Synchronization Errors in High-Speed Digital Image Correlation

Phillip L. Reu\(^1\) and Timothy J. Miller
Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185

ABSTRACT
The combination of digital image correlation (DIC) and new high and ultra-high speed digital imaging systems has yielded an extremely powerful tool for measuring the full-field results of explosively driven events. However, limitations in the hardware and the inherent difficulty of synchronizing camera clocks beyond a megahertz have raised questions about possible errors in the DIC results due to a lack of synchronization. This paper explores the synchronization of high-speed cameras experimentally and then uses synthetic images based on the range of experimental synchronization errors to calculate the expected 3D-DIC measurement errors.

Keywords: High-speed imaging, digital image correlation, uncertainty quantification

1. INTRODUCTION
Digital image correlation in conjunction with radically improving digital imaging systems has opened an entirely new field of quantitative and full-field deformation and strain measurement. A review of the method is ably covered in [1,2]. There are a number of factors that contribute to the uncertainty of digital image correlation, including, image quality, image distortions, and camera synchronization. The content of this paper is limited to camera synchronization. We will focus on two camera types: The high-speed Phantom V12 cameras made by Vision Research, Wayne, NJ and the ultra-high speed HPV-2 cameras made by Shimadzu Corporation, Kyoto Japan. The cameras were tested using both a visual method via an LED array system and by checking the integration strobe output pulses with an oscilloscope. After determining a reasonable synchronization error of less than 400 ns, simulations of the effects of synchronization errors were accomplished using numerically shifted images at realistic experimental velocities. The resulting displacement errors and strain errors caused by the lack of synchronization are presented in Section 3.

2. CAMERA SYNCHRONIZATION STUDY
2.1. High-speed camera synchronization
High-speed imaging for this paper consists of single-detector cameras that capture images in the range of 4,000 to 1 million frames-per-second. Currently there are a number of vendors selling cameras that fit this description. The vendors of this equipment, unfortunately, do not make their synchronization error specifications readily available for the camera user. This is understandable when one considers that the synchronization is dependent not only on the camera clock and circuitry but also on the user supplied connectivity between the cameras. A good start to predicting the camera synchronization potential is by checking the clock resolution of the camera. The Phantom v12 has a 56 MHz clock that yields a timing granularity of 17.875 ns. This sets a hard lower limit on the possible synchronization accuracy of the cameras. In fact, when the two Phantom clock signals are inspected on an oscilloscope and triggered on one camera signal, a jitter approximately the size of the clock accuracy can be observed. The Shimadzu camera has a 16-MHz clock but synchronizes the cameras differently such that the difference between the strobe on the two cameras is dependent on the synchronization cable length, rather than the internal camera clock.

2.2. Experimental setup and equipment for testing of high-speed cameras
Sandia National Laboratories photometrics group or Mechanical Environments department currently uses cameras manufactured by Vision Research Corporation. Two of these cameras, the Phantom v 7.3 and v 12, are the most useful for DIC field work due to their combination of speed and monochrome resolution. The v12 cameras were tested for synchronization using a commercially available LabDIC device, made specifically for testing camera synchronization with 100 LED emitters on a board sequenced/programmed for timing certification

\(^1\) plreu@sandia.gov
The fastest LED array rate for the LabDITC is a 1-μs on and 1-μs between LEDs. The array field, as imaged by the v12 cameras is shown in Figure 2. Unfortunately, at the fastest acquisition rates, the LED rate was not adequate to absolutely determine synchronization. The LED array check only indicates synchronization within ±½ μs. To further determine how well the cameras were synchronized, a Tektronix 2-GHz digital oscilloscope was used. Each camera has a strobe output that is synchronized with the integration time of the camera. One camera was selected as a Master (clock) and was tethered to a slave camera with care taken to ensure that equivalent cable lengths were used to attach the strobe signal to the scope to prevent any cable delays. The scope was then triggered on the Master camera to measure the time difference between the two cameras. This allowed measurement of the synchronization down to the nanosecond.

Figure 1. LabDITC timing system with synchronized cameras setup for testing.

Figure 2. LabDITC LED array imaged by a master/slave DIC camera pair.

