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High/Ultra-high speed imaging as a diagnostic tool

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Abstract. The ability to see what is happening during an experiment is often critical to human understanding. High and ultra-high speed cameras have for decades allowed scientists to see these extremely short time-scale events; starting with film cameras and now with digital versions of these cameras. The move to digital cameras has invited the use of computer analysis of the images for obtaining quantitative information well beyond the qualitative usefulness of merely being able to see the event. Digital image correlation (DIC) is one of these powerful and popular quantitative techniques, but by no means the only possible image analysis method. All of these analysis techniques ask more of the camera technology than simply providing images. They require high-quality images that are amenable to analysis and do not introduce error sources that compromise the data. Possible error sources include image noise, image distortions, synchronization and spatial sampling issues. As a minimal starting point, the introduced errors must be well understood in order to put error bounds on the results. This is because in many experiments some result is better than no result; with the caveat that the error sources and the relative confidence of the data are understood. The concepts will be framed in relation to ongoing ultra-high speed work being done at Sandia. A call and challenge will be given to begin thinking in more detail about how to successfully turn these cameras into diagnostic instruments.

Introduction

Digital image correlation (DIC) is a numerical technique that allows an experimentalist to calibrate a stereo-camera rig and make *quantitative* three-dimensional displacement and shape measurements. The DIC methodology has been well studied and used with standard digital cameras with great success over the last 15 years. The availability of high and ultra-high speed cameras along with the success of DIC has opened up an entire new range of experiments that have been heretofore impossible to do. The exciting part is that as camera technologies improve, the ability to apply DIC to new problems also improves. There is a caveat: High-speed experiments in general often degrade the performance of DIC, and the user needs to be aware of these compromises. This paper briefly surveys the most salient issues to the application of DIC at high-speeds and discusses solutions and warnings regarding its application. The discussion will include:

1. Camera technology related problems
2. Lighting issues
3. Equipment protection induced errors
4. Image synchronization errors
5. Image blur errors
6. Sensor noise induced errors

Understanding Camera Technology

High-speed imaging technology breaks neatly into two categories: High-speed and ultra-high speed imaging. Fig. 1 outlines the current state of the art in camera technology showing the frame rate and resolution (recording times) of the various cameras. The high-speed cameras are all manufactured using similar technology; a fairly large pixel CMOS detector where different sections of pixels can be addressed. The fundamental limitation to their speed is the rate at which the pixel data can be read off of the detector. This is the reason that in order to increase frame rate with these cameras, the resolution must be decreased. The oft quoted 1 Million frames-per-second (fps) is usually for only a few pixels of resolution, making it more of a large photo-diode than a camera. The ultra-high speed cameras come in three varieties; rotating mirror, beam-split optical paths, and memory on the chip. The first two methods use an optical system of either replicating the image or moving the image to acquire multiple images on different detectors (or portions of a detector) at extremely high rates. Both camera types, because of their complex optical paths, create problems for DIC. The traditional calibration methods for DIC (particularly 3D) correct for the more standard radial lens distortions, but not the distortions created by these systems. A larger problem, with the rotating mirror cameras are image registration problems and varying image distortions. The cameras that use beam splitters also use image intensifiers to add gain and control the framing and exposure of the detectors. These cameras are currently the state of the art and can reach speeds of 1 Billion fps. The problem from a metrology point of view is that the cameras were created for imaging *not* for making quantitative measurements. Inherent in the camera design is a large amount of non-radial distortions and a large amount of image noise. These issues do not make the cameras completely unusable for DIC, but they do severely limit the accuracy and increase the noise in the measurements. This in turn greatly decreases the strain resolution, which is derived from the primary measurement of displacement. These cameras also have a drawback in that they have a very limited number of frames; typically only 8, 16 or 32 frames. At high frame rates, this puts pressure on the experimentalist’s ability to predict when an event will occur and trigger the experiment appropriately. This is not trivial.

