High-Speed Cameras For Equipment Troubleshooting

Introduction

Video contains more information about an event or action than any other type of recorded media. A video clip of an event will require >1,000x more disk space to store and bandwidth to transmit than any textual description of the same event – thereby lending credence to the old adage that "a picture is worth a thousand words." High speed video (HSV) in particular generates a lot of information in a short amount of time. This white paper explores the acquisition, synchronization, and storage of high speed video for use in troubleshooting machinery and equipment. It is intended for end-users and integrators with some exposure to video analysis but who may be new to high-speed cameras and the types of video they produce. While examples of compatible accessories are provided, these are not intended to be endorsements of any particular product or vendor.

Specific topics discussed include:

1. Advantages of using high speed video
2. Whether and what type of high-speed camera is needed
3. Comparison to more complex machine vision systems
4. Commitments in time and money to capture HSV
5. Assessing return-on-investment
6. Synchronizing multiple cameras for one event
7. Accessories and supporting equipment
8. Acquisition and storage of high-speed video

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What is a High Speed Camera?

High-speed cameras are similar to conventional video cameras but have the ability to capture images at higher rates and increased shutter speeds (reduced exposure) beyond that of conventional video recorders. Consumer video cameras typically have image resolutions of 640x480 (VGA) and record images 30 times per second. Although the new "high-definition" TV format of 1920x1080 is finding its way into home theaters, most digital video recorders are still VGA. Two different types of camera are commonly referred to as "high speed" – 1)those that operate at ≤30-Hz but with short exposures (shutter speeds 1/1000 or less) and 2)those that operate both at short exposures and frame-rates >30-Hz. If an event is occurring at high speed but only a small number of images are needed, then the first type of camera may be sufficient. If the event lasts less than $1/30^{th}$ of a second, a frame-rate greater than 30-Hz is required to not miss the action and a true "high-speed camera" is needed.

The function of a high-speed camera is to generate video files and the good news is that files generated by high-speed cameras are of the same format as those generated by conventional video recorders. Even though the video may be recorded at a high speed, it is ALWAYS played back at a slower rate than recorded. The most common audio/visual format is the Audio Visual Interleave (or AVI) format. An AVI file created by a high-speed camera should playback just as one created by a conventional video recorder. Common video player applications like Windows Media Player or QuickTime Player sometimes have trouble displaying video captured at frame-rates >1,000fps. Any high speed camera will come with software to record and playback video. Third-party AVI editing programs like VirtualDub and AVIfrate can adjust the AVI frame-rate to play in Media Player and QuickTime. Most high-speed cameras do not record audio because of the audio sampling problems arising from the variable frame-rates used during recording.

High-speed cameras come in a wide range of resolutions and maximum frame-rates – from 320x240 at 60 frames-per-second (fps) to 1280x1024 at 1,000fps. SVSi's GigaView™ is a portable camera that captures 1280x1024 images at 530fps for up to 30-seconds direct to on-board memory or streams 640x480 images at 250fps for hours on end. The minimum shutter speed is 1/1,000,000 or 1-microsecond – fast enough for most real-world applications. Almost all high-speed cameras use complimentary metal oxide semiconductor (CMOS) sensors and can be windowed to increase the frame-rate. The table below shows the maximum frame-rate possible for each GigaView image size. The minimum frame-rate in all cases is 30-Hz.

Image Size (hor x vert)	Max Frame-Rate (Hz)
1280 x 1024	532
720 x 480	1,135
320 x 256	2,128
160 x 128	4,256
640 x 480	250 (continuous)

Who Needs High Speed?

Most users who venture into the world of high-speed cameras have already tried capturing video with a home camcorder and observed that they cannot see the necessary details of the event under study because of motion blur or because the event was missed entirely. The advantages of high speed cameras compared to conventional video-recorders are three-fold:

1. high frame-rate (120-17,000fps)
2. short exposure (shutter speeds to 1/1,000,000)
3. high resolution (>1-megapixel)

In many cases, the shutter speed and frame-rate can be determined fairly quickly by trial and error. But that assumes that the user already has a high-speed camera and can play around with it. What if you're interested in acquiring a high-speed camera but don't know which one to purchase based on frame-rate and shutter speed?

