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Developing a Super Slow-Motion Camera for HD

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Super slo-mo replays have become such a regular part of the vocabulary of television sports and events that it is impossible to imagine life without them. Broadcasters and producers migrating to HD are aware that their audiences expect the same production values, which means delivering super slo-mo, with the same replay speeds and operational convenience, but with the higher quality of high definition.

The practicalities of television outside broadcast coverage, though, are such that super slo-mo cameras have to provide a live real-time output as well as send the high-speed output to a server for replay. So most of the design constraints are centered on ensuring that the camera output, whether live or in slow-motion replay, matches in image quality and colorimetry the regular cameras used elsewhere on the production.

Background

Slow-motion replays are now widely accepted as an integral part of television sports coverage. Indeed, many sports, including top-level rugby and cricket and American football, now rely on replays to help the match officials judge critical action.

To create a slow-motion replay that appears smooth, it is necessary to have a camera and a recording system that is capable of shooting faster than the normal 50 or 60 fields or frames per second rate. Capturing more pictures than normal then playing those out at the standard rate gives you smooth motion at a slow speed.

This was the thinking behind the development of the LDK 23, which set the standard for live slow-motion system, or super slo-mo. The LDK 23 shot at three times normal speed, producing 75 or 90 frames each second depending on the video standard, giving perfect motion at one-third normal playback speed.

The important point here is that the technology existed for this to happen within a live production without complex processing or delay. Essentially all that happened was that, with a special super slow-motion server, the 3X output could be recorded, then played back instantly at variable speed. The recording could be as long as needed: normally super slo-mo server channels are permanently recording, capturing the entire event.

Without this approach, viewers had to put up with jerky motion, or there was a significant delay while complex processing and rendering took place to estimate the in-between pictures. This did not produce satisfactory results and was of no practical value in fast-action sports because of the processing delay.

Today the broadcast market sees a number of very high-speed cameras: speeds as high as one million frames per second have been quoted. But these are limited to very short recording durations—a fraction of a second in the case of the highest speeds—and the outputs need to be downloaded and processed before they can be used. This makes them attractive for very specialist applications, but not a practical proposition for live applications.

Sports broadcasters are now used to the idea of 3X super slo-mo, and directors are used to being able to call for replays instantly. They are an established part of the language of television sports.

But sports is leading the migration to HD for broadcasters around the world. Audiences expect landmark events—such as the 2006 FIFA World Cup and Euro 2008 in European football, and the 2008 Olympics and Paralympics—to be covered in HD throughout, and increasingly there is an expectation that other, more routine sporting events should also be available in HD.

So there is a significant demand for an HD super slo-mo system. The development of such a camera, though, faces a number of technical demands if it is to meet the uncompromised quality standards that viewers expect of HD and the ease-of-use expected by sports producers. This paper looks at some of these design challenges and how they have been resolved in the Grass Valley LDK 8300 super slo-mo camera.

Signal-to-Noise Ratio

A top-end professional television camera uses as its imager a CCD. In the future, CMOS sensors may achieve sufficient quality for the task. In this context, it does not matter whether the imager is CCD or CMOS, though, as both work in a similar way.

The CCD imager is a chip on which there are a large number of photosites. These photosites convert light energy to electrical energy: they collect photons falling on the photosite and output a signal that is proportional to the number of photons collected. In the CCD's output amplifier the signal charges will be converted into a proportional output voltage. The output voltage from the imager is very low, and has to be immediately amplified before being converted from analog to digital for downstream processing.

The imager output is directly proportional to the amount of light falling on it, but it is also directly proportional to the length of time that it is exposed to that light. It is counting photons: if you reduce the time that you are counting photons then of course you reduce the number that hit the imager. Shooting at three times the normal frame rate means that the imager is exposed for one third of the normal time for each frame, reducing the output from the imager and degrading the signal-to-noise ratio at the front end of the camera.