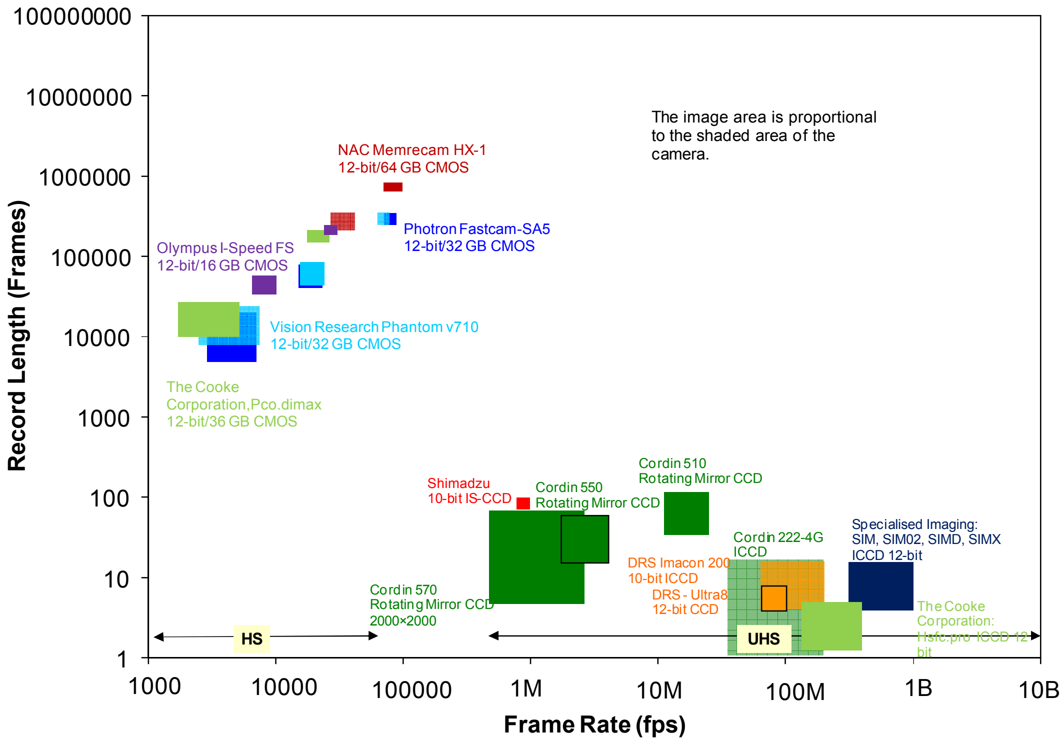

Figure 1. Survey of high and ultra-high speed cameras

The other ultra-high speed camera design uses memory built into the imaging detector. This removes the problems of image distortion introduced with the beam splitters, rotating mirrors, and intensifiers, but has two important drawbacks: it limits the resolution of the camera and it requires a lot of space between the pixels, creating a camera with extremely low fill factors. The low fill factor does not impact the sensitivity of the detector, which is generally quite high, but has a much more subtle effect on DIC through possible aliasing of the images.

Image quality is an inherent issue with *all* of the ultra-high speed cameras due to their design and the limits of physics. With high speed cameras, the image quality is not usually a problem if appropriate lighting can be brought to bear on the experiment. For UHS cameras however, even with perfect lighting, which is very difficult to supply, there will be image quality issues due solely to the camera design. An excellent review of these problems has been given by Tiwari [1].

A Series of Compromises

Lighting

The next most important contributor to a quality measurement after the camera selection is the lighting. Lighting is difficult because not only is the intensity important but the distribution of the light. Lighting intensity is an issue because the exposure must be short enough that motion blur is minimized. Having adequate light also allows the camera gain to be minimized, which in turn reduces the noise in the images. The dual requirements of stopping motion blur and having a small gain along with maintaining the flatness of the illumination make lighting particularly difficult. "Flatness" is a photographer's term which refers to light that seems to come from everywhere at once; think of the light on an overcast day. The light is diffuse. Why is flat light important? It avoids highlights on the image. Highlights are particularly difficult to avoid in situations where the object is curved or becomes curved during the experiment. With direct illumination from flash lamps, you will always have a portion of the camera that has highlights as illustrated in Fig. 2 (bottom right). Because obtaining the required light intensity with flat light can be difficult the compromise is often made that some data will be lost due to poor lighting. Another example of lighting problems is direct sunlight. The left side of Fig. 2 shows two HS experiments, the first with cloud cover which provides a flat illumination of the surface (at the expense of exposure time); the bottom shows a full sunlight illumination. It is difficult to remove the shadows, and data is compromised or lost completely in those regions.