High Speed Streaming Video for Monitoring and Surveillance

GigaView's high speed recording to on-board memory is designed specifically for equipment troubleshooting. Its ability to continuously record 640x480 images at 250fps is a complimentary feature for when things are working fine and you would like to keep them that way. For a packaging or production line that is working perfectly, there may be no indication when things break down – especially if the fault occurs at a previously reliable place on the line. By recording every detail of an entire 8-hour shift to hard disk at high speed, the video can be played back in the event of an unexpected failure, disruption, or sabotage. Unlike conventional video rate surveillance, GigaView's streaming feature is designed for high speed machinery to capture every detail at high speed. It has the unique feature of being able to stream 640x480@250fps video to hard disk at the same time that it captures 1280x1024@500fps to on-board memory for those applications where a critical event occurs and more information is needed.

Manufacturing Example

As an example, consider a containerboard manufacturer with a paper line running at 2,000-ft/min. Occasionally, imperfections, debris, or faulty rollers will cause a small tear to form at the edges of the paper and propagate across the entire width. At that point, everything comes to a halt as the paper line is re-threaded and started again. A high speed camera can be used to identify what caused the tear, where it originally formed, and how it propagated. But what frame-rate and exposure is necessary to capture the information. A short exposure may be necessary to reduce motion blur during troubleshooting. But how short is short? A speed of 2,000-ft/min is equivalent to 33-ft/sec or about 11,000-pixels/sec for a 1024x1024 image. If the camera's field-of-view (FOV) is approximately 3-feet x 3-feet centered on the edge of the paper, a half-inch tear at the edge is approximately 14-pixels long and takes about 100-milliseconds to traverse the 3-foot window. At 30-Hz video rates approximately 3 frames of the tear will be captured during this interval and will probably be sufficient to at least see the tear. However, motion blur should be kept to <1-pixel for clear stop-action images dictating a shutter speed of 1/11,000. Although useable video can be recorded at slower shutter speeds (and

higher motion blur), the equation below can be used as a rule-of-thumb to estimate shutter speeds.

$$shutter\ speed = \frac{1}{exposure}$$

$$where \quad exposure = \frac{FOV\ (in\ \ feet)}{velocity\ (in\ \ feet/\sec) \times number\ of\ \ horizontal\ \ pixels}$$

Now assume that, not only do you want to record the tear, you want to actually record the instant the tear starts to propagate. At 30-Hz, the paper moves (and the tear propagates) over a foot between consecutive frames so that chances are very small that you will capture both the fault before propagation and the instant of propagation. So how fast of a frame-rate do you need? To capture the break, the imperfection, debris, or fault must move less than the maximum desired tear propagation (1/2") between frames. At 33 feet-per-second, the paper will move 0.5-inches in 1.25-milliseconds so that a frame-rate greater than 1/0.00125=800-fps is required to have a reasonable chance of recording the break.

Investment and ROI

Once purchased, the good news is that the investment required to implement a high speed camera for troubleshooting applications is very small. They are designed, packaged, and delivered with software for ease-of-use even for a novice. The GigaView camera begins recording high speed video as soon as power is applied. Just attached a lens, point it at the trouble spot, and begin recording. In less than 30-minutes, a first-time user can successfully learn to operate the camera. Unlike a machine vision system which also uses digital cameras, there is no programming or learning required. The camera is not processing images to determine pass/fail – only recording high speed motion for playback purposes.

The actual return-on-investment (ROI) realized from a high speed camera varies by product and manufacturer. The dual objectives of increasing annual production yields and reducing scrap material costs both benefit from production line troubleshooting with high speed cameras. A reasonable ROI goal would be to have GigaView pay for itself in 3-6 months. The equation for calculating ROI based on total annual production is:

$$ROI_{TAP} = \frac{Acquisition\ Cost}{Total\ \ Annual\ \ Production \quad \times \quad Percent\ \ Production\ \ Increase}$$

If a plant's total annual production is $5M/year and corporate goals for the year are a 0.5% increase in production, this represents an annual production increase of $5M/yr×0.005=$25,000/yr. If GigaView's acquisition cost is $12,000, then it pays for itself in 0.5-years (6-months) based on production increase alone. The equation for ROI based on materials cost reduction is similar:

$$ROI_{MC} = \frac{Acquisition\ Cost}{Materials\ Cost \quad \times \quad Percent\ \ Scrap\ \ Reduction}$$

