Using High-Speed Cameras for Sports Analysis

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 in particular generates a lot of information in a short amount of time. The proliferation of on-line video repositories such as YouTube, video.google, and video.yahoo among others validate video as a communication, educational, and entertainment media. This white paper explores the acquisition, synchronization, and storage of high speed video for use in post-processing video analysis software. 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 vendor.

Specific topics discussed include:

1. Whether and what type of high-speed camera is needed
2. Synchronizing multiple cameras for one event
3. Accessories and supporting equipment
4. Acquisition and storage of high-speed video
5. Software features and vendors

Southern Vision Systems, Inc. • 8215 Madison Blvd, Suite 150
Madison, AL 35758 • Phone: (256) 461-7143 • Fax: (256) 461-7145
www.southernvisionsystems.com • email: info@southernvisionsystems.com

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 10-60 frames per second. High speed cameras have VGA or higher resolution and typically record images at 200 frames-per-second or higher. Frequently, consumer video cameras that operate at high shutter speeds are erroneously referred to as high-speed cameras even though the frame-rate is standard 30-Hz. A true high-speed camera will operate at high frame-rate(≥200-Hz) and high shutter speed (≤1/1000th of a second). SVSi offers several high-speed camera lines with frame-rates from 200-17,000-Hz and shutter speeds as low as 1/500,000th of a second. Although capable of high frame-rates, any high speed camera should also be capable of operating at 30-Hz if desired.

The function of high-speed cameras 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. The most common audio/visual format is the Audio Visual Interleave (or AVI) format defined by Microsoft. An AVI file created by a high-speed camera should playback just as one created by a conventional video recorder. Most high-speed cameras do not record audio because of the audio sampling problems arising from the variable frame-rates used during recording.

SVSi's StreamView™ is a portable battery-powered camera designed for quick and easy set-up in the field that captures 640x480 (VGA) images at 200fps. The minimum shutter speed is 1/100,000 or 10-microsecond – fast enough for any sporting event. Almost all high-speed cameras can be windowed to increase the frame-rate. The table below shows the maximum frame-rate possible for each various image sizes. The minimum frame-rate in all cases is 30-Hz. StreamView-LR is useful for analyzing golf swings, pitching, batting, track and field, and gait analysis for dog/horse racing. For even higher speed recording, SVSi's GigaView™ camera records 1280x1024 at 532-fps. Both cameras come in monochrome and color versions with complete software for camera set-up, video recording, and slow-motion replay.

StreamView-LR

GigaView

	StreamView-LR	GigaView
Image Size (hor x vert)	**Max Frame-Rate (Hz)**	**Max Frame-Rate (Hz)**
1280x1024	N/A	532
640 x 480	200	1,136
320 x 240	370	2,272
160 x 120	640	4,550

Southern Vision Systems, Inc. • 8215 Madison Blvd, Suite 150
Madison, AL 35758 • Phone: (256) 461-7143 • Fax: (256) 461-7145
www.southernvisionsystems.com • email: info@southernvisionsystems.com

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. 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? As an example, let's assume the user wishes to record a batter in a baseball game in order to improve their swing. It helps to capture the bat and ball with minimal motion blur in order to determine their relative positions. A short exposure may be necessary to determine the batter's motion throughout the swing. But how short is short? Assume that the ball is moving at 98-mph or approximately 144 feet-per-second and that the camera's field-of-view (FOV) is approximately 10-feet x 10-feet centered on the batter. The ball takes about 70-milliseconds to traverse the 10-foot window and the duration of the batter's swing is about quarter of a second. At 30-Hz video rates, approximately 5-10 frames will be captured during this interval and will probably be sufficient to see the various stages of the swing. However, motion blur should be kept to <1-pixel for clear stop-action images. For a 640x480 image with 10-foot FOV, the ball traverses all 640 vertical columns in 70-milliseconds or 1-pixel in 70/640=0.11-milliseconds. This is equivalent to a shutter speed of 1/10,000. 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 swing, you want to actually record the instant the ball contacts the bat. At 30-Hz, the ball moves almost 5-feet between consecutive frames so that chances are very small that you will get the instant of impact. So how fast of a frame-rate do you need? To capture the impact, the ball must move less than the diameter of the bat between frames. At 144 feet-per-second, the ball will move 3-inches in 1.7-milliseconds so that a frame-rate greater than 1/0.0017=600-fps is required to have a reasonable chance of recording impact. On the other hand, if a batter's complete swing lasts 0.5-seconds, a 200-Hz frame-rate will give 100 images from start to finish. This is more than enough detail to record every nuance of the swing.

