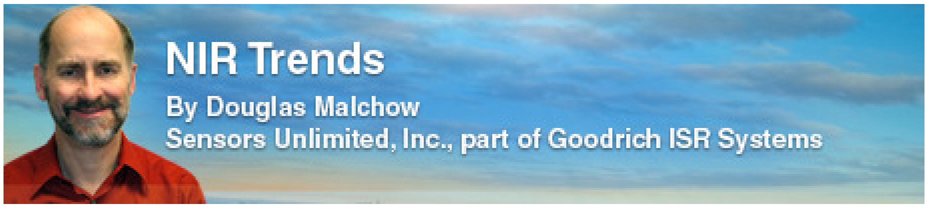


Using A High-Line-Rate SWIR Line Scan Camera To Capture Fast-Changing Optical Light Variation

By Douglas Malchow, Sensors Unlimited – Goodrich ISR Systems

This article describes observations about office lighting that were discovered while investigating ways to illustrate the speed of a new high-speed, indium gallium arsenide (InGaAs) line scan camera (SU1024LDH2). The camera's 11 microsecond (µs) time resolution captured arcing in the magnetic ballast of overhead fluorescent lamps, but only on alternate phases of the power cycle. The light fixture was later changed from the magnetic ballast to a high-frequency electronic ballast, which eliminated the arcing and reduced the light variation. The images taken with the SU1024LDH2 camera will illustrate our findings.

The high-speed line scan camera was developed for use in the short-wave infrared (SWIR), specifically for optical coherence tomography (OCT) applications, but will also serve to capture transient spectra and/or fast-moving processes. In recent years, the development of fast line scan cameras, both visible and non-visible, has been driven by OCT, the biomedical method of imaging microscopic structures in living tissue (see the *Sidebar* on page 2).

For OCT, increasing the camera's line speed minimizes the blur created by motion, whether it is movement caused by the patient or movement in the interferometer's optical path. In August 2010, Sensors Unlimited – Goodrich Corporation (Princeton, NJ) started shipping the fastest shortwave infrared line scan camera to serve the spectral-domain OCT market. It operates at the high line rate of 91,911 Hz, which almost doubles the line rate of the company's previous offering. The first time the new camera was used in an OCT research lab, the ophthalmologists observing the system's higher-resolution imaging of a human cornea, said to the students in the room, "You are seeing structural details in the cornea never before been seen *in vivo* in a patient!" Previously, such detail had only been seen in excised histology samples.

As seen in the 11/17/10 edition of the Photonics Online (**www.photonicsonline.com**) newsletter.

As part of the development effort to achieve higher line-rate speeds, a convenient method to document the speed of the camera was needed. Coincidentally, it had been previously observed that many line scan images showed significant variation in brightness versus time, and understanding why became the focus of the investigation. It soon became clear that light from AC-powered lamps is never constant, with the variation in intensity synchronized with the power line frequency. This was noticed whether the camera lens was focused on the reflection of an incandescent light, or directly on a standard office-type fluorescent lamp. By using high-speed imaging, one quickly sees that the light variation is at twice the power line frequency, as the light output from the lamp peaks on both the positive and the negative cycles of the power line sine wave. In the United States, the light output ripple frequency is 120 Hz. Thus, the camera line rate can be demonstrated by counting the number of lines between cycles of the ripple.

Optical Coherence Tomography

In this biomedical imaging technique, light from an optical fiber is projected into live tissue, and structures from within the tissue scatter a small fraction of the light back into the fiber. This is then sent into an interferometer, which strips off randomly scattered light and also any light from outside the range of interest that is established by the length of a reference arm. In the spectral domain (SD) OCT version of the technique, the light from the interferometer is dispersed by wavelength onto a linear-diode-array camera. By processing the spectrum in the computer, first to convert the spectrum's dispersion to be linear in wavenumber units, then performing a fast Fourier transform (FFT), a depth profile is created showing the location of the back-scattering structures. A 3-D image volume is generated by using scanning mirrors to scan the tissue in both X and Y directions. As with other tomography datasets, this volume can then be sliced to produce hundreds of images with the resolution of a microscope histology slide, showing detail 1 to 4 mm into the tissue.

This article documents these observations and reports on an anomaly noticed on one fluorescent light fixture, where intense flashes were noted. These occurred only at the ends of the tubes, and only at alternate peaks of the power cycle.

Screen shots with descriptions of the methods used to study the lamp output variations and observations drawn from the resulting data are used in the figures below to show the variation in light output versus time. The data acquisition and light variation analysis was performed with Sensors Unlimited – Goodrich ISR Systems proprietary software, SUI Image Analysis, which is distributed free with both the company's area and line scan cameras.

Incandescent Lamp Ripple

The first screen shot (*Figure 1*) shows an image of moving toy race cars. This image was built from 1,000 lines taken after the upper car passed a photosensor. Though the cars are actually the same length, as seen in the color photo of *Figure 2*, note that the faster car appears shorter in *Figure 1* as the line scan camera was operating at a steady rate (4,400 lines per second). This image demonstrates the ability of InGaAs cameras to see through silicon, as the company ID is visible though a piece of polished silicon wafer which is partially mounted over the logo plate on the left-hand car. The logo is also clearly seen through the blue paint covering the ID for the car on the right (compare the images between *Figure 1* and *Figure 2a*).