The two methods of synchronizing Phantom cameras are frame synchronization (FSYNC) mode and Inter-Range Instrumentation Group (IRIG) synchronization mode. IRIG provides standards for timing signals that can be read by many cameras and provides a means of synchronizing multiple cameras as well as other data acquisition devices. The IRIG-B3 timing signal is one of the more commonly supported timing formats. It is a one-kilohertz signal amplitude-modulated with the day of the year and time of the day down to the nearest millisecond. Specialized electronic circuits in the camera are capable of processing an IRIG-B signal to achieve microsecond time resolution. A Symmetricom GPS time-base receiver was used to supply the IRIG-B signal to the two cameras. All cable lengths were kept below 3m.
For the Phantom V12 cameras, FSYNC mode runs the cameras in a master/slave configuration, with the master camera supplying a timing pulse at the frame rate. This method was used for this study. Another possible arrangement of the FSYNC is to use a function generator to create a pulse train to be used by both cameras in the slave mode. This method facilitates the interlacing or other non-synchronized timing arrangement of multiple cameras. One drawback to the implementation of FSYNC mode is the variable delay between the time the camera receives the frame pulse and the time of the actual image acquisition. This delay is typically in the range of 4-μs for the Phantom cameras. The phrase “in the range” is used purposely here because the actual delay is not specified and may not be constant from camera to camera. The delay should be experimentally determined when the cameras are setup in the field. The Phantom camera control software has a feature that can compensate for the time delay by setting the “Frame Delay” to the appropriate value. Delay values obtained in our testing have been stable over the course of months of testing. Another drawback to the FSYNC mode is that the cable length must be limited to less than 10-m, which can be problematic for much of the large-scale field testing done at Sandia. This limitation often dictates the use of IRIG-B, which does not have this limitation.

2.3. Experimental testing of ultra-high-speed cameras
While there are a number of ultra-high-speed cameras that can be utilized for DIC, the simplest and least error prone is the Shimadzu-ICCD. This camera utilizes a single detector with integrated memory with a frame rate of 1 Mfps at a resolution of 320×260 pixels. The first model HPV-1 cameras were not able to be synchronized via typical methods [1], but have been successfully used for 3D-DIC. The newest model HPV-2 includes a method of synchronizing the camera clocks via a standard network cable and is the camera model used in this paper.

2.4. Synchronization test results
The synchronization testing of the Phantom v12s yielded some surprising results. After recording the images with the cameras, the images were checked to make sure that they were synchronized to within ±½ μs using the LabDITC LED array. All results reported here met that standard, whether in FSYNC or IRIG mode. The strobe pulse was also measured for both cameras which indicated that the FSYNC mode achieved better synchronization than the IRIG mode as shown in Table 1. While the IRIG times reported by the cameras seemed to indicate that the IRIG synchronization was within 10-ns, actual times measured using the strobe were often hundreds of nanoseconds off. This is understandable when one considers the difficulty in extending the accuracy of a one-kilohertz timing signal to sub-microsecond times.

It is therefore important to note that the IRIG time reported by the camera is only an estimate of the true synchronization and an oscilloscope should be used to check the actual synchronization. Fortunately, if one measures the delay between the two cameras with a scope, this delay can then be set on the cameras via the Phantom control software to compensate – and this can be done with sub-microsecond accuracy on the V12 cameras. Once the compensation is entered, the cameras can be synchronized to within the time base resolution of 18-ns. The results for a variety of different camera settings are shown in Table 1.

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

For the ultra-high speed Shimadzu cameras, the LabDITC LEDs were synchronized in the corresponding master/slave images. 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.

### 3. NUMERICAL SIMULATION DIC ERRORS CAUSED BY SYNCHRONIZATION

#### 3.1. Synchronization error simulation methods
Depending on the type of event being measured, the rate of motion of the object can vary dramatically. In addition to the rate of motion, the direction of motion is also a critical parameter in the resulting error produced by lack of synchronization. The fundamental error is caused by one camera taking a picture slightly after the other, capturing the object after it translated a small amount. Remembering that DIC results are functioning at a sub-pixel resolution (1/100th), it is easy to imagine that an object can indeed have moved between the left and right images being taken. To illustrate how the synchronization errors measured above might affect a real test series, an explosively driven plate is used as an example case in this section. The original data was taken with a V12 camera with the resolution set to 400×416 pixels and a frame rate of 36,000 frames/second. The field-of-view was 48 inches, giving a pixel size of 3.0 mm/pixel. A typical velocity measured for this experiment was 396 m/s. With a worst case synchronization of 350 ns, a 0.03 pixel shift can be calculated between the master and slave camera images. Image blur in this analysis is being ignored. Therefore, the results presented here are for shifts of between 0 and 0.1 pixels as a worst case scenario.

