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Extending Digital Image Correlation to Moving Field of View Application: Error Assessment Using Outdoor Centrifuge

Timothy J. Miller [1a], Edward F. Romero[a], Hubert W. Schreier[b], and Michael T. Valley[a]
[a] Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185
[b] Correlated Solutions, Inc., 120 Kaminer Way Parkway Suite A, Columbia, SC 29210

ABSTRACT

Conventional tracking systems measure time-space-position data and collect imagery to quantify the flight dynamics of tracked targets. However, they do not provide 6-degree-of-freedom measurements combined with spin rate, wobble, angle-of-attack, and other flight related parameters associated with non-rigid body motions. Using high-speed digital video cameras and image processing techniques, it may be possible to measure test-unit attitude and surface deformations during key portions of the test-unit's trajectory.

This paper briefly presents the dual laser tracker digital image correlation (DLTDIC) technique and the experimental setup on Sandia National Laboratories' large outdoor centrifuge. Results from experiments conducted at ranges of 222.5 and 518.2 meters are presented. A companion paper entitled "Centrifuge Based Laser Tracker Uncertainty Quantification and Capability Development: A Two Part Series" provides detail regarding single and dual laser tracker time-space-position uncertainty quantification and the experimental approach used to quantify "ground-truth" measurements for the DLTDIC error assessment.

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Keywords: **Digital Image Correlation (DIC), Stereo Camera System, Laser Tracker, Atmospheric distortion.**

1 Introduction

The mission space of Sandia National Laboratories' laser trackers [1] is expanding from their traditional role in acquiring time-space-position-information (TSPI) of flight test vehicles acquired during flight tests to providing precision attitude and flight dynamics information. This includes 6-degree-of-freedom measurements together with spin rate, wobble, and other flight related parameters. Measurement accuracy requirements vary depending on application, but typical expected positional accuracies are on the scale of centimeters and angular accuracy requirements are one to two tenths of a degree. These requirements emphasize the need for enhanced capabilities.

Initial results from experiments in 2007 and 2008 indicate that it is possible to measure test-unit attitude by applying digital image correlation (DIC[2]) techniques to images collected from two laser trackers [2]. The first experiment, using a rocket sled [3], demonstrated that the dual laser tracker digital image correlation (DLTDIC) technique is viable. The second set of experiments conducted in 2008 was designed to evaluate the accuracy and precision of the technique [4]. This paper summarizes some of the results from the 2008 experiments and details the process used to evaluate them.

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[1] tjmille@sandia.gov, Phone 505-284-8194

[2] DIC is a full-field measurement technique that processes images from a pair of calibrated time-synchronized cameras to estimate the 3D shape, displacement, velocity and strains of a specimen that has been prepared with a high contrast speckle pattern.

The DLTDIC technique is presented in Section 2. The experimental approach and setup for the second phase of experiments are detailed in Section 3. Test data and results are presented in Section 4. Conclusions and proposed future work are discussed in Section 5.

2 Background

The basic DLTDIC technique involves post processing synchronized image pairs collected from a stereo camera system (i.e., two laser trackers) to calculate the full-field 3D positions on the test-unit's surface. First, a pseudo camera calibration is computed using (a) locations of the trackers in the world coordinate frame, (b) pointing data from the trackers when they are both locked onto a stationary target, (c) nominal lens size and (d) the pixel location of the stationary target in the left and right images. Next, DIC is applied to find and track corresponding sub-pixel locations of the speckle pattern on the test-unit for each image pair. The sub-pixel correspondences are then triangulated using the intrinsic and extrinsic parameters of the stereo camera system that have been determined for each image pair. The set of triangulated points represents unique positions on the test-unit's surface for each time frame. The transformations are then found that align a rigid-body description of the test-unit with the triangulated points. These transformations formulate the attitude and position of the test-unit for each time frame. For a more complete description of the DLTDIC technique see reference [3].