One possible solution would be to use a special imager, developed with low signal-to-noise as its primary design requirement. The disadvantage of this would be that its pictures would not match the other cameras being used at the event.

This would probably be unacceptable even if the output of the camera was only used for slow-motion replays. But in practical situations the super slo-mo camera is used as part of the standard shoot and differences in image quality, certainly in HD, would not be tolerable.

Equally, having a standard camera alongside the super slo-mo camera is not an acceptable solution. The additional capital and operational cost of camera, cable, and operator would add to the budget, and in many sports applications there is only one perfect spot for the camera, not two side by side.

So the decision was made to use the same head block in the Grass Valley LDK 8300 HD super slo-mo camera as its normal speed equivalent, the LDK 8000. This uses DPM™—dynamic pixel management—to create native 1920 x 1080 and 1280 x 720 from the same imager without compromise.

In the super slo-mo camera, ultra low-noise electronics minimize the impact on noise. In 3X operation it achieves a signal-to-noise ratio of 54 dB, significantly better than other slow-motion cameras on the market and an acceptable noise floor for HD.

Another design decision taken in the LDK 8300 was that it should offer native 2X as well as 3X super slo-mo. Some sports—basketball, for instance—are so fast that there is no time to replay an incident at three times its length before the live game has moved on.

The reason for allowing a 2X setting is that this can be achieved using the clock at the camera headend. This gives a 50% increase in the exposure time for each frame, with a consequent increase in output from the imager and improvement in the signal-to-noise ratio.

Whether shooting at 2X or 3X, the normal speed output for live use is created at the camera control unit (CCU). The sophisticated algorithms, which blend the two or three video phases into the standard-speed output, also improve the signal-to-noise figure by a further 3 dB. The result is that the LDK 8300 can be intercut seamlessly with the LDK 8000 camera, in HD, without any visible effect to the audience.

Data Rate

It is well known that uncompressed HD, as 720p or 1080i, has a data rate of 1.5 Gb/s. If you are shooting at three times normal frame rate, therefore, you are faced with a data rate of 4.5 Gb/s.

To accommodate this data rate Grass Valley™ was forced to develop a new fiber system. It uses either SMPTE hybrid fiber cables or two cores of standard single-mode dark fiber cables, and operates securely over distances of up to 4000m, including the delivery of power to the camera. With local power at the camera head, even longer distances can be covered.

The base station is specially developed to unpack the triple bandwidth of video (for 3X speed), carry out the necessary processing, then offer the output as three parallel HD-SDI signals to an external recording device. The base station also creates a very high-quality normal speed output for live use.

This requires two sets of algorithms: for progressive and for interlaced image capture. The camera always operates at the native rate of the production, so if the requirement is for 1080i that is what is generated in the headend electronics. As can be readily appreciated, creating a single real-time stream of interlaced HD video from three interlaced frames per output frame calls for very complex mathematics and consequently a great deal of processing power in the base station.

It is very difficult to create smooth slo-mo in interlaced formats, and this is an issue that broadcasters have to address. For the sort of action events that require super slo-mo, 720p is a much better format. However, it is important that the technology does not impose restrictions on the operational requirements of the production company, so the processing power and capability is included to create a very high-quality, real-time 1080i output.

At present there are no operational requirements for 1080p production. The design of the camera is prepared for this standard should it come into use. The chief challenge will be the data rate between the camera and the base station: transmitting 9 Gb/s without jitter or glitches, even over fiber, is a very significant challenge. Grass Valley engineers are working on a new, universal transport standard that will accomplish this when the time comes.

In transmission and processing, latency is an important issue especially when intercutting between the normal speed output of an LDK 8300 and a regular LDK 8000 camera, and the entire fiber system has been designed for minimum processing delays.