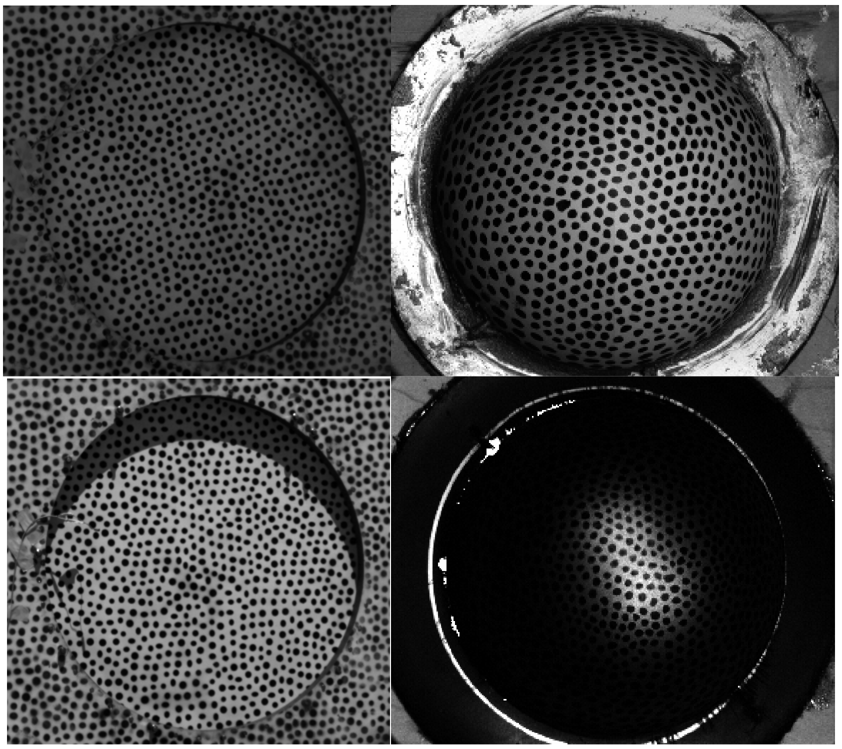

Fig. 2. Examples of good (top row) and poor quality (bottom row) images from HS (left side) and UHS (right side) imaging. Note the highlight and shadows which are unavoidable due to test constraints.

Camera Protection

The next contributor to DIC errors will most likely be camera protection. Often these cameras are being used for explosive or other violent processes where a layer of protection will be required for camera safety. These will add distortions to the images which will degrade the measurements. DIC software only corrects for the typical lens distortions which are radial in nature. Any other optic in the path, such as the camera protection shield, will not have radial distortions, and will not be corrected by the DIC calibration. An estimate of the errors in pixels can be obtained by translating a flat plate with a speckle pattern and looking at the distortions caused by the protective plates. These can often be very large, of the order of pixels! Care must be taken to adjust the assumed accuracy of the DIC solutions to account for these distortions as they will not show up in the DIC noise floor calculations. They only appear when the test object is translated. The DIC software does not know whether the sample has been strained, or the light path was distorted by the optics.

Fig. 3. Shimadzu cameras in the protective enclosure. Thick lexan sheets cause large distortions. Bottom image shows a fragment lodged in the lexan after the test.

Another option for camera protection is a mirror. A first surface mirror will have much lower distortions than a Lexan plate, and for shrapnel can be a good solution, because the cameras can be positioned behind a metal enclosure with only the mirror in the path of the explosive pressure and fragments. Problems can occur in that now both the camera and the mirror need to remain stationary for the calibration to remain valid. A standard camera calibration will work with these systems.

Camera Synchronization

A primary assumption of DIC is that the images are taken simultaneously; that is there is no relative motion of the test object between the left and right image. An unfortunate fact is that the reported camera time (in IRIG mode) *cannot* be relied on as a measure of the synchronization of the cameras (See Table 1). They may indicate that the time is the same, but that does not indicate that they are truly synchronized even when the reported significant digits on the camera clock seem to indicate that they are. The only method to ensure synchronization is to inspect the exposure framing pulse of both cameras with a high-speed oscilloscope and to check their alignment. With the Phantom cameras, by entering the appropriate frame delay as indicated by the oscilloscope, it has always been possible to synchronize the cameras to within the error of the internal camera clock rate. Once the smallest synchronization error has been found, it is good practice to calculate the relative motion of the object during the error period. The approximate effect of this motion error can be found by translating one of the stereo images by the relative shift. Calculations by the author have indicated that a horizontal shift causes the largest displacement error, and a shift towards (or away) from the camera creates the largest strain errors. Again, with fast moving objects, even a small synchronization error will lead to sub-pixel shifts of the object between the two stereo images.

Table 1. Phantom V12 timing results (Note that IRIG frame rates are limited to being both divisible by 4 and 10).