The first experiment, using a rocket sled, focused on the proof-of-concept of the DLTDIC technique. The initial set of algorithms and processes were developed during the first phase of the study. Later phases will refine the DLTDIC technique and determine the necessary enhancements to the laser trackers to achieve the accuracies required for evaluation of flight system performance.

The second phase focuses on quantifying the accuracy of the new technique in the presence of atmospheric turbulence against test-units undergoing attitudinal and positional variations. Sled track testing demonstrated that the technique is practical, but the high cost and variability of sled track testing made multiple repeatable tests impractical. To obtain repeatable and economical test data, experiments were conducted using Sandia National Laboratories' large outdoor centrifuge. On the centrifuge, the trajectory and attitude of the test-unit changes continuously with a known position and attitude. In addition, each revolution represents an independent test.

3 Approach and Experimental Setup

The basic approach for evaluating the accuracy of the DLTDIC technique consisted of collecting test data at different ranges and comparing the results with three independent measurement techniques. The primary measurement technique consisted of a stationary DIC system capable of measuring the full-field position of the side of the test-unit. The second measurement source included two incremental encoders directly attached to the centrifuge shaft, a 5000 pulse per revolution incremental encoder used for angular position, and a 900 pulse per revolution incremental encoder used for angular velocity. The third measurement source consisted of a single Phantom[3] V7 digital camera ("Dog House" camera) mounted in an instrumentation rack located at the center of rotation with a moving FOV that included the test-unit and quadrille markers accurately located on the centrifuge test arena wall. The markers on the centrifuge arm, test-unit and centrifuge arena wall were measured using a laser based coordinate mapping machine (CMM). The test-unit was painted entirely with a speckle pattern containing quadrille markers embedded within the pattern. The markers are used to register the full-field DIC results with the test-unit unit's geometry and with a rigid-body description of the centrifuge arm.

Tests were conducted at three different ranges: 222.5, 518.2, and 1000 meters. Focal lengths for the three different ranges were 800mm, 2000mm, and 4000mm, respectively. In addition, one set of data collected at the 518.2 meter range used a focal length of 1600mm. The 1600 and 4000 millimeter focal lengths were achieved by doubling 800 and 2000 millimeter lenses with a 2X extender. Figure 1 shows the lens and camera arrangement used in the laser trackers at the 1000 meter range.

The trackers were positioned such that the angle between them was approximately 40 degrees at the three different ranges. Laser tracker locations and lenses, stationary DIC camera locations and lenses, and speckle pattern dot size[4] were selected to optimize imaging for both the stationary and laser tracker fields-of-view. This was simplified by using high resolution Phantom V10[5] cameras for the stationary DIC system and Phantom V7[6]

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[3] Vision Research, Wayne, New Jersey, www.visionresearch.com
[4] The nominal dot size of the speckle pattern is 3 to 5 pixels per speckle dot
[5] Resolution = 2400x1600
[6] Resolution = 800x600

cameras in the laser trackers. This camera and lens arrangement allowed for the horizontal FOV of the stationary and laser tracker cameras to be approximately 13.7m and 4.6m respectively. Images from both stationary DIC and DLTDIC systems are shown in (Figure 2).

Figure 1. Opposing views of one of the camera and lens arrangement used in the laser trackers. The lens is a 2000mm refractive Celestron® lens attached to a 2X extender to achieve a nominal focal length of 4000mm. The camera is a Phantom V7 high-speed video camera.