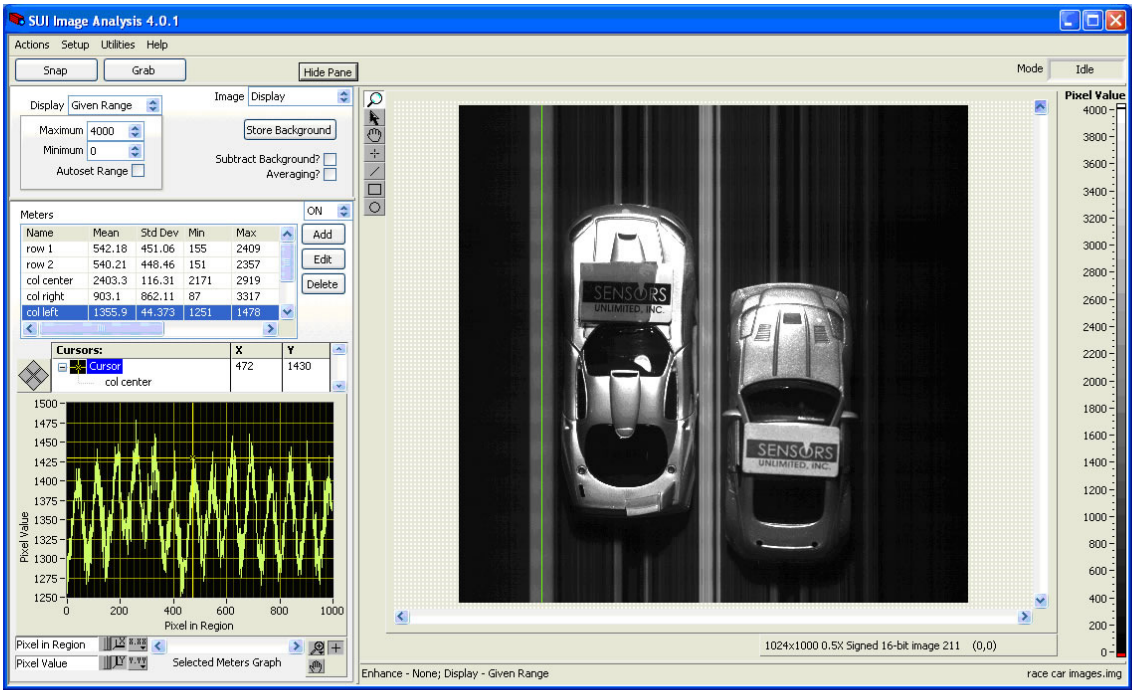


Figure 1: Incandescent lamp ripple — the vertical green cursor visible on the above image to the left of the cars and the associated line profile graph on the left shows the ripple riding on top of the incandescent lamp illuminating the scene.

Now, examine the light area to the left of the car images in both *Figures 1* and *2a*. *Figure 1* shows that there is a green cursor line running vertically through this area. The software generates a line profile of intensity variation along this line, which is shown in the graph to the lower left of the main image in *Figure 1*. The resulting graph shows the light intensity variation versus time, and we see the power line ripple on top of the average light level.

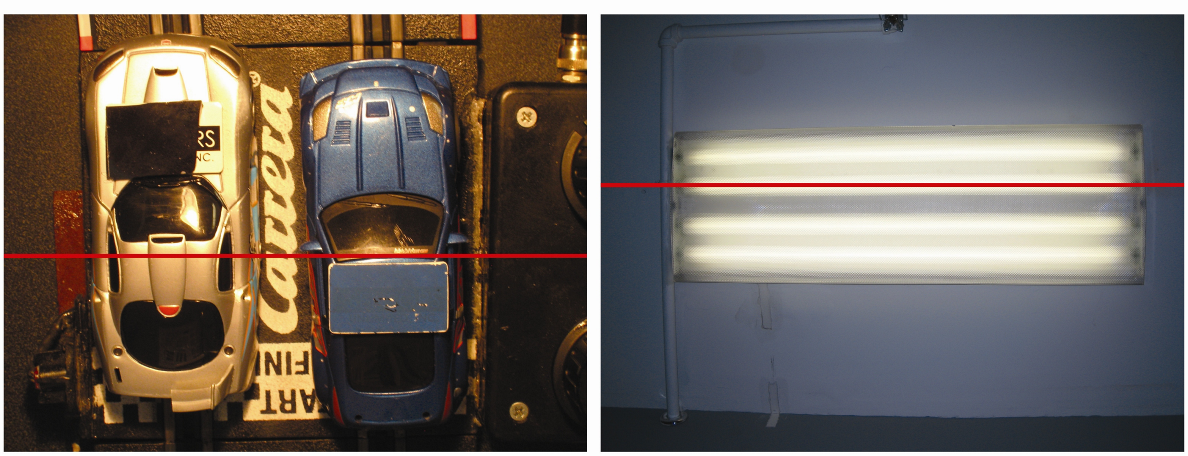


Figure 2a (left): Color photo of race cars with a red line showing where the line scan camera was focused.
Figure 2b (right): Photo of new T-8 bulbs in light fixture with image line in red.

Fluorescent Tube Output

The next image (*Figure 3*) shows the much larger output variation versus time of a standard fluorescent lamp (shown in *Figure 2b*). The image was created by aligning the line array along the length of the tube and recording the light output. The number of lines in the image was chosen to match the time period of an even number of power cycles in order to “freeze” the ripple; otherwise, the ripple pattern would drift up or down the image with successive images. In this instance, the SU1024LDH2 camera was running at 46,816 lines per second (lps) and the drift in the image nearly stopped with an image height of 780 lines. The ratio of the line rate to the image height yields a frame rate of 60.02 Hz, with a reciprocal value of 16.661 ms. Since the image shows two bright-dark cycles, we can deduce that the ripple is occurring at the nominal rate of 120 Hz. This higher frequency can be explained by considering that the arc exciting the fluorescent tube would occur on both the positive and negative peaks of the power cycle, as is the peak power output from incandescent lamps. The subsequent image in *Figure 4* was recorded at 91,912 lines per second, and 1,532 lines are also used to capture two cycles. However, with the shorter exposure time of 7 µs instead of 17.4 µs, the signal is smaller, reducing the signal-to-noise ratio.

