Shimadzu Review

Development of "HyperVision HPV-X" High-speed Video Camera

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Abstract

We developed the HPV-X high-speed video camera, which incorporates the FTCMOS high-speed image sensor based on the technology of CMOS image sensor. It can capture images without decreasing the spatial resolution at high-speed capturing. It provides two capturing modes, one is speed-priority mode (HP mode) and the other is resolution-priority mode (FP mode), therefore it can capture images in various experimental situations. Our HPV-X, which has a maximum frame rate of 10,000,000 fps, enables visualization of instantaneous phenomena that have never been seen before and to uncover processes of various phenomena, therefore it can help in analysis of physical phenomena, development of new materials, development of space technologies, and development of micro processing. This paper describes the HPV-X and applications of high-speed photography.

Keyword:High-speed photography, High-speed video camera, CCD, CMOS image sensor

1. Introduction

High-speed video cameras are used to capture video images of phenomena not visible to the human eye and replay them in slow motion so that the phenomena can be visualized. Viewing images of high-speed phenomena recorded at a high temporal resolution allows the user to obtain very detailed information. Therefore, high-speed cameras are used as a general-purpose analytical tool in a wide array of applications. With increasing technological development in recent years, users need to record faster phenomena in more detail than before. Therefore, there has been a demand for ultra-fast recording capabilities that far exceed previous recording speeds. In 2005, Shimadzu released the HPV-1 high-speed video camera based on CCD technology, featuring a high-speed IS-CCD (image storage CCD) image sensor capable of capturing 1 million frames per second (fps). And now, in response to users that require an even faster video camera, we have co-developed a high-speed FTCMOS™ (frame transfer CMOS) image sensor (in joint research with a research group headed by Professor Shigetoshi Sugawa of the Graduate School of Engineering, Tohoku University) that is based on a CMOS image sensor. Through this research, we have developed the HPV-X high-speed video camera, capable of recording images at 10 million frames per second, which is ten times faster than previous models. The HPV-X allows the user to visualize a wide variety of ultra-high speed phenomena that were not previously visible. For example, it is expected to promote development of high-performance composite materials, elucidation of high-speed physical phenomena, development of aerospace technology, and development of technology that employs printed electronics to create resource saving circuits.
This paper describes the HyperVision™ HPV-X high-speed video camera.

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2. High-Speed Video Cameras

2.1 Conventional High-Speed Cameras

Commonly used high-speed video cameras are referred to as IC-memory type high-speed video cameras, which have high-speed image sensors (CCD or CMOS image sensors) that output parallel image signals via multiple output terminals. These camera systems also include a large-capacity external high-speed memory for recording the image signals. High-speed imaging is accomplished by reading the image data concurrently via the multiple high-speed image sensor output terminals and transferring this massive amount of data at high speeds to the large-capacity internal memory in the camera for recording. Since the recording time is determined by the amount of large-capacity memory available, the camera offers the advantage of being able to extend the recording time by increasing memory. However, the disadvantage is that due to physical limitations of the high-speed image sensors, the number of output terminals is limited to a maximum of 64 to 128. This limits the total amount of data that can be transferred, which means that the number of image pixels must be reduced to increase the recording speed. Consequently, high-resolution images with over a million pixels can be recorded at speeds of a few thousand fps, but at 1 million fps, the available image resolution is reduced significantly to a few hundred pixels. (See Fig. 1)
In contrast, cameras referred to as image converter or rotary prism type cameras are also available, which accomplish ultra-high speed imaging by rapidly switching between positions where images are formed and switching between image sensors arranged at those image positions. Both of these camera types are capable of ultra-high speed imaging in the 20 to 200 million fps range. However, the limited space available for image sensors restricts the number of frames that can be captured, resulting in only 8 to 24 images being obtained, which makes it difficult to capture video images. Image converter type cameras use a photomultiplier tube for photoelectric conversion. The disadvantage of the tube is that its phosphor screen is easily damaged from exposure to intense light. As for rotary prism type cameras, the mechanical precision of the prism rotary drive mechanism can make it difficult to align the light axes of the multiple image sensors. Therefore, due to inconsistency between the axes of captured images, rotary prism type cameras have the disadvantage of being poorly suited to image processing. (See Fig. 2)