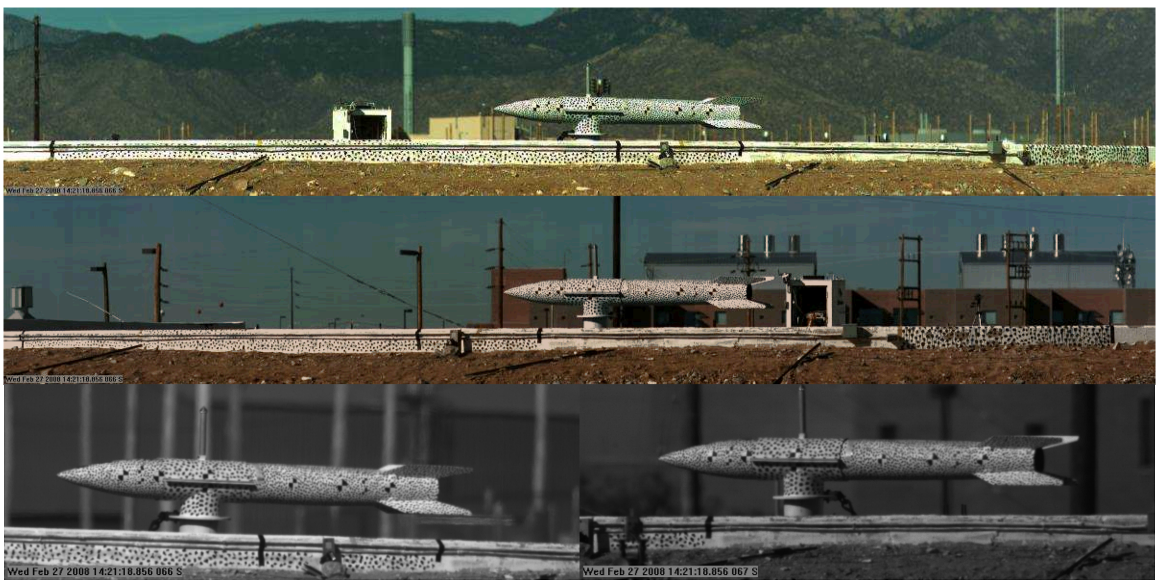

Figure 2. Sample images from stationary DIC left and right cameras (top and middle images, respectively) and images from left and right laser trackers (bottom two images).

For each day of testing, atmospheric data composed of temperature, wind speed and direction, pressure, humidity, and turbulence strength (C_n^2) were collected. At the beginning of each test day[7] the stationary DIC and DLTDIC systems were calibrated using a 2.4 square meter calibration grid composed of a 6x6 set of dots spaced 400mm apart. Three of the dots contained smaller white dots in their centers and were located such that every dot in the 6x6 array could be uniquely identified. At the end of each day of testing, the centrifuge arm was placed at 7 static positions that spanned ±30 degrees from of the center line between the trackers and the stationary DIC system. At each position, quadrille markers located on the centrifuge arm were measured using a coordinate mapping machine. After the arm position was measured and before moving it to the next position, twenty images were collected from the stationary DIC system, both trackers, and the “Dog House” camera. Prior to the test series the inboard and outboard quadrille markers on the test-unit were measured relative to the markers located on the centrifuge arm as well as the markers located on the floor and wall of the centrifuge. These measurements provide the data necessary to align the centrifuge, DIC and DLTDIC coordinate systems. Figure 3 shows quadrille markers located on the centrifuge’s arm and wall and on the test-unit.

[7] On last day of testing when the calibration was conducted directly after the test.

Figure 3. The left image shows the outboard quadrille markers on the test-unit. The right image shows some of the quadrille markers located on centrifuge arm. In the background of both images, some of the quadrille markers located centrifuge wall can be seen.

The centrifuge (i.e., world) coordinate system was defined to be nearly identical with the coordinate system used by the laser trackers. The origin is located at the center of rotation of the centrifuge arm. It was established by fitting a circle to position data collected from the end of the centrifuge arm using a laser-based CMM. The center of the circle and its normal define the location and direction of the Z-axis. The origin was translated along the Z-axis to coincide with the top of the instrumentation rack located at the center of the centrifuge. The positive Y-axis was selected to bisect the locations of each tracker on the first test and to be perpendicular to the Z-axis. The X-axis is orthogonal to the Y-Z plane following the right hand rule. This results in a world coordinate system where the X-axis points generally west, the Y-axis points generally south and the Z-axis points up (see Figure 4).