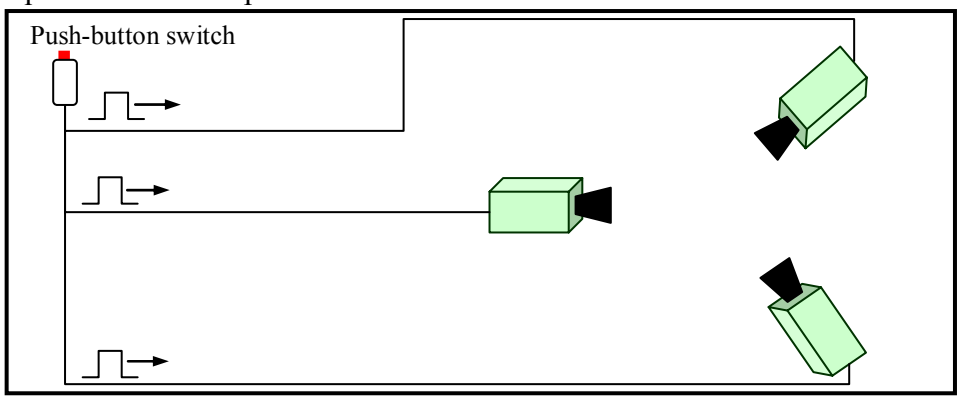
Synchronizing Multiple Cameras

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

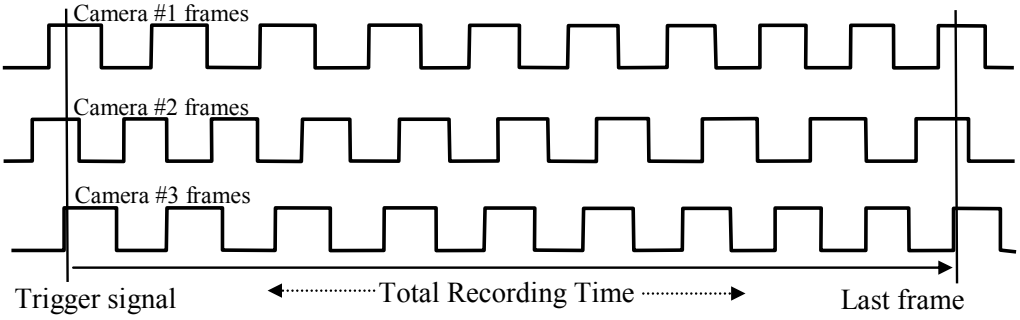
tracking, accurate timing, and precision measurements. For these applications, all cameras must be synchronized to a high degree – typically to a time interval much less than the frame period (33-milliseconds for conventional video recorders).

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.



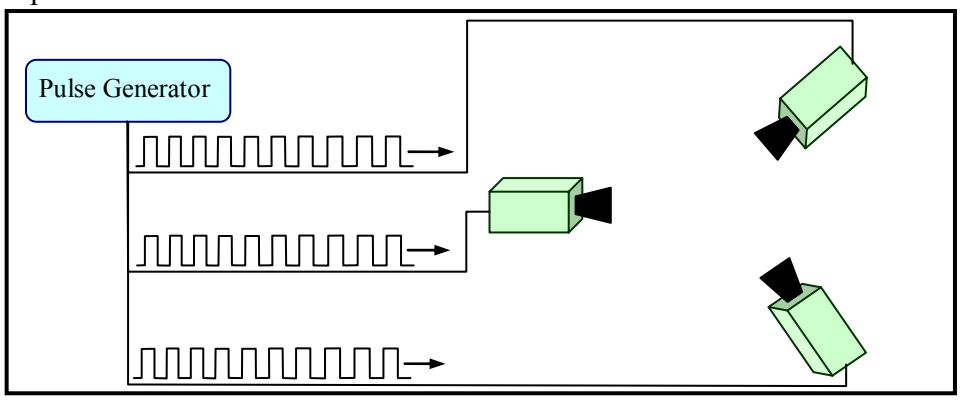
For instance, if all cameras are recording at 500-Hz, the first frame of each of the videos occurs within 2-msec. All subsequent frames from each camera have the same relative delay as shown in the schematic below.



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.

Southern Vision Systems, Inc. • 8215 Madison Blvd, Suite 150
Madison, AL 35758 • Phone: (256) 461-7143 • Fax: (256) 461-7145
www.southernvisionsystems.com • email: info@southernvisionsystems.com

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. Compact Fluorescent – rapidly becoming more common with new models on the market every day, these lights typically use a high-frequency flicker-free ballast. Although most compact fluorescent bulbs are between 7-30W, their efficiency makes a 30-W bulb almost as bright as a 100-W incandescent.

5. 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 most high speed cameras to configure the camera, store recorded video, and playback in reasonable detail. 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. Both StreamView-LR and GigaView comes with a gigabit Ethernet interface that is backwardly compatible with 10/100-ethernet. Both cameras 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.

RAM and hard disk capacity should be sufficient to store any conceivable quantity of video during a recording session. For example, StreamView-LR records directly to host RAM and stores approximately 12-secs of video per gigabyte(GB). GigaView records to on-board memory and can hold up to 16-GB of imagery. A color camera generates 3x the amount of on-board memory 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 both StreamView-LR and 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. A laptop without a gigabit Ethernet port can easily and cheaply be retrofitted using a PCMCIA or ExpressCard gigabit Ethernet adapter.

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. Sometimes the same software package will allow video analysis after recording. 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 but the next section includes a short list of video analysis software.

Software Providers

A partial list of video analysis software is below:

Dartfish	ASTAR Learning Systems
APAS from Ariel Dynamics, Inc.	SportsCAD
ImageJ from National Institute of Health	Video Point
Motionview from AllSportsTec.com	Silicon Coach
Sports Motion Pro-Trainer	MotionPro
cSwing	Contemplas
MotionCoach	Swinger from Webbsoft

Costs range from free for ImageJ to $200 - $2,000 for commercial packages depending on various options. Sports Motion's Pro-Trainer software is reasonably priced with most of the relevant features for sports analysis. Both StreamView-LR and GigaView generate AVIs that can quickly and easily be opened in Pro-Trainer and other software packages.