3. HyperVision HPV-X High-Speed Video Camera

3.1 FTCMOS Sensor

High-speed video at 1 million fps can be too slow for capturing ultra-high speed phenomena, such as explosions, shock waves, high-speed projectiles, laser applications, sparks, and plasmas. Therefore, users asked us to develop a high-speed video camera that can exceed 1 million fps. In response, we considered using a high-speed image sensor that could exceed 1 million fps, but concluded that due to problems with heat generation from CCD type burst sensors, as described above, we could not achieve the desired speed by continuing to pursue CCD technology. For example, since the power consumption required to drive the CCD is proportional to the recording speed, a simplified calculation suggests that increasing the speed ten fold when driving the CCD at 10 million fps would consume about 10 W × 10 = 100 W. The heat generated from concentrating 100 W of power on a chip that is only a few square centimeters would deteriorate the image sensor performance or even damage the sensor.

Therefore, to develop a substitute for the CCD, we partnered with a research group headed by Professor Shigetoshi Sugawa of the Graduate School of Engineering, Tohoku University to jointly develop an FTCMOS burst type sensor based on CMOS image sensor technology.[4), 5)] CMOS image sensors consume less power than CCD sensors because only the portion of memory involved in the recording process and the associated circuitry are active during recording. Therefore, the FTCMOS sensor can be operated on about 23 W of power when recording at 10 million fps. Fig. 4 shows the overall structure of the FTCOMS burst type CMOS image sensor, with a portion shown enlarged. Memory areas are located above and below the pixel area in the center of the FTCMOS sensor. The structure is designed to keep these areas spatially separated. The photodiodes in the pixel area and the corresponding memory for recording images are connected by metal wires so that pixel signal outputs are recorded concurrently in memory at high speed. Furthermore, to ensure adequate signal charge even during ultra-high speed recording at 10 million fps, the sensor has been designed with larger photodiodes, which results in a high aperture ratio of 37%. There was concern that the larger photodiodes would cause excessive image lag during ultra-high speed imaging at 10 million fps, but optimizing the electric potential distribution profile within the photodiodes has reduced image lag to an acceptable level.

3.2 HPV-X High-Speed Video Camera

The HPV-X high-speed video camera we have developed is shown in Fig. 5 The instrument specifications are indicated in Table 1. The system consists of a camera head, power supply unit, and control computer.

The camera head includes the FTCOMS sensor described above and its drive circuit, control circuit, and power supply circuit. It controls communications with the control computer, controls the video capture timing to capture high-speed video using the FTCOMS sensor, and transmits the captured image data to the control computer. The camera head is connected to the control computer via a gigabit Ethernet cable. Control software running on the control computer is used to specify camera parameters for capturing video and to display captured video images.

(1) Imaging Modes

The HPV-X features two imaging modes. The HP (half pixel) mode prioritizes imaging speed, whereas the FP (full pixel) mode prioritizes resolution.

To ensure an adequate aperture ratio in the FTCMOS sensor, each transmission wire connecting the pixels to memory is designed to be shared by four pixels. Therefore, to achieve the maximum imaging speed (10 million fps), the signal output is reduced so that only two pixels share each transmission wire. This is referred to as the HP mode. The HP mode reads the signals from only half as many pixels (50,000 pixels), but the 100,000-pixel format is restored by reading the signals from the pixels in a zigzag pattern and then interpolating between them during post-processing. In addition, the HP mode allows 256 frames to be recorded by using only two pixels worth of memory for each pixel. The FP mode, on the other hand, captures the signals from all 100,000 pixels, but is able to record only 128 frames.