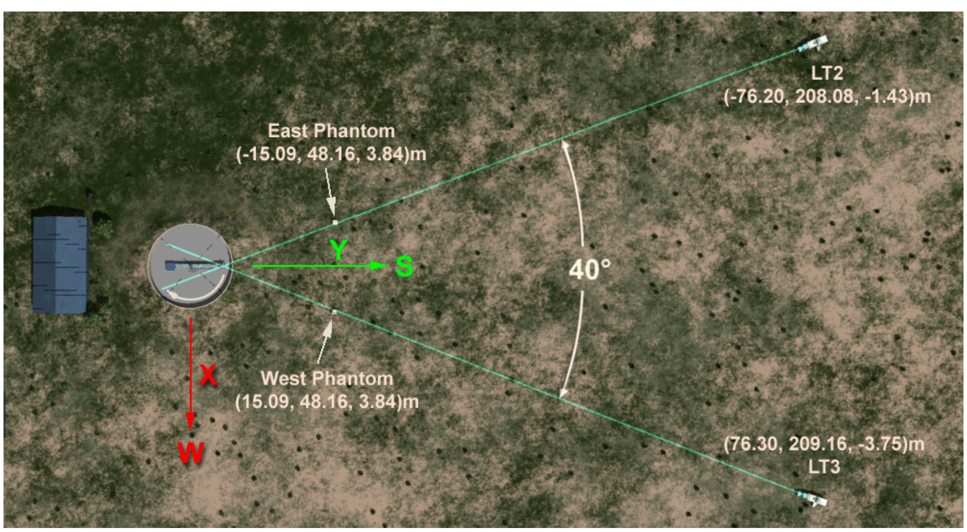

Figure 4. Overhead view of experimental setup showing the tracker positions for LT2 and LT3 at the 222.5 meter test range.

The test-area is defined as the arc[8] spanning 40±10 degrees bisected by the Y-axis. Each test contains at least one pass of the test-unit, if not more. The 3.6 meter long rocket shaped test-unit was affixed on top of a pedestal placed at the end of the 10.7 meter centrifuge arm. Test-unit mounting hardware was designed to withstand a constant acceleration of up to 10g. With a test radius of 10.543 m from the center of rotation to the centroid of the test-unit, a nominal angular velocity of 3.05 rad/s (0.485 rev/s, 29.12 RPM) and tangential velocity of 32.2 m/s was achieved. The centrifuge was ramped up to test speed in 130 seconds and held constant for 500 seconds before data collection began. This ensured that centrifuge speed was stable and the laser trackers were locked on to the target.

4 Test Data and Results

In order to compare the TSPI and attitude results from each system with the best estimate of the true position and orientation of the test-unit, the data from each system needed to be aligned with the world coordinate frame. A common method for aligning data from various 3D data acquisition systems such as CMMs, laser trackers, and DIC systems is to measure corresponding fiducials with each system and find the transformation that aligns one system to another. We chose to use the static position data that was collected at the end of each day of testing for this purpose[9]. As mentioned previously, we measure the position of the arm at each static location using a CMM and aligned them with the world coordinate frame. The position of the arm was measured because the height of the test-unit made the direct measurement of the outboard quadrille markers at each static position impractical. Using the static arm measurements, copies of the outboard markers from survey data were transformed to each static position, thus providing a set of outboard marker positions to align to. Transformation matrices for aligning the data from the stationary DIC and DLTDIC systems were calculated by computing the transformations that optimally aligned the outboard marker positions as measured by each system with the transformed static outboard marker positions in a least-squares sense.