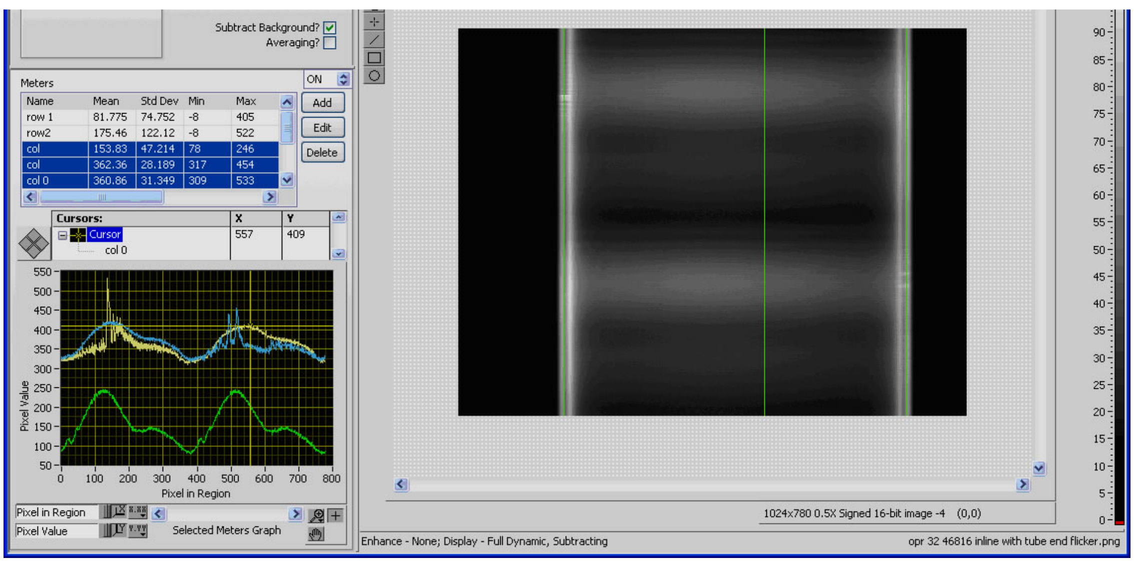


Figure 3: Capturing the lamp output variation over the power line cycle.

Figures 3 and *4* show three vertical cursor lines, one in the center and two aligned with the ends of the tube. Each cursor generates its own intensity-versus-time profile displayed in the graph on the left of the screen shot. The yellow trace is from the vertical green cursor on the left side of the image, the green trace is from the central line, and the blue trace is from the cursor on the right end of the tube.

Examining the images of the tube output at each of its ends clearly shows an anomaly, one that jumps from one end of the tube to the other end on alternate cycles. This indicates that the arcing only occurs during one of the polarities of the base power line sine wave. As the anomaly was noticed on both tubes of the two-tube ballast and not on a nearby light fixture, it is presumed that the arcing is associated with the ballast rather than an individual tube contact. The ballast insulation may be breaking down, but just on the positive or just on the negative peak of the power cycle. This lamp was powered from a rapid-start type of ballast, also known as an iron or magnetic ballast.

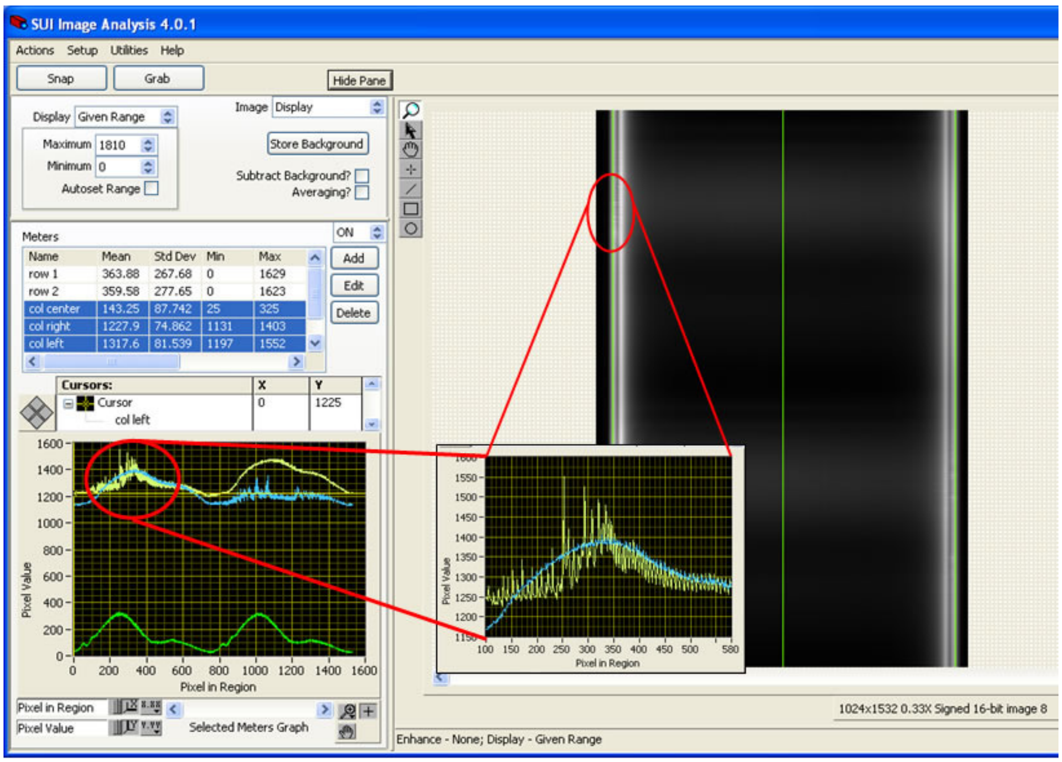


Figure 4: Examination of ballast arcing at 92 kHz.