If corporate goals are 1% reduction in scrap materials and yearly material costs are $1M, savings of $1M/yr×0.01=$10,000/yr are realized. ROI based on material savings alone is 1.2-years. Combining production increase and material savings, the overall ROI is:

$$ROI_{Total} = \frac{\$12,000}{\$25,000/yr + \$10,000/yr}$$

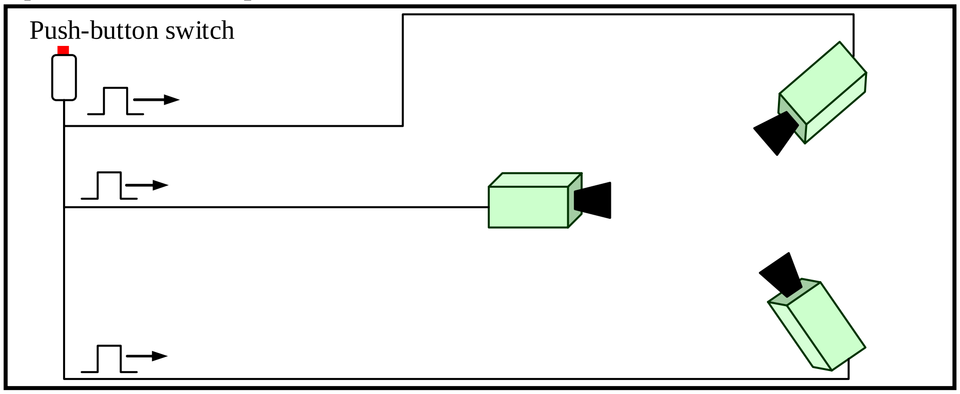
Based on this model, GigaView's ROI is 0.34-years or 4-months.

Synchronizing Multiple Cameras

Some video analysis software packages have the ability to process multiple AVIs of one event taken from different views. In doing so, three dimensional information about an object or motion in the event can be extracted and stored for applications such as tracking, accurate timing, and precision measurements. For these applications, all cameras must be synchronized to a high degree – typically to a time interval much less than the frame period (33-milliseconds for conventional video recorders).

As examples of multiple camera synchronization, let's consider four different ways that multiple GigaView cameras can be synchronized to less than one frame period.

1. Externally triggering multiple cameras with one pulse.
   Each GigaView can be set up to accept a +5V TTL or switch closure trigger that can start or stop recording. If all cameras are told to record the same number of frames at the same frame-rate and exposure after receiving the trigger, then the first image of each video on each camera will all be within an interval of time equal to the frame-period.



For instance, if all cameras are recording at 500-Hz, the first frame of each of the videos occurs within 2-msec. All subsequent frames from each camera have the same relative delay as shown in the schematic below.

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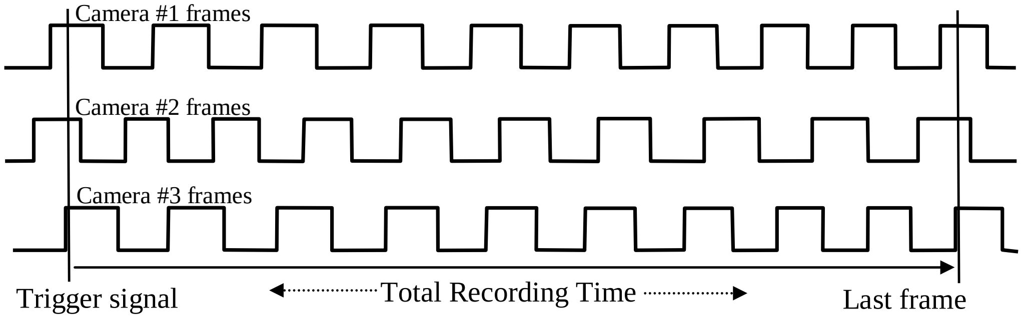
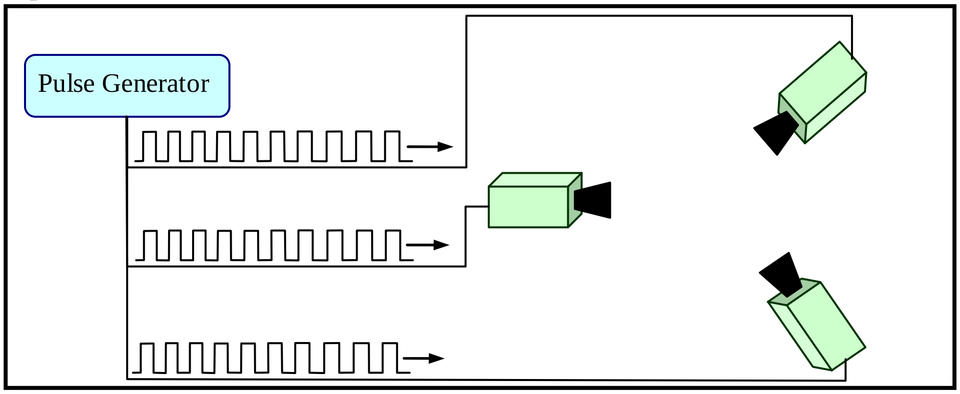


Each camera was free-running with its own clock before receiving the trigger signal and the trigger signal can come anywhere in a frame period. The trigger identifies the start frame and their relative positions in each video. The last frame of each video maintains this relative position and drifts only by 5-microseconds per second of recording time. This technique is simple to set up, requires only a manual push-button switch to activate, and maintains a high degree of relative synchronization. Its only drawback is the poor (1/frame-period) synchronization on start.