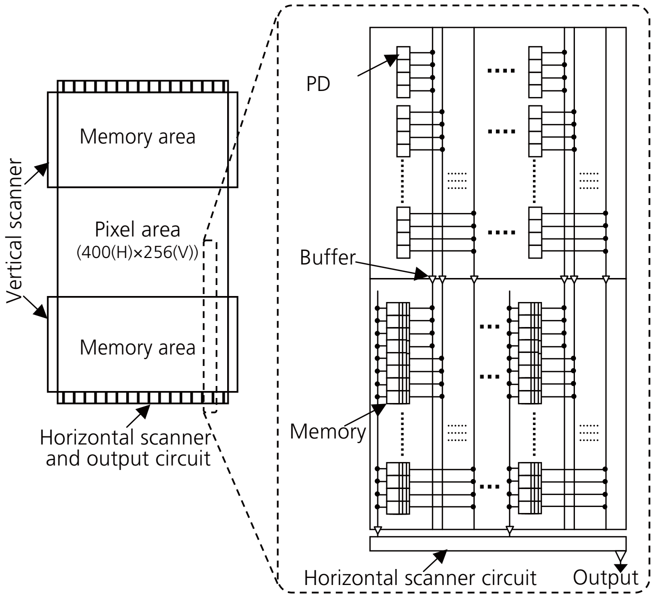


Fig. 4 Schematic diagram of FTCMOS sensor

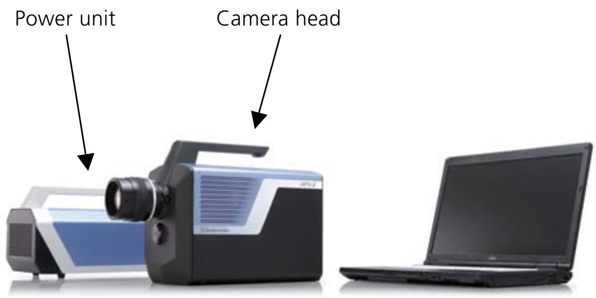


Fig. 5 HPV-X high-speed video camera

(2) Exposure Time

Due to properties of the CCD, the exposure time for the IS-CCD depends on the imaging speed. At low imaging speeds, it is not possible to set short exposure times. However, for the FTCMOS sensor, exposure time can be set independently of the imaging speed, which is a key feature of the CMOS image sensor. This means that exposure time can be set independently in 10 ns increments to any exposure time above a minimum 200 ns for any imaging speed between 60 fps and 2,000,000 fps. Consequently, images do not blur even at low imaging speeds.

(3) Lens Mount

The HPV-X features a Nikon F-mount configuration that supports a wide variety of commercially available lenses. Although in recent years there is an increasing number of lenses designed for electric aperture control that do not include an aperture ring, lenses with manual aperture adjustment are often preferred for scientific measurement applications. Therefore, for user convenience, the HPV-X features an aperture knob on the front to allow the user to manually adjust the aperture on lenses that do not include an aperture ring.