Using the full time resolution of the camera, *Figure 4* shows the instability of the arcing at one end of the tube versus the relative calm at the other end. The inset shows the line profile graph expanded around the yellow trace's arcing. This corresponds to the bright horizontal line segments on top of the left column, which are seen inside the red circle on the main image. The green trace in the line profile graph is the intensity profile of the center green cursor on the image. It shows the glow from the phosphors in that part of the tube coming to their peak output slightly ahead of the peak output from the tube ends. Also, take note of the consistent wrinkle in the upslope of the main peak; this will be used as a reference point in the next measurement.

Determining The Camera Speed

The image in *Figure 4* shows that two cycles of the lamp output variation are completely captured in an image of 1,532 lines at the SU1024LDH2's fastest nominal rate of 91,911.8 lps, almost exactly 1/60th of a second. Because of fractional differences between the camera line rate and the line frequency, an image captured with an integer number of lines won't quite match the power line frequency, and so the light output ripple image will shift a bit from frame to frame in the time direction.

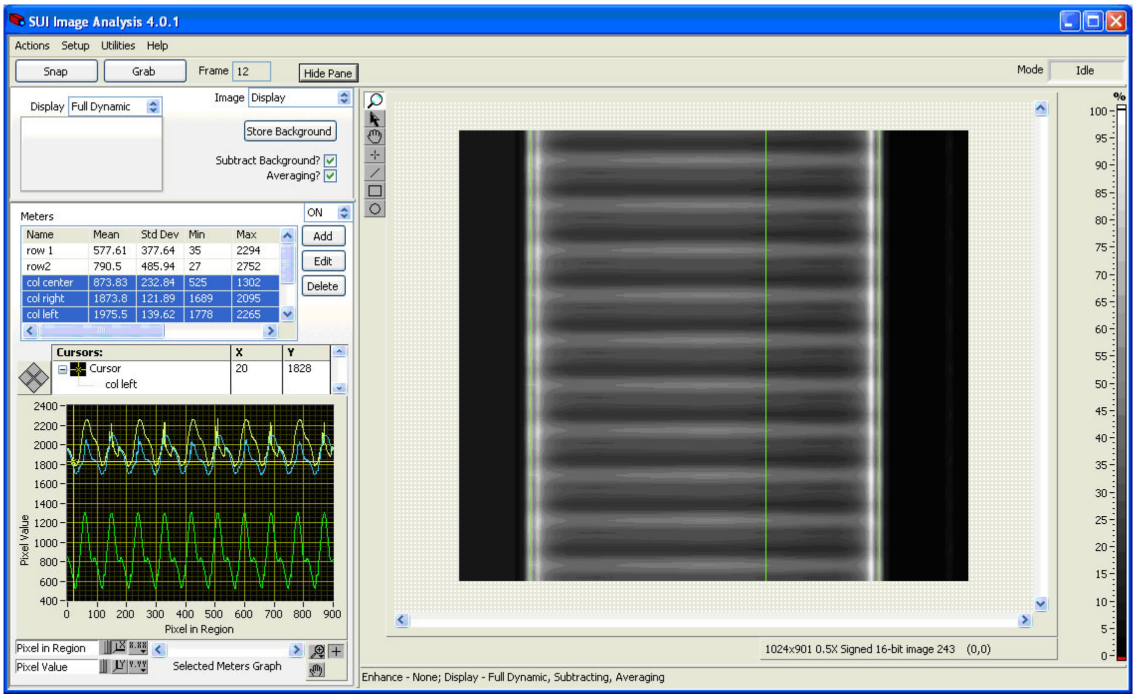


Figure 5: Measuring the power line frequency and camera line rate in a single frame.

To determine the actual power line rate, the camera frequency was first slowed to capture more cycles per frame while keeping the number of lines per image reasonable. With the camera line rate of 10,813 lps, times 1/120th of a second (0.008333) times 10 cycles, the image height would be 901.03 lines for 10 cycles.

As this is not an integer multiple, there is still a slight frequency mismatch and the image actually drifts vertically a little. By measuring the drift, one can improve the precision of the measurement further. This is done by taking a movie of successive frames and tracking the drift over time.

In the Utilities menu of SUI Image Analysis, the Video Recorder utility opens the screens shown in *Figure 6a, b, c*, and *d*. *Figure 6a* shows the 1802 line frame at the end of the acquisition of 100 frames. In *Figure 6b*, the frame index has been moved to zero and the cursor was used to note the line number associated with a feature of the lamp emission. Take note that just below the dark valley between peaks, there are a couple of brighter lines on either side of a few darker lines. This variation is very consistent from cycle to cycle, and it was the sharpest feature, aside from the unstable arcing. The arc impulses shift in time relative to the power cycle and can't be used as a timing mark. The mouse cursor was placed over the dark valley feature and its line number, 92, noted. In the right-hand images, this particular feature has shifted down to line 224. This shift indicates the mismatch between the rectified power line frequency of 120 Hz, the camera's line rate, and the number of lines per frame. Since 100 frames were recorded with 1,802 lines per frame, the total number of lines acquired by the video is 180,200 lines, but we see that the feature drifted another 132 lines down the image. It can also be said that the camera acquired another 132 lines over the expected number that would have been acquired if the frame rate was matched to lamp variation frequency. Thus, the actual power line frequency can be calculated by dividing the number of cycles acquired by the number of lines it took to record those cycles, then multiplying by the camera line rate.