2. Frame synchronization with an external pulse generator.
   If a high degree of synchronization is required both starting the videos and between frames for the duration of the recording, then the simplest technique is to use an external pulse or function generator that supplies TTL pulses to all cameras simultaneously. Several manufacturers make suitable pulse generators but each should be capable of supplying 5V pulse outputs at frequencies between 30-100 kHz. The Protek Model B8011 function generator is one example that retails for about $250USD. Only one pulse generator is required for all cameras with the output of the generator split off and going to the "External Trigger" input of each camera. Once pulses of the appropriate frequency and amplitude are at each camera, selecting GigaView's "Frame Synch" mode will capture one image for each trigger pulse received until the total number of specified images is captured.



By starting all cameras to record then starting the pulse generator, the first frame of each video will be synchronized to within 0.2-microseconds. This degree of frame synchronization holds for all frames captured so that the final frames of each video are also synchronized to 0.2-microseconds. This technique is relatively simple to set up and maintains a very high degree of synchronization both on start and relative frame synchronization even over long recording periods. It does require an additional pulse generator.

3. Clock synchronization.
   By outputting the clock on one of the cameras to all the others, each camera can be driven off the master clock as if they are one camera. The only de-synchronization between cameras is the delay caused by the cables connecting the cameras. The degree of synchronization achieved with this technique can be as high as 0.001-microsecond. However, each camera will require custom modification and the additional cost and complexity do not usually warrant implementation.

4. GPS synchronization.
   Highly accurate time signals are broadcast over the Global Positioning System signal along with positional information. GigaView has an option to read this time signature with an additional electronics board installed inside the camera. Each camera can then be told to start a frame capture based on an absolute GPS time and maintain this time synchronization throughout the recording process. Both video start and relative frame synchronization are maintained to 1-microsecond no matter how long the recording process takes. While not as precise as clock synchronization, this technique is easier to implement and can be used to encode absolute date and time on the imagery. Additional items that will have to be purchased are one GPS antenna, one code generator, and a de-modulator card for each camera. Outdoor access to GPS signals is also required.

Accessories and Supporting Equipment
In many cases, the same lenses, tripods, and lighting used for conventional photography can be used for high-speed cameras. Below is a list of accessories and some of the things to consider when purchasing.

Lenses
Unlike most conventional video recorders, high-speed cameras to not come with lenses and one must be specified on purchase. While there are a wide variety of fixed focal length and zoom lenses available in C-, F-, or M-mount formats, very few high-speed cameras are available with auto-focus and auto-exposure features. SVSi's GigaView camera has an auto-exposure feature that adjusts each frame's exposure on a frame-by-frame basis to compensate for fluctuating light conditions. This feature does not mechanically adjust an iris within the lens as do most video-cameras but the effect is the same.

C-mount and F-mount lens adapters are the most common adapters for high-speed cameras. If the imager size is >2/3" CCD, a C-mount to F- or M-mount adapter allows use of a less-expensive 35-mm lens. Because of the short exposures typically used with high-speed cameras, lenses with large apertures (f/# ≤3) are required. Navitar, Pentax, and Schneider are some lens manufacturers with large area, large aperture lenses. The

Navitar DO-5095 lens, for example, has a 50-mm focal length, 0.95 aperture, and comes with manual focus and iris.

The focal length of the lens will depend on the desired field-of-view of the video and the distance of the camera from the object being recorded. The equation below can be used as a rule-of-thumb for estimating the lens focal length:

$$focal\ length\ (in\ millimeters) = 25 \times \frac{distance\ (in\ feet)}{FOV\ (in\ feet)}$$

Tripod

Any tripod that can support 10-20-lbs and has a ¼-20 thread adapter will work with GigaView and most high speed cameras. GigaView has mounting holes on all four sides for ease of installation. The Manfrotto 724b ball-head tripod is an example of a compatible tripod.