Table 1 Specifications of HPV-X high-speed video camera

Lens mount	Nikon Fmount	
Image sensor	FTCMOS image sensor	
Recording speed (Frame rate)	HP mode	10 Mfps, 5 Mfps (fixed)
	FP mode	5 Mfps (fixed)
	Both modes	Varia ble recording speed (in a 1/(10 ns) interval) in a range from 60 fps to 2 Mfps
Continuous recording capacity	HP mode	256 frames max.
	FP mode	128 frames max.
Resolution	HP mode	50,000 pixels (zigzag lattice pixel array)
	FP mode	100,000 pixels (400 (horizontal) × 250 (vertical))
Color/Gradations	Monochrome, 10 bits	
Exposure time	50 ns fixed (at 10 Mfps), 110 ns fixed (at 5 Mfps)	
	Variable in a 10 ns interva l starting from 200 ns in a range from 60 fps to 2 Mfps	
External trigger input	Two channels (TRIGIN, STANDBY) TTL level (5 V), capable of either positive or negative polarity	
Recording mode	Internal trigger, external trigger, continuous trigger	
Optional output	Two channels (The exposure start timing, trigger detection timing, etc. are output by setting.)	
Trigger point settings	Can be set to any frame from the second frame onwards	
Interface	1000 Base -T/100 Base-TX, 1 port	
External monitor output	NTSC/P AL output	
Data memory format	10-bit dedicated format, BMP, AVI, JPEG, TIFF (8-bit and 16-bit formats supported)	
Camera head	160 mm(W) x 330 mm(D) × 260 mm(H), approx.6.4 kg	
Power unit	150 mm(W) x 392 mm(D) × 185 mm(H), approx. 5.2 kg	

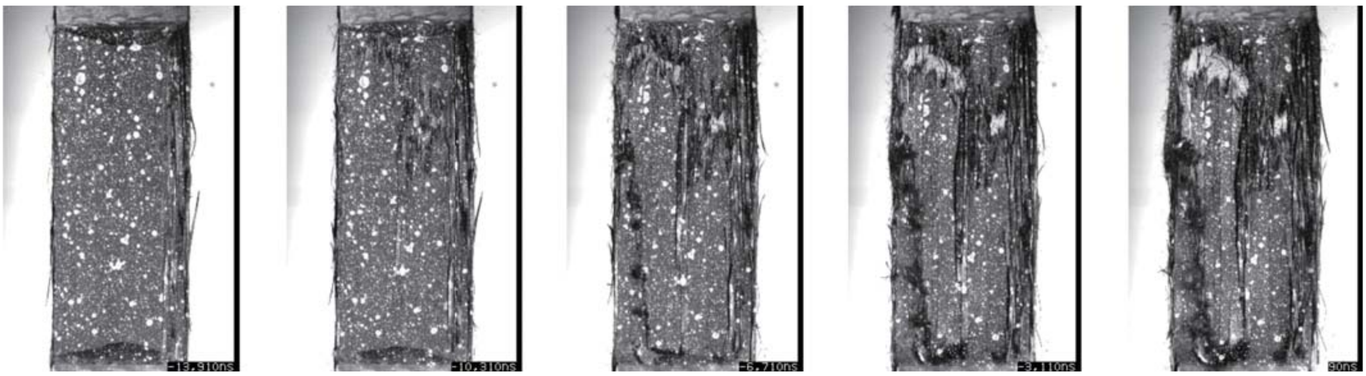
4. Example of Capturing High-Speed Video

4.1 Composite Material Testing

Due to their light weight, high strength, high rigidity, and other properties, carbon fiber reinforced plastics (CFRP) are widely used in aircraft, automobiles, high-speed rail cars, and other transportation equipment or as a reinforcing material in concrete. Due to their high strength and rigidity, CFRP materials exhibit fracture behavior at extremely high speeds, which is difficult to capture adequately using previous high-speed video cameras. Fig. 6 shows images from a high-speed tensile test (using a Shimadzu HITS-T10 high-speed tensile testing machine) of a zero-degree unidirectional CFRP (CFRP-UD) material, captured with the HPV-X at 5 million fps. The images show how initially a longitudinal crack develops on the right edge of the specimen, parallel to the fibers, before the entire specimen fails from fracturing. The specimen strain distribution can be visualized by analyzing the high-speed images from this kind of material testing using the DIC (digital image correlation) method. This method uses a series of digital images showing the process of specimen deformation to calculate the amount and direction of deformation on specimen surfaces simultaneously by performing pattern matching between the images of the printed random pattern on the surface. Fig. 7 shows an example of analyzing the strain distribution of the CFRP before it starts to fail by the DIC method. Higher strain levels are indicated by a darker red color, and it moves from the end of the specimen toward its center. The Fig. also shows that the strain level decreases after the specimen starts to fracture.