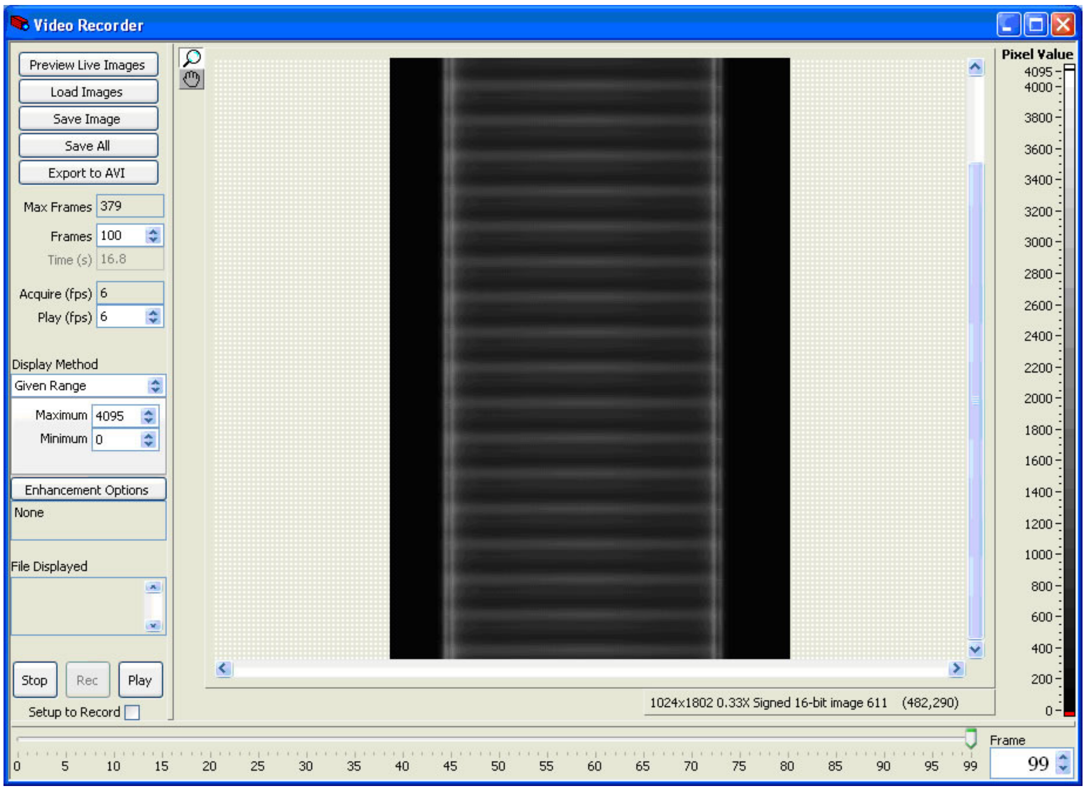


Figure 6a: Video recorder screen showing last frame of 100 frame video, capturing 20 cycles of the 120 Hz light pulses from office fluorescent lamps.

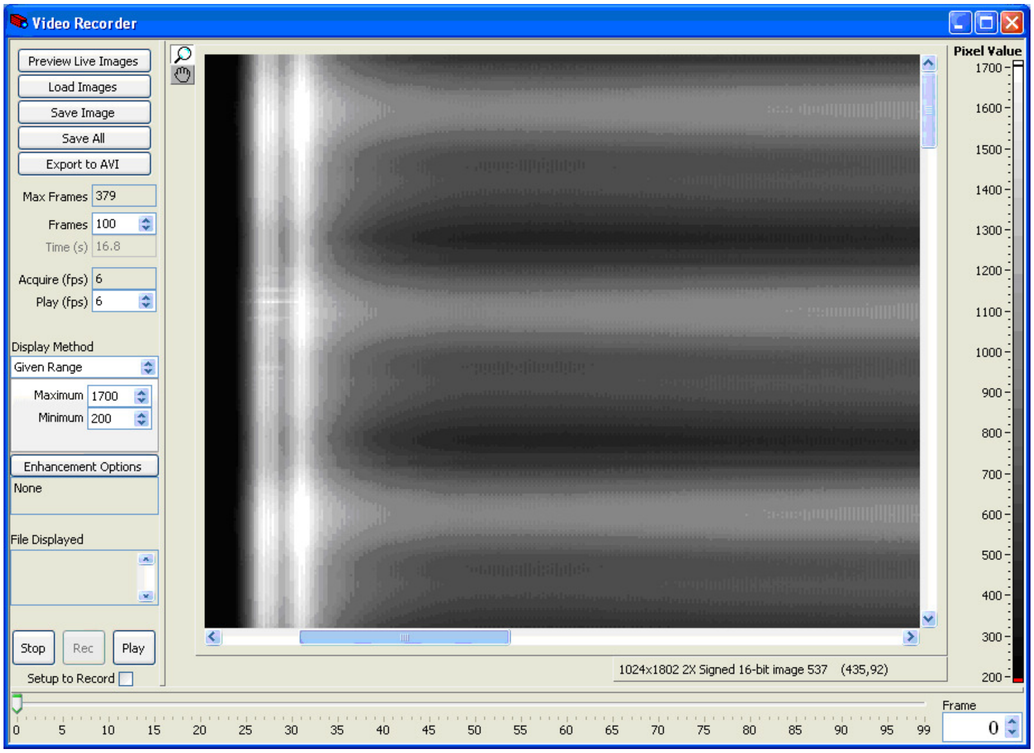


Figure 6b: Expansion of top left corner of frame, showing position of light output pattern versus time in frame 0, with the reference line at line 92.