Lights

Ensuring sufficient illumination during high speed video recording is essential. The best, least-expensive, easiest-to-use light source is the sun. However, not all recording can take place outdoors and there are several alternate illumination options. One lighting feature that should be carefully considered is the fluctuation or flickering caused by ballast-driven lights such as fluorescent or HMI (hydrargyrum medium-arc iodide). These types of lights are driven by AC currents and show significant changes in intensity at recording frame-rates ≥120-Hz. High-frequency ballasts have been proposed for HMI lights but are not commonly available. This doesn't mean do not use these types of lights – just be aware of the fluctuation tendencies. For example, SVSi's GigaView camera can be synchronized to the AC frequency using a line filter so that each frame exposure is at the same point on the line frequency and the light appears steady. This only works at frame-rates of exactly 30, 60 and 120-Hz. Beyond that, alternative frames will show intensity variations.

1. Halogen – this type of lighting is the least expensive, brightest, most common illumination source on the market. When powered with an AC/DC converter, halogen lights exhibit minimal fluctuations or flickering. However, these lights put out a lot of heat and care must be taken not to overheat any object in the recorded scene. They also emit a significant amount of infrared radiation that can degrade resolution and color clarity. GigaView has an infrared blocking filter to prevent this wavelength from affecting the image but, even with a filter, the images may look redder under halogen lighting. A 1,000-Watt quartz halogen work light can be purchased for under $50 from building and home supply stores.

2. HMI – these lights are bright, have very good color temperature, and do not emit significant infrared compared to halogen lights. Unfortunately, intensity fluctuations caused by ballast operation limit their use for high speed video.

Several lighting providers now offer "flicker-free" ballast options but these are generally relegated to professional supply shops. Count on paying several hundred to several thousand dollars for flicker-free HMI lights.

3. Fluorescent – probably the most common light source next to incandescent lights, fluorescent lights yield acceptable color clarity. However, they tend to be too dim for most frame-rates over 200-Hz and are susceptible to intensity fluctuations caused by ballast operation. These can be purchased at any lighting or home supply store.

4. Quartz halogen spotlight – most of the light sources mentioned above have a fairly large emission angle (10^o or larger) and are intended to deliver light over a fairly broad area. Many times, the object of interest is relatively small but without access so that the camera must be located several feet away. For those situations where a lot of light needs to be delivered to a small object a distance away, a battery-powered quartz halogen spotlight is inexpensive and relatively efficient at keeping a small divergence angle. The Vector VEC-192 20-million candle power spot-light can be purchased on-line for about $60.

Computer

A host computer is required for any high speed camera with internal memory to configure the camera and store recorded video. The major features affecting the type of host computer are interface and hard disk capacity. The most common interfaces for high speed cameras are USB, Ethernet, and CameraLink interfaces. It would be hard to find a computer without one of the first two interfaces while the third type interface requires an additional PCI card to be installed on the host computer before it will recognize the camera. GigaView comes with a gigabit Ethernet interface that is backwardly compatible with 10/100-ethernet. GigaView will recognize the type of Ethernet interface and auto-negotiate up or down depending on host capabilities. Most USB high speed cameras will have the higher speed USB-2 specification. USB-1 will take an inordinate amount of time for downloading video and should be avoided.

Disk capacity should be sufficient to store any conceivable quantity of video during a recording session. For example, GigaView can hold up to 16-GB of imagery and a color version generates 3x that quantity for red/green/blue. It doesn't take long to fill up a hard disk if each file is 16x3=48-gigabytes. For comparison, the hard disk requirement for installing the GigaView software is 10-MB. Download times for 16-GB over USB-2 or Ethernet can take 20-30 minutes and should be considered.

Desktop and mini-tower host computers work well with GigaView. However, they are not very portable and can be a nuisance to take into the field. Laptops and tablet-PCs in particular are much more portable and come with sufficient interfaces and hard disk capacities. The Tabletkiosk eo V7110 tablet-PC comes with 512-MB of ram, a 60-GB hard disk and USB-2 interface – all in a hand-held package with a 7" LCD display.

Using a Belkin Gigabit-USB network adapter and powering GigaView from a portable battery pack, a tablet-PC and camera make for a very concise portable system.

Software Techniques

Any high speed camera should come with software that allows the user to control the camera, capture video, and download to hard disk. Third-party video analysis software is available from numerous suppliers for special applications. All software video analysis packages start by importing a video – whether AVI, raw, or a format proprietary to the camera manufacturer. From there, common video editing features are contrast/brightness adjust, object tracking, color enhancement, edge detection, test and graphics overlay, smoothing, image subtraction, rotation, cropping, and resizing to name just a few. There are too many software video editing features to cover in this white paper. Suffice it to say that there are many more video analysis software suppliers than high speed camera manufacturers.