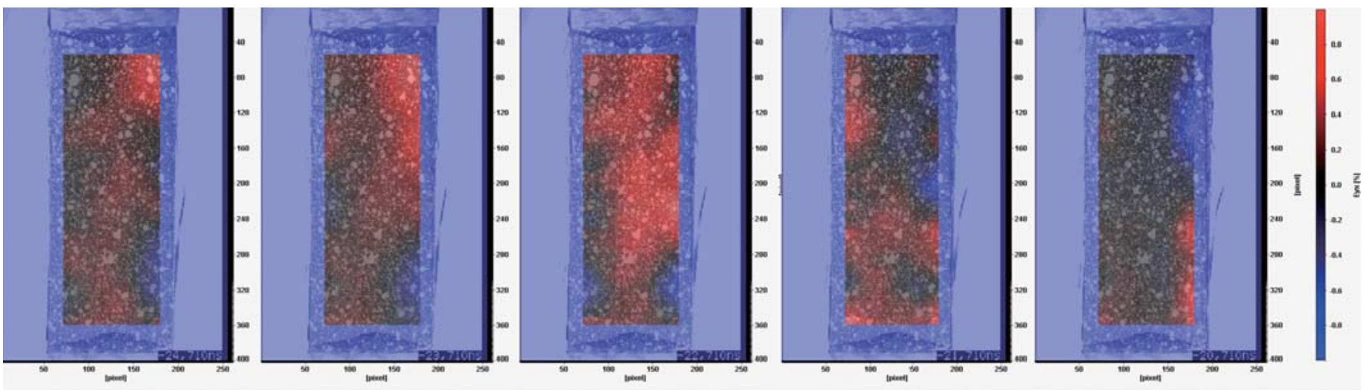
4.2 Impact of High-Speed Projectiles

Space debris refers to the large amounts of abandoned spacecraft, parts jettisoned during rocket separation, explosion fragments, and other space junk that orbits the Earth. In lower altitude orbits, this debris travels at high speeds of about 10 km per second, which could cause serious damage if it were to hit a satellite or space station. Therefore, research is being conducted to determine the phenomena that would occur in the event of an impact with space debris and to confirm and verify the defensive performance of satellites. Fig. 8 shows one example of space debris research, which captured images of a high-speed plastic bullet shot with a gas gun through a vacuum chamber as the projectile hit a metal plate. The speed of the high-speed projectile was about 3 km/s, which was captured at 10 million fps using the HPV-X. The Fig. shows that the plastic bullet changes into a plasma by the heat from its impact into the metal target, and the plasma disperses after that.



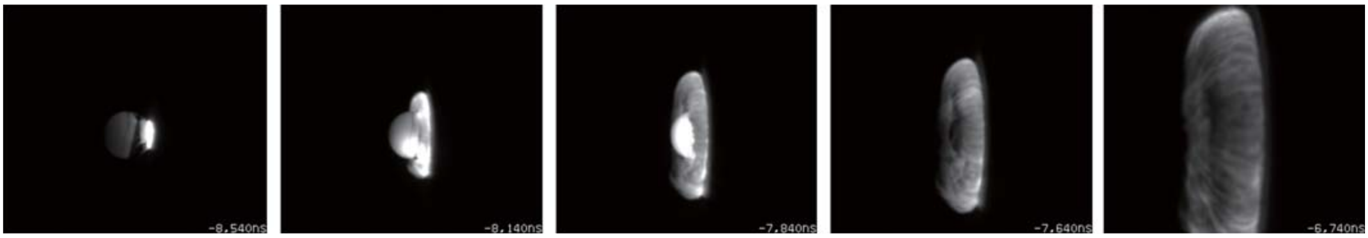
-13.91 µs　-10.31 µs　-6.71 µs　-3.11 µs　0.09 µs