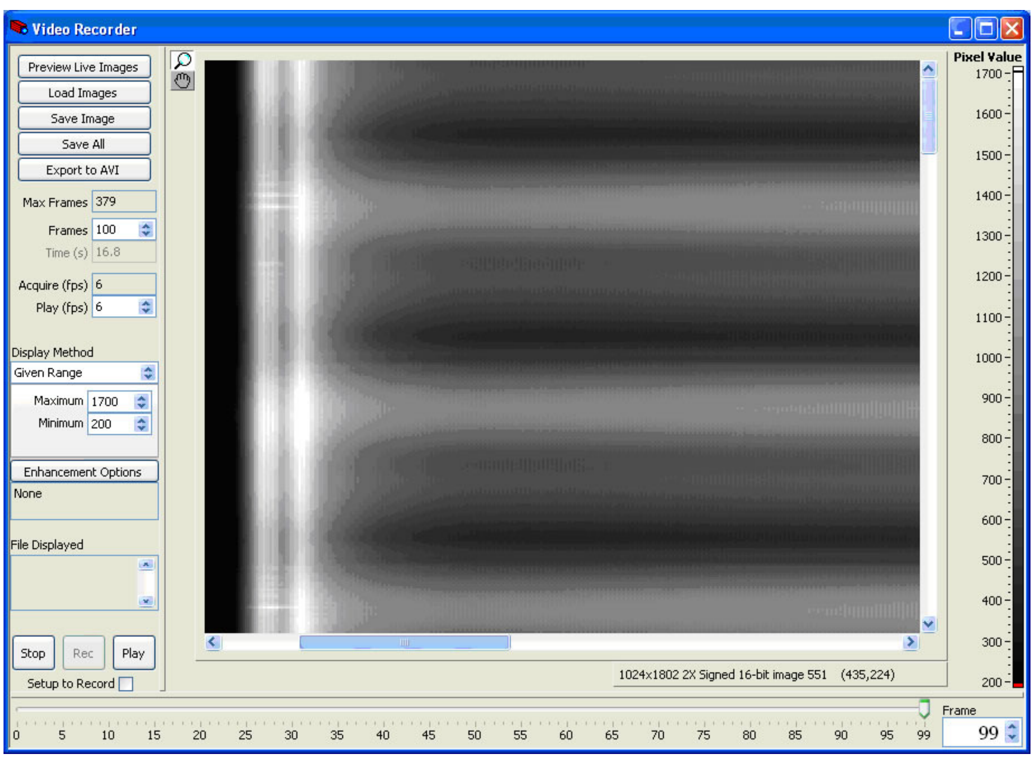


Figure 6c: Same expansion at frame 99, showing shift of light output pattern down to line 224 of frame.

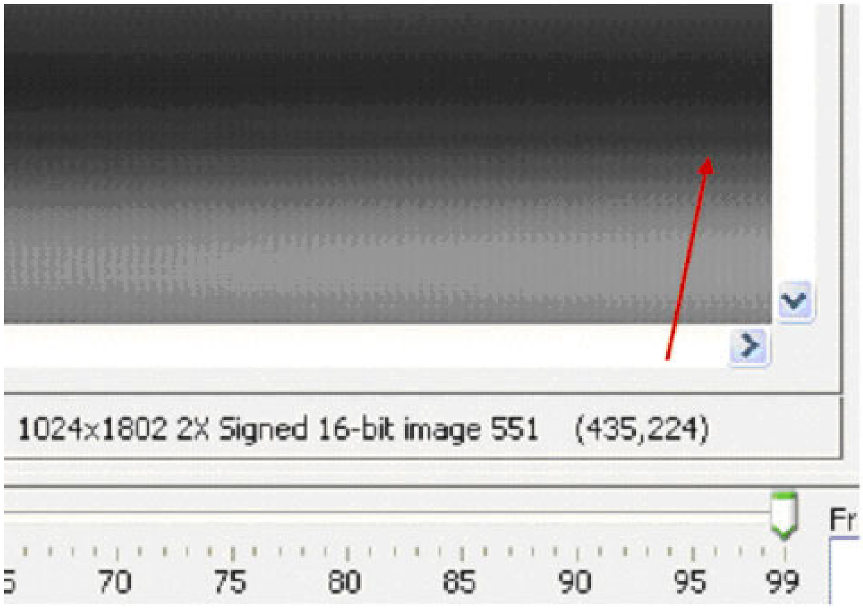


Figure 6d: Cursor intensity is 552 counts and its position is at (X,Y) position (435,224). The red arrow points to the dark feature used to gauge image position drift from frame 0 to frame 99.

Since the camera clock rate is crystal controlled to a tolerance of +/-25 ppm, the camera line rate for the test could range from 10,812.88 to 10,813.42 lps. Using a Fluke 179 Multimeter, the power line frequency was observed to actually vary from 59.96 to 60.02 Hz several times within the course of an hour. Similar experiments using the camera's fastest line rate, and capturing 200 light cycles with 153,200 lines showed the camera rate to be running at 91,911.14 lps.

Square Pixel Imaging

The previous images of the fluorescent lamps were acquired with the spectroscopy version of the SU1024LDH2 camera, with a pixel height of 500 µm (on a pitch of 25 µm). *Figure 7* shows images of the same light source that were acquired using a camera with 25-µm square pixels, which was also used for capturing the race car images. The signal-to-noise ratio drops with the smaller pixel due to the reduced sensitivity, but the structure of the light fixture diffuser facets are now resolved. This demonstrates that not every machine vision case is best filled with square pixel formats. When the line rate and exposure time can be chosen to match the time that the features of interest are captured in the aperture, the tall pixel greatly improves system sensitivity. Choosing the tall pixel might also be done to ignore features unimportant to the intended purpose of the imaging, such as when monitoring the edge alignment of a thin coating on another surface, for example in manufacturing packaging films or applying adhesive coatings.