Three cases were considered: an \( x \)-translation shift, a \( y \)-translation shift and a \( z \)-translation shift. The \( x \)- and \( y \)-translations were calculated by taking the right image of a stereo pair and performing a Fourier phase shift on the image corresponding to the desired amount of subpixel shift. The left image was left unshifted. The images were then imported into Vic3D and a solution was obtained using the calibration parameters for the stereo-system. The \( z \)-translation was done by taking a polynomial expansion on the right image about the center pixel, while again leaving the left image unchanged. Strain was not directly simulated, however, it should be noted that the \( z \)-translation is a uniform strain in a 2D sense.

#### 3.2. Results of synchronization errors
A number of practical conclusions can be drawn by looking at the results of the simulation. Figure 3 shows the false displacement magnitude calculated for the three sub-pixel shift directions. The magnitude in this case is calculated in the traditional way as the square-root of the sum of the squares of the three displacements, \( u \), \( v \) and \( w \). Because the cameras are calibrated, the results are presented in millimeters. It should be noted that these false displacement values will change depending on the calibration parameters of a given DIC setup. As can be seen the largest errors result from the \( x \)-direction shift. Making this error even more dangerous is the fact that the shift is also along the epipolar line of the two cameras, resulting in no error warnings during the correlation process. The other two shifts will cause a warning error due to the violation of the epipolar constraint during solution. The false displacement magnitude is uniform in effect over the entire correlation area for the \( x \)- and \( y \)-translations and was primarily represented as out-of-plane displacements. For the \( z \)-translation, the result is bowl shaped as shown in Figure 4.
The strains were also calculated at each of the sub-pixel shift errors from 0 to 0.1 pixels. The largest errors were for the 0.1 pixel shift. Note: Only translations and not strains were applied to the right image. The $x$-shift yielded strains that were less than 120-μm/m and the $y$-shift yielded strains that were less than 10-μm/m for all three strain components, $e_{xx}$, $e_{yy}$ and $e_{xy}$. The strain errors for these two cases are therefore of no real concern due to the fact that the strain noise is typically on the order of ±100 μm/m. For the $z$-shift error, the results are shown in Figure 5, and are of a larger magnitude. This is understandable as the shift in this direction looks like a uniform biaxial strain about the center point.
4. CONCLUSIONS

4.1. Practical notes on setting up cameras in the field
While the results above give a general idea of the problems that may be caused by a synchronization error, they are test specific due to the relationship of the calculated results with the given camera calibration. However, looking at the synchronization results of the cameras, a few conclusions can be drawn on how best to setup cameras in the field for DIC testing. These conclusions should be valid regardless of the type of high speed cameras used. The first point to be made is that FSYNC mode is generally superior to IRIG for shorter cable lengths. FSYNC also allows the user a wider range of frame rates and is not limited by the typical IRIG rule of having the rate be divisible by both 100 and 4 for the Phantom v7 and divisible by 100 for the Phantom v12. This often gains a few thousand frames per second in acquisition rate. However, regardless of which method is used, it is preferable to check the synchronization of the cameras with a scope and to set the delay on the cameras using the camera control software to get the minimum synchronization error. When this is done, sub-pixel shift errors below the resolution of the correlation algorithms will result for almost all high speed DIC testing. Another important item to note is that the IRIG time stamp reported is not necessarily the correct time. This is due to the inherent limitations of the IRIG signal. Reporting the IRIG time as the standard for accuracy of the synchronization is not valid; a mistake this researcher has made in the past. In the final conclusion however, when employing these extremely powerful imaging tools for full-field metrology and by using some care in setting up the cameras, synchronization should not be an issue for either the Shimadzu or Phantom v12 cameras.

ACKNOWLEDGEMENTS
I would like to thank Hubert Schreier for providing the z-shifted images – as well as many enlightening conversations concerning the details of DIC. The concept for this short study was prompted by an insightful question posed by Jean-Jose Orteu at Photomechanics 2008. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

REFERENCES

\[4\] This is claimed by the vendor but not yet confirmed by this researcher.