The stationary DIC data was processed using Vic-3D[10] and the position data corresponding to the outboard markers were extracted. The DLTDIC data was processed by first estimating a camera calibration for Vic-3D based on the position of the laser trackers in the world coordinate frame, the pointing angles of the trackers when the test unit was near the Y-axis, and nominal value for the lenses in the trackers. Given this estimated calibration, Vic3D was able to correlate the reference image. At this point, a feature in Vic-3D that “fine-tunes” the camera orientation parameters in the calibration was applied. This enabled Vic-3D to correlate the image pairs from the trackers. The left and right sub-pixels locations for the outboard markers found by the correlation process were then extracted. These sub-pixel locations were then triangulated using unique camera calibration parameters calculated using the nominal lens value, the pixel location of the retro[11] in both images, and the TSPI from each tracker. The resulting outboard location from both the stationary DIC and DLTDIC systems were then transformed using the transformation matrices evaluated using the process outlined in the above paragraph. Once this was done, the rigid-body attitude and position from each system was estimated by aligning a model of the outboard markers for each time step resulting in the TSPI of the test-unit’s centroid and its attitude.

The evaluation of the best estimate for the true position and attitude of the test-unit was complicated by the fact that the images from the “Dog House” camera did not coincide in time with the images from the other cameras collected during the test. Consequently, we decided to rely solely on the timing information from the one-pulse per revolution trigger signal and the 5000 pulse per revolution encoder on the centrifuge. This data provided an angular position versus time of the centrifuge arm from which the position of centroid and the attitude of the test-unit (assuming rigid-body) were estimated. This estimated position and attitude (i.e., pose) vs. time were then used as the “ground-truth” or expected data value for comparing the stationary DIC and DLTDIC results to.

Table 1 shows a summary of some of the test parameters for the results that are presented in this paper. The test names in the table follow the pattern of TXPY => Test-X Pass-Y. In addition to the test passes shown in the table, there were five more passes at the 222.5 meter range, one more pass at the 518.2 meter range, and two pass at the 1000 meter range that have yet to be analyzed. Once all the data has been analyzed, we will prepare an accuracy statement for the DLTDIC system.

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[8] The size of the arc is based on the ability of the DIC and DLTDIC systems to correlate at the extreme ends of the arc.
[9] For stationary DIC systems, it is common to place speckled backboards with embedded quadrille markers to align the data with a world coordinate frame. However, this technique is not practical for moving field-of-view systems such as DLTDIC.
[10] Vic-3D is a software application developed and distributed by Correlated Solutions, Inc.
[11] The retro position is found by manually inspecting the left and right reference images for the bright return of the laser.

Table 1. Test parameters associated with the data present in this paper.

Test Name	Date	Time	Range (meters)	DLTDIC Lens (mm)	Frame Rate (fps)	C_n^2	Tangential Velocity(m/s)
T2P2	2/27/08	15:21:18.706066	222.5	800	1000	6.46e-14	30.69
T5P1	2/29/08	15:47:31.904041	518.2	2000	1000	7.49e-14	31.25
T5P2	2/29/08	15:47:33.961041	518.2	2000	1000	7.49e-14	31.19
T5P3	2/29/08	15:47:36.026041	518.2	2000	1000	7.49e-14	31.04
T5P4	2/29/08	15:47:38.095041	518.2	2000	1000	7.49e-14	31.10

We decided to compare rigid-body pose as estimated from each system with an expected pose estimated from the angular position vs. time of the centrifuge arm. This approach has the drawback that the exact pose of the test-unit is unknown. Of the six body-centric parameters (i.e., X, Y, Z positions and rotations about the X, Y, Z axes), only the TSPI of the test-unit can be estimated closely[12] excluding a bias shift[13]. This is due to uncertainty in the alignment of the pre-test survey data with the global coordinate frame as well as uncertainty in the distance between the test-unit's centroid and the center of rotation. Furthermore, the attitude data is only an estimate based on static data and assumes the test-unit and arm assembly behaves as a rigid-body. The most accurate of the rotational parameters is the rotation about Z, but this value is also based on the position of the arm. With all this being said, Figure 5 shows attitude and TSPI results from Test-5 Pass-1 (T5P1) where the DLTDIC system was 518.2 meters away from the centrifuge and spaced 354.9 meters apart.