Frame Rate (Hz)	Sync Mode	Camera Exposure (µs)	IRIG Error (ns)	Strobe Error (ns)	Corrected Error (ns)
64,000	FSYNC	1	640	28	18
64,000	IRIG	1	10	330	18
66,037	FSYNC	0.3	1150	26	18
175,000	FSYNC	0.3	7400	50	18
175,000	IRIG	0.3	10	356	18
320,000	FSYNC	0.3	82,000	55	18
320,000	IRIG	0.3	10	276	18

For the ultra-high speed Shimadzu cameras the strobe pulses from the cameras were measured with an oscilloscope and were synchronized to within 7-ns using a 3-m network cable. A ~20-m cable was also used resulting in a 50-ns synchronization error. The synchronization was not only dependent on the cable length but also on the cable quality as demonstrated by a 50-ns delay which was measured using an extremely short “home-made” network cable.

Camera Motion

Most large scale tests result in camera motion; whether this is from the impact of a large object with the ground, or pressure waves from an explosion. For many tests, this occurs *after* the event of interest is over, but not for all tests. For those where data needs to be recovered there are now options to remove camera shake. This is best done by having a number of stationary points in the background which can be used to create a correct camera calibration for each image, or to translate the images or data back to the correct location as if the camera had not moved. Some techniques to remove camera motion are outlined in a paper by Miller [2]. Even with excellent restoration, there will be an effect on the final uncertainty of the measurement. Remember, the assumption is that DIC is calculating the match to within $1/100^{th}$ of a pixel. It does not take much camera motion to exceed your desired DIC accuracy.

Camera Fill Factor

Fill-factor refers to the “active” portion of the detector that captures the incoming photons. With the Shimadzu camera in particular, there are possible issues caused by the extremely low fill-factor of the detector. The current HPV-2 Shimadzu has a 14% horizontal and 73% vertical fill-factor. Traditionally digital cameras have much higher fill factors, on the order of > 90%. The effect in a “1D analog” is the same as a box-car sampling of an analog signal. The size of the sampling window is proportional to the fill-factor. The largest problem with the low fill-factor will be in cases where aliasing is a possibility. Spatial aliasing with a camera is similar to temporal aliasing, that is, you need to have enough samples (pixels) over the signal period to correctly measure the signal. The same Nyquist limitations that apply for temporal signals apply to spatial samples. In DIC spatial aliasing occurs when the speckles are too small (< 3 pixels) or there are sharp edges in the image (i.e. high frequency content). With these cases, the low fill-factor will increase the errors, which show up as greater noise in the measurements. For DIC applications the low fill-factor is not a problem if the speckle sizes are kept larger than 5 pixels to ensure they are not aliased. Furthermore, the use of subsets in the DIC helps compensate for the effect of the low fill by providing more information for the matching. To test these ideas a 2D experiment was setup where exact subpixel shifting was able to be done. Different fill-factors and speckle sizes were investigated with this experiment to determine the effects of the low fill factor on DIC. The methodology of the experiments is described in [3, 4]. The final results confirmed that if the speckles were not aliased, the 2D matching errors were not increased by the low fill factor.

Conclusions

The extension of DIC to high and ultra-high speed imaging typically involves some degradation in the measurement quality. Some of these compromises are caused by the inherent technology of the cameras themselves, including added noise and image distortions added by the extra optics in the system with intensified and rotating mirror cameras. Or low fill-factor for the Shimadzu cameras. Other errors are intrinsic (inherent) to the experimental setup itself, such as motion blur and lighting. With nanosecond exposures it can be difficult to setup lighting which meets the requirements of being bright enough to minimize camera gain and noise while not creating high-lights and difficulties for the DIC algorithms. Other errors are created by the needs of the experiment themselves including camera synchronization errors, camera protection and experiment induced camera motion. None of these errors in and of themselves invalidate the use of DIC (or other optical methods) for making measurements; however, care must be taken in understanding and quantifying the added uncertainty in the DIC measurement [5, 6]. It is not adequate to assume that the errors obtained with standard laboratory CCD camera setup will be obtained in these situations. Even taking into account the greater errors, there is still a large class of experiments where there are *no competing* measurement methods. The path forward in these situations is to adequately understand the compromises and quote the results with appropriate error bars. As a measurement community we should not be satisfied with the status quo. These camera technologies can be improved or better methods for compensating their short-comings need to be developed. For instance using lenslets on the Shimadzu to remove the low fill-factor or camera shake mitigation that has already been developed. It is always valuable as a community to share and discuss advances made in these areas.

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