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Abstract

Results from initial laboratory investigations with the dot projection photogrammetric technique are presented for three wind-tunnel test articles with a range of surface scattering and reflection properties. These test articles are a semispan model and a micro air vehicle with a latex wing that are both diffusely reflecting, and a highly polished specularly reflecting model used for high Reynolds number testing. Results using both white light and laser illumination are presented. Some of the advantages and limitations of the dot projection technique are discussed. Although a desirable final outcome of this research effort is the characterization of dynamic behavior, only static laboratory results are presented in this preliminary effort.

Introduction

Several image-based, non-contacting video measurement techniques, including Projection Moiré Interferometry (PMI) and Videogrammetry have been used for shape characterization in wind tunnel applications at NASA and elsewhere[1]. These techniques are capable of providing quantitative measurements of model deformation and dynamics, but each has some limitations or constraints. The often extensive processing requirement for classic PMI restricts its use in real-time applications.

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Videogrammetry, while capable of providing spatial positions of targets in near real-time at higher accuracy than PMI, has traditionally relied on a limited number of either painted or retro-reflective targets attached to the surface of a model. This limited number of targets may provide incomplete surface characterization and, in addition, requires time for target application.

Dot projection techniques attempt to fill the gap between the two aforementioned systems, providing a completely non-contacting spatially complete surface measurement technique suitable for near real-time applications. The method of obtaining object space coordinates described here is based on the projection of a dense dot pattern (targets). Images are collected and processed from two instrumentation grade video cameras to yield the three-dimensional shape of the object based on the spatial coordinates of the projected dots. While several systems employing retro-reflective and painted targets and projected Moiré fringes have been widely used in wind tunnels at NASA, dot projection techniques have not yet been used at all.

The projection of structured light onto a surface has been extensively used for the surface reconstruction of static objects for more than a decade in various research and industrial applications. More recently efforts to develop non-contacting optical techniques have expanded to include not only model deformation measurements during wind tunnel tests, but also ground based testing of a new generation of Ultra-Light Inflatable Space Structures (UIS)[2,3,4]. Concurrently, the aeronautics community is focusing technology development toward a new generation of biologically inspired flight systems (BIFS) and micro air vehicles (MAV)[5]. One common aspect these technology development programs share is their focus on membrane construction for critical components. An example of each is shown in Figure 1. The material density requirements for each of these programs will restrict the use of attached retro-reflective targets and therefore there is a need for a comparably accurate system with near real-time capacity to support dynamic structural characterization, validation, and control of these membrane structures.

Figure 1: UIS and MAV Vehicle Examples

The potential for commercialization of a dot-projection photogrammetric system has also been recognized by industry. Both Geodetic Systems,Inc. and ShapeQuest, Inc. have commercially available products based on the concept of dot projection.[6,14]

As technology advancements continue at a rapid pace in high-resolution CCD video cameras, storage capacity, and central processing speeds, the development of numerous digital image processing software packages has automated many of the tasks that previously required a detailed understanding of the principles of photogrammetry and image processing, Thus a range of high-accuracy applications are feasible, even for the novice. For our purposes we seek to provide a continuous spatial model of the test article without the requirement for attached targets and lengthy post-processing requirements. The goal of this initial investigation was to evaluate the advantages and constraints associated with the use of dot projection as a method of gathering three-dimensional shape data.

Technology Spectrum

The basic data for photogrammetric measurements are images. In general, an image is the result of a perspective projection of a three-dimensional (3-D) object to two dimensions (2-D). The photogrammetric solution provides a quantitative relationship between 3-D position, and/or deformation and the 2-D image plane data recorded by one or more cameras. Over the last two decades a variety of photogrammetric techniques have been used in a number of wind tunnel tests to provide wing twist and model deformation measurements.[7] Originally, the techniques were developed for use with still-frame film cameras, but the rapid development of CCD technology led to the successful migration from film to video technology. Photogrammetry combined with image processing has been found to yield accurate and near real-time data, but at a limited number of points on a given model.

At the other end of the technology spectrum is the PMI technique, with generally lower accuracy than the photogrammetric techniques, but with more complete