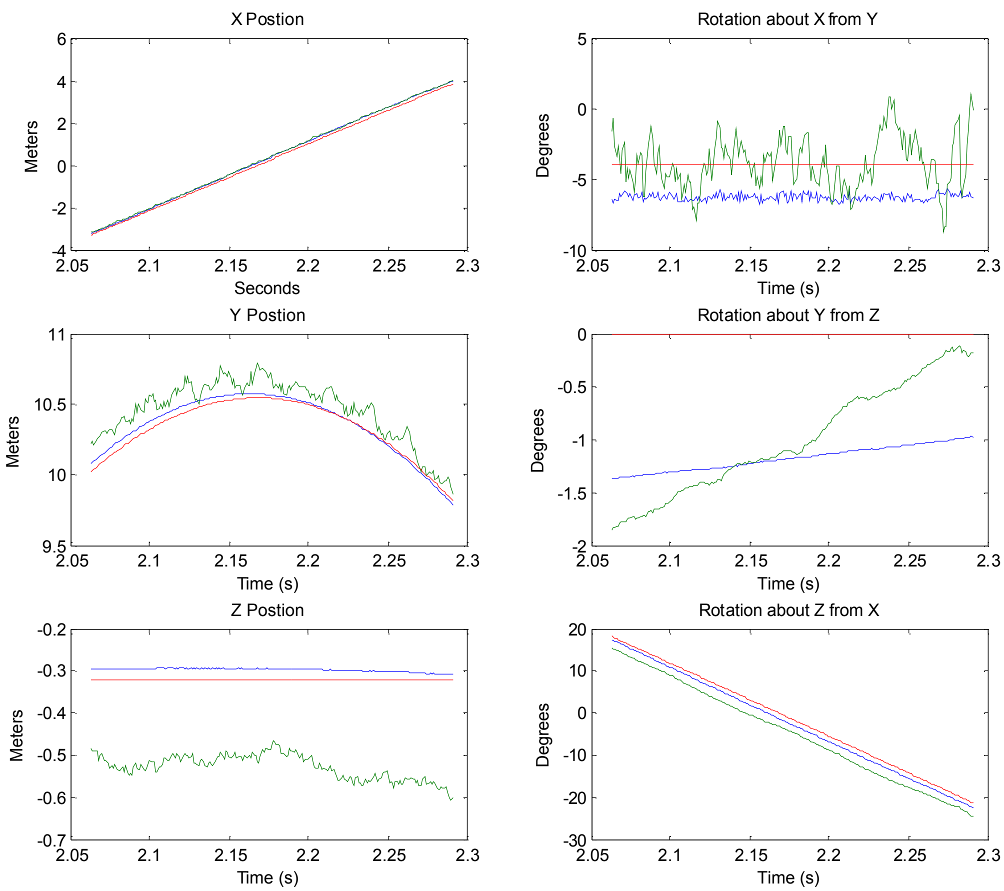

Figure 5. Test-5 Pass-1 TSPI data (left column) and attitude data (right column). The expected value is shown in red, the stationary DIC data is shown in blue, and the DLTDIC data is shown in green.

[12] We do not have this value quantified as yet, but we believe it to be less than ± 25mm.
[13] Given that we do not have image data from the "Dog House" camera the arm position has been extrapolated based on the one-pulse per revolution trigger signal measured at the beginning of the test.

The difference between expected value and the measurements from the stationary DIC and DLTDIC systems are shown in Table 2 and Table 3; and the difference between the stationary DIC and DLTDIC systems are shown in Table 4.

Table 2. Comparison of the expected pose of the test-unit with the values from the DIC system.