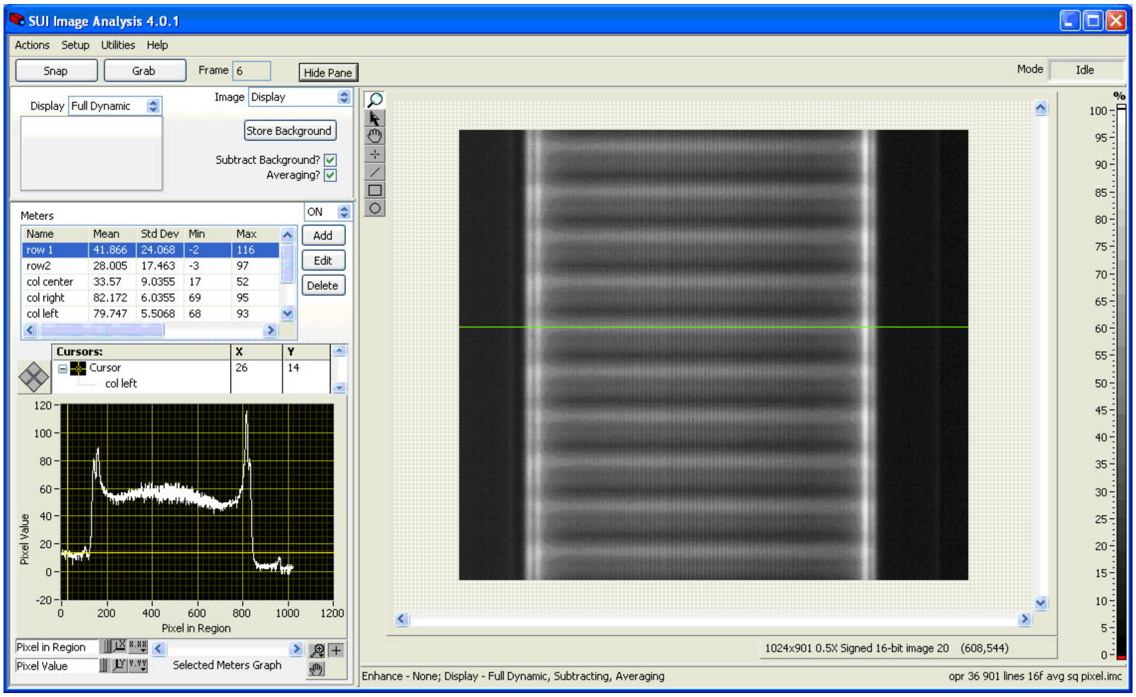


Figure 7: Imaging with a square pixel array.

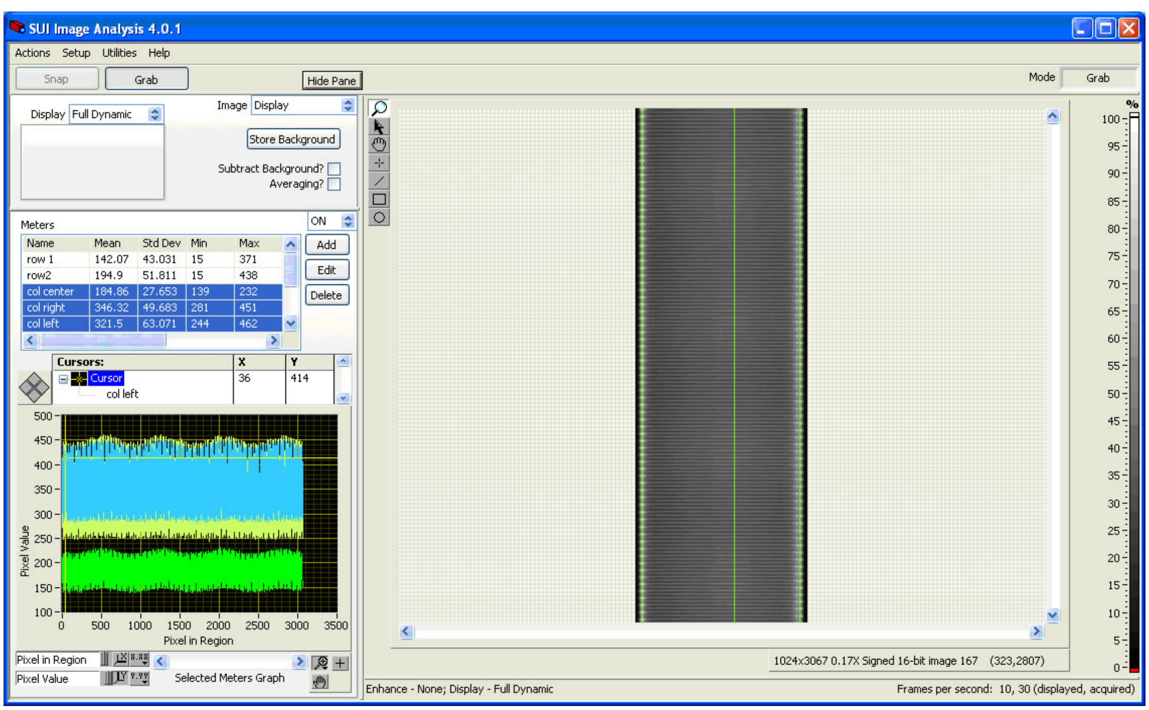


Figure 8: Light output from high efficiency fluorescent lighting.