Making the super slo-mo system fit seamlessly into the production environment is also a primary consideration. The camera can be controlled from a standard operational control panel (OCP), so racking and matching super slo-mo cameras to standard cameras is a simple operation. Grass Valley's camera control system uses Ethernet to link the OCP panel and the camera's base station itself, and LDK 8000 and LDK 8300 cameras can be controlled on the same network.

Flicker

When sports take place under artificial lighting, there is another important issue to consider: flicker.

While the eye integrates the output of electric lights so that the level appears constant, those lights are actually cycling with the mains frequency. Typically this is not an issue with television cameras: a 50 fields per second camera under 50 Hz lighting will always receive the same amount of light—effectively integrating the illumination over a complete cycle—so the picture will appear stable.

But when shooting at 150 frames per second, successive frames will receive a different amount of light because it will capture a different part of the power sine wave. When slowed down, these changes in light levels will appear as a visible and distracting flicker. This flicker appears not just with single-phase lighting but also with two or three phase lights and discharge lamps.

While other high-speed cameras ignore this problem, and as a result show a very disturbing flicker under artificial lighting conditions, Grass Valley has developed a compensation system to eliminate it. A simple automatic gain control is not sufficient for high-quality results: players moving quickly through the frame would fool the detectors and actually risk introducing flicker rather than reducing it.

The Grass Valley solution, called AnyLight, uses very sophisticated algorithms running in the signal-processing unit. Control is important: any image processing of this nature risks introducing motion blur, which would be unwanted. AnyLight has five presets (including off), which allows the vision engineer to dial in precisely the amount of correction required for each setup.

These presets are:

- optimal – no flicker reduction, for use in optimal lighting conditions
- good – artificial lighting with minor amplitude changes, including incandescent or well-balanced three-phase lighting, and mixed daylight and artificial lighting
- fair – when there are significant amplitude changes, such as under fluorescent lights
- poor – for lighting with major amplitude changes, like HMI, MNHD, gas discharge lamps, and neon
- extreme – which results in a completely flicker-free image but does introduce an increased level of motion blur, and used only when there are extremely challenging lighting conditions. This setting uses a different flicker reduction algorithm than the other three.

The LDK 23 mk II standard-definition super slo-mo camera introduced flicker compensation and rapidly became regarded as the benchmark. Qualitative evaluations of AnyLight in the LDK 8300 HD camera suggest that it is an even more effective implementation.

Obviously the AnyLight processing, like the signal blending for the normal-speed output, has to be done in real time. It is equally important that it, too, is performed with very low latency, to ensure there are no jumps in the action, particularly when cutting from a regular LDK 8000 camera to an LDK 8300.

Conclusion

Super slo-mo replays have become such a regular part of the vocabulary of television sports and events that it is impossible to imagine life without them. Broadcasters and producers migrating to HD are aware that their audiences expect the same production values, which means delivering super slo-mo, with the same replay speeds and operational convenience, but with the higher quality of high definition.

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We can summarize the design challenges, therefore, as:

- The ability to capture full-resolution HD pictures at 2X and 3X normal speed
- Delivering identical image quality from the optical block and camera head, and comparable signal-to-noise ratio
- A transport system to carry the high data rates (4.5 Gb/s for today's HD) over standard cables and practical distances, including those pre-installed in sports venues
- A means of minimizing the effect of lighting flicker in slow-motion replays
- Good signal processing to create a smooth, stable, and clean real-time signal from the high-speed video, even from an interlaced output
- Maximum commonality between components and operations for normal and super slo-mo cameras, including lens and viewfinder mounts, and operational control and master control panels

Meeting all these challenges was demanding, and Grass Valley did not rush to market with a compromised offering.

The LDK 8300 super slo-mo camera was first used on the Euro 2008 football championships in June 2008. At both that event, and in Beijing later in the year, production companies had the opportunity to directly compare the performance of the LDK 8300 with its competition: the widely held view was that the LDK 8300 meets all of the technical and operational requirements and, thanks to its very low noise and its flicker reduction, it creates a visibly superior image.

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