Expected - DIC	**Mean Difference**			**Standard Deviation**		
TSPI (in meters)	**X**	**Y**	**Z**	**X**	**Y**	**Z**
T2P2	-0.158	-0.029	-0.031	0.014	0.041	0.008
T5P1	-0.118	-0.021	-0.025	0.024	0.029	0.004
T5P2	-0.116	-0.020	-0.022	0.024	0.028	0.004
T5P3	-0.104	-0.020	-0.024	0.027	0.026	0.004
T5P4	-0.115	-0.020	-0.024	0.023	0.028	0.004
Attitude (in degrees)	**Rx from Y**	**Ry from Z**	**Rz from X**	**Rx from Y**	**Ry from Z**	**Rz from X**
T2P2	-1.397	-0.023	1.274	0.297	0.103	0.189
T5P1	2.295	1.177	1.156	0.231	0.114	0.174
T5P2	0.933	1.237	1.182	0.225	0.115	0.175
T5P3	1.905	1.302	1.103	0.221	0.112	0.188
T5P4	1.905	1.302	1.168	0.221	0.112	0.173

Table 3. Comparison of the expected pose of the test-unit with the values from the DLTDIC system.

Expected - DLTDIC	**Mean Difference**			**Standard Deviation**		
TSPI (in meters)	**X**	**Y**	**Z**	**X**	**Y**	**Z**
T2P2	0.215	-0.002	0.137	0.033	0.050	0.010
T5P1	-0.139	-0.126	0.206	0.025	0.061	0.029
T5P2	-0.129	-0.092	0.218	0.023	0.057	0.026
T5P3	-0.137	-0.095	0.214	0.022	0.057	0.027
T5P4	-0.140	-0.108	0.212	0.022	0.062	0.029
Attitude (in degrees)	**Rx from Y**	**Ry from Z**	**Rz from X**	**Rx from Y**	**Ry from Z**	**Rz from X**
T2P2	-1.284	0.156	-0.405	0.697	0.058	0.131
T5P1	-0.158	1.001	3.257	1.823	0.514	0.326
T5P2	-1.163	1.097	3.294	3.151	0.478	0.210
T5P3	0.332	1.038	3.245	2.692	0.487	0.184
T5P4	0.789	0.939	3.343	2.194	0.488	0.294

Table 4. Comparison of the DIC pose of the test-unit with the values from the DLTDIC system.

DIC-DLTDIC	**Mean Difference**			**Standard Deviation**		
TSPI (in meters)	**X**	**Y**	**Z**	**X**	**Y**	**Z**
T2P2	0.372	0.027	0.168	0.037	0.090	0.013
T5P1	-0.021	-0.105	0.230	0.021	0.050	0.026
T5P2	-0.012	-0.072	0.241	0.020	0.047	0.024
T5P3	-0.034	-0.076	0.238	0.025	0.050	0.024
T5P4	-0.025	-0.088	0.236	0.019	0.051	0.027
Attitude (in degrees)	**Rx from Y**	**Ry from Z**	**Rz from X**	**Rx from Y**	**Ry from Z**	**Rz from X**
T2P2	0.113	0.179	-1.679	0.738	0.068	0.287
T5P1	-2.453	-0.176	2.102	1.801	0.400	0.251
T5P2	-2.096	-0.140	2.112	3.146	0.365	0.236
T5P3	-1.573	-0.264	2.142	2.706	0.376	0.288
T5P4	-1.116	-0.363	2.175	2.198	0.380	0.220

The standard deviations of the errors between the expected TPSI of the test-unit and the stationary DIC position measurements are relatively close (less than 41 mm) considering that the stationary DIC system cameras were

50.5 meters from the center of the centrifuge and 30.2 meters apart for each test. The same could be said for the TSPI measurements from the DLTDIC system considering the positions of the laser tracker at the 222.5 and 518.2 meter ranges.