Fig. 6 Destruction of CFRP by high-speed tensile testing machine
(Frame rate: 5 Mfps, Time stamps are relative time from trigger input)



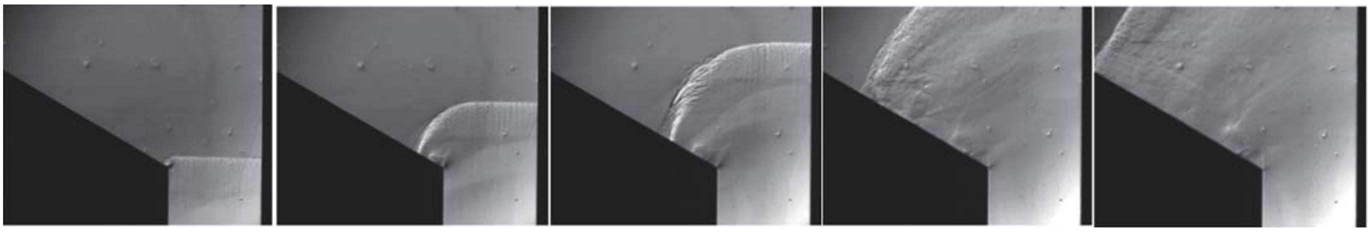
-24.71 µs　-23.71 µs　-22.71 µs　-21.71 µs　-20.71 µs

Fig. 7 Destruction map of strain in CFRP with DIC by high-speed tensile testing machine
(Frame rate: 5 Mfps, Time stamps are relative time from trigger input)



-8.54 μs | -8.14 μs | -7.84 μs | -7.64 μs | -6.74 μs

Fig. 8 Impact of high-speed projectile
(Frame rate: 10 Mfps, Time stamps are relative time from trigger input)



81.79 μs | 88.79 μs | 96.29 μs | 107.79 μs | 113.79 μs

Fig. 9 Diffraction of detonation wave
(Frame rate: 2 Mfps, Time stamps are relative time from trigger input)

4.3 Diffraction of Detonation Waves

A detonation wave refers to a combustion wave that travels through a flammable gas at supersonic speeds by interaction with shock waves. Detonation waves travel at extremely high speeds between Mach 5 and 10 and provide huge amounts of energy. Therefore, research is being conducted on its fundamental properties for use in engineering applications. Fig. 9 is an example of detonation wave images recorded at 2 million fps by HPV-X. It shows waves generated by detonation, together with impact waves, progressing through the tube as plane waves (first frame) and then diffracting at the bend (second frame). After diffraction, the detonation and impact waves diverged (third frame). Then the detonation caused reignition where the waves diverged (fourth frame). The detonation wave was traveling at about 2 km/s. (This imaging example was provided by Professor Jiro Kasahara at the University of Tsukuba.)

5. Conclusion

We have developed the HPV-X high-speed video camera, which features a high-speed FTCMOS sensor that employs CMOS image sensor technology. The HPV-X is capable of capturing ultra-high speed video images at a maximum speed of 10 million fps, ten times faster than previous models, while still achieving high resolution at high imaging speeds. This system enables the visualization and observation of even faster phenomena than ever before. Therefore, we anticipate it will be used widely as a useful analytical tool in many different industrial and advanced research fields.

We would particularly like to express deep gratitude to Professor Shigetoshi Sugawa of the Graduate School of Engineering, Tohoku University and Hideki Mutoh of Link Research Corporation for their participation in jointly researching the system. In addition, we are deeply grateful to Professor Jiro Kasahara at the University of Tsukuba for providing high-speed imaging data. A portion of the FTCMOS development was conducted as part of the theme Verification of the Practicality of Ultra-High Speed Optical Imaging Technology (December 2009 to March 2011) for the Japan Science and Technology Agency's (JST) Adaptable and Seamless Technology Transfer Program Through Target-Driven R&D (A-STEP). We are deeply grateful for this help from JST.

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