High-Efficiency, High-Frequency Lighting

Since arcing was noticed in the lighting fixture, the ballast and tubes were replaced with the new high-efficiency T8-style tubes and electronic ballasts. These ballasts operate at much higher frequencies, providing light more continuously. This can be seen in *Figure 8*, where many more light impulses are recorded for the same line scan rate used earlier. The image height is 3,067 lines here, in order to make the remaining small 120 Hz ripple a bit more visible on top of the much higher underlying frequencies.

Figure 9 shows an expansion of the line profile traces, again with the yellow/blue traces giving the light output from the ends of the tube, and the green trace from the phosphor in the center. The phosphor exhibits an output variation period of about 20 lines at 91,911.14 lps, for a frequency just below 4,600 Hz. The expanded traces from the tube ends show the ballast's stimulation frequency is close to the Nyquist rate of the camera, just under 46 kHz, with the blue and yellow traces peaking 180 degrees out of phase with each other.

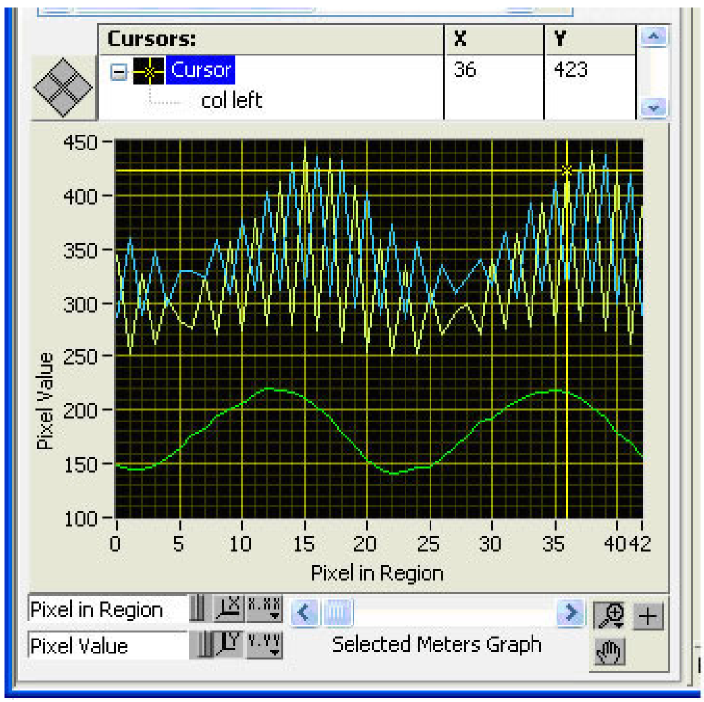


Figure 9: Expansion of first 42 lines captured from the high-efficiency lamps, showing very high frequency pulses from the tube ends and a 4,600 ripple frequency for the phosphor output.

Summary

In summary, Sensors Unlimited – Goodrich ISR Systems' new SU1024LDH2 high-line-rate line scan camera (see *Figure 10*) has been shown to provide accurate time recordings of rapidly changing optical phenomenon and, by extension, to provide line rates for imaging moving objects for machine vision applications, or capturing 3-D volumetric images with SD-OCT. The article also illustrates the versatility of the image analysis software that is included at no charge with the purchase of any area or line scan camera manufactured by Sensors Unlimited – Goodrich ISR Systems. For more information, please visit **www.sensorsinc.com**.

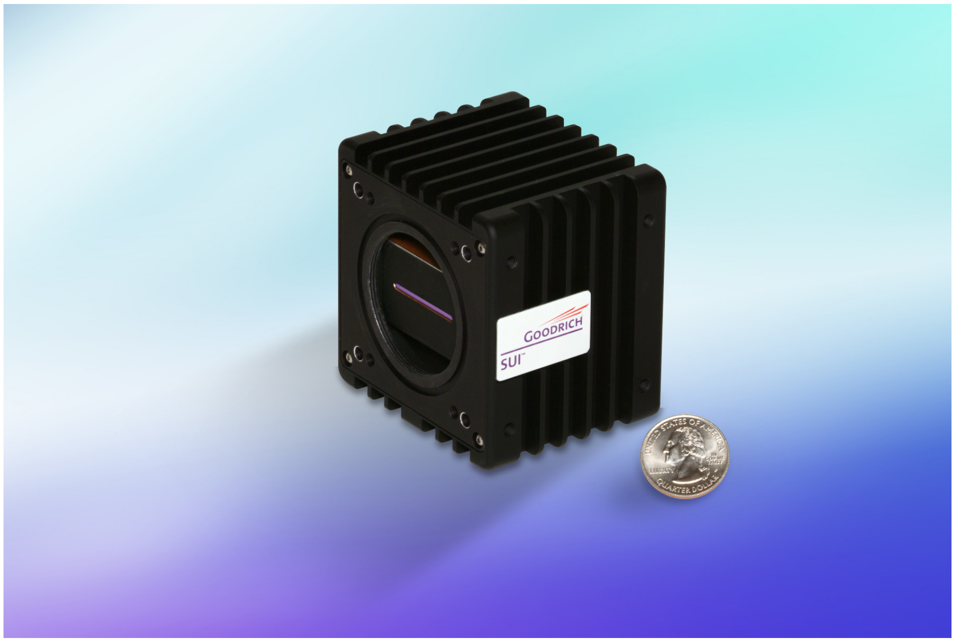
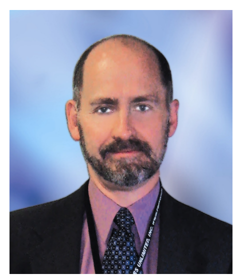


Figure 10: Sensors Unlimited – Goodrich ISR Systems' new 92 kHz InGaAs line scan camera, SU1024LDH2 (Model # SU1024-LDH2-1.7RT-0500 or -0025).

About The Author



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