On the other hand, the standard deviations of the errors for the attitude data are larger then we would have hoped for the rotations about the X axis (Rx from Y). This is due to two reasons. The first is that only test-unit marker positions were used to estimate attitude instead of the full-field data[14]. The second is the fact that this measurement is governed by the ability of the DIC and DLTDIC systems to measure the distance of the markers relative to their own coordinate frames. In other words, small changes in the position of the test-unit markers result in greater changes in the test-unit's Rx from Y attitude measurement. With this being said, it does not appear that the test-unit rotates about the X-axis. The rotation of the test-unit about Y from Z (Ry from Z) shows that the test-unit pitches down as it passes through the test-area for all four of the Test5 passes. However, for the only pass in Test 2 that we have data for, the data indicated the test-unit pitched up. The rotation of the test unit about the Z axis is mostly due to the test-units X and Y position. Hence, errors in this parameter are specifically governed by the expected position of the arm as mentioned above.

Given that the exact pose of the test-unit is unknown, we also decided to compare the estimated velocities from the systems. Table 5 shows the velocity results from the test data. The percent errors between the velocities measured by the 5000 pulse per revolution encoder and the stationary DIC system are lower then 1.3 percent whereas the percent errors of the DLTDIC system is below 1.9 percent. However, the data in Table 5 shows that DIC system velocities are only better than the DLTDIC system 6 out of 10 times.

Table 5. Comparison of Estimated Test-Unit Tangential Velocities.

Estimate Test-Unit Tangential Velocities							
Test Name	Encoder (m/s)	DIC (m/s)	Encoder – DIC (m/s)	% difference Encoder & DIC	DLTDIC (m/s)	Encoder – DLTDIC (m/s)	%difference Encoder & DLTDIC
T2P2	30.69	30.73	-0.0462	-0.150	31.01	-0.3214	-1.047
T5P1	31.25	31.59	-0.3364	-1.076	31.47	-0.2200	-0.704
T5P2	31.19	31.53	-0.3408	-1.093	31.77	-0.5756	-1.845
T5P3	31.04	31.44	-0.3937	-1.268	31.37	-0.3284	-1.058
T5P4	31.10	31.44	-0.3371	-1.084	31.56	-0.4590	-1.476

5 Conclusions and Next Steps

The pre-test survey and post-test static data collect at the end of each day of testing are at the heart of the results reported in this document. As such, both systematic (bias) and random (precision) measurement errors propagate through to the end results of the accuracy study. At this point, we believe the larger discrepancies in the TSPI data are the result of spatial and temporal alignment errors and that the attitude errors can be reduced using the full-field results rather than marker positions.

Although the preliminary results presented in this article did not asses errors through strong turbulence, the results we obtained are promising. Preliminary results indicate that the DLTDIC technique has a strong potential to enhance our current measurement capabilities and information not available from laser tracker data alone. The technique appears to be well suited to many moving field of view applications such as missile tracking and missile performance characterization. Further refinement of the DLTDIC technique, including a complete model for the camera and mirror system, as well as the use of image features as additional information to update the calibration in each frame, are expected to further improve the results and make the technique applicable to a wide variety of applications.

At this point we are pursuing the following next steps:

1. Investigate the value of dynamically updating the calibration using known target characteristics (i.e., the speckle pattern itself), fixed calibration boards, and/or known points in the field of view.
2. Investigate the value of dynamically updating calibration parameters by tracking small motions of the retro-reflective target in the images.

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[14] The final accuracy quantification will use full-field results.

3. Test and enhance the DIC algorithm that updates the reference image throughout the data acquisition to allow surface measurements of rotating test-units or of images distorted by atmospheric turbulence that do not correlate well.
4. Add processing techniques to evaluate environmental dynamics (e.g., shockwave duration, spin rate, etc).
5. Incorporate atmospheric mitigation methods to reduce image distortions to enhance the possibility of measuring surface strain.
6. Add slave trackers to the 2 tracking systems to improve 6 degree of freedom sensitivity and operating range.
7. Replace laser ranger with a new pulsed picosecond Raman laser ranger system[15] to provide range accuracy on the order of cm. Add atmospheric mitigation technologies and hot spot tracking enhancements[16].
8. Conduct sled ejector tests and missile tests.

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[15] Institute of Applied Physics, Nizhny Novgorod, Russia
[16] University of Maryland Intelligent Optics Lab