.41m
125 mm lens =	33.42 inches =	0.85 m
135 mm lens =	30.95 inches =	78.61 cm
150 mm lens =	27.85 inches =	70.75 cm
200 mm lens =	20.89 inches =	53.06

Table 13 Field-Of-View for Various Lens for a Given Distance

Time Stamp

Time Stamping is the process of marking each frame with a time. The time could be Real Time, Elapse Time, IRIG Timing or User Defined Time. Real Time contains the date and time of day. Elapse Time is the cumulative time starting at the beginning of recording and going to the end. It can be expressed as a negative number if the time corresponds to frames that are before the trigger frame. The trigger frame is defined as frame (0) and it is when the analyzer begins counting time as positive integers. Typically, Elapse Time is expressed in 100's of microseconds. IRIG Timing is a government standard defined as a timecode. This timecode has different formats depending on the class of IRIG. There is IRIG A, IRIG B and IRIG C. IRIG A has a resolution of 1 mess. IRIG B has a resolution of 100 microseconds and IRIG C has a resolution of 10 microseconds. The timecode format combines the date and time of day down to the resolution of the standard. Applications requiring multiple cameras separated by large distances require synchronizing to a common time standard. Typically, the master IRIG generator sends out an RF signal that is received by all the IRIG receivers. The IRIG receivers then re-sync to the broadcast signal. IRIG has wide use in military and range applications.

All of these time formats are written either into the analog video as an embedded timecode or it is written into the file format for each image. Therefore, time stamping is the method of correlating images to time.

Beyond Year 2000

The next ten years will usher in a new era of technology for motion analyzers. These new technologies will enable motion analyzers to be smaller in size, lighter in weight, higher in resolution, more sensitive to light and able to record digital images for a longer time.

The size of motion analyzer's has become smaller over the last ten years. Systems that weighted 250 lbs in 1980 are now replaced with a higher performance motion analyzer that weighs 11 lbs and 1/16 th the size. The recording technology and the miniaturization of electronics has had a large influence.

Resolution is steadily increasing with the advancement of the semiconductor industries ventures into higher density integrated circuits. The pace of this advancement has mirrored the DRAM production. DRAMs memories are very similar in structure to an imaging sensor. Today, the DRAM memories are approaching 64 MB. In the next ten years the DRAM memories will approach 1024 MB densities. Within the next 5 years, imaging sensors should reach 1024 x 1024 x 1000 fps, 1 Giga-pixel. Therefore, it is feasible that a 4X to 16x resolution over today's standard of 512 x 384 pixels.

Most motion analyzers are using CCD technology for imaging. Their sensitivity has been increasing over the older NMOS sensor technology. During the 1980's, motion analyzer's sensitivity could be characterized as being less than 200 ASA. Today, the same averaging for sensitivity would be under 2000 ASA. Within 10 years, the sensitivity should double once more. The pixel size well be larger and the well depth will be greater. However, although this is technologically possible, a factor of economics in the size of silicon will bear on what actual gets produced.

Today, motion analyzers use DRAM based storage technology. In the past, longer record times where possible with magnetic storage technology. In the future, either higher density DRAM memories or real-time image compression will be used to extend the record time. However, if the sensor resolution remained the same, this could be a true prediction. If the resolution increases 4x to 16x, a new storage technology will be needed. It may necessitate going back to low cost and high capacity magnetic recording in the digital domain.

If the past is any indication of where our industry is heading, the technology will continue to advance, the motion analyzers will become simpler to operate and they will have higher performance. The advancement is possible due to the synergies with other key technologies. These include high definition digital television, computer peripherals, video-on-demand products and military imaging applications. All have contributed to the technology required for the next generation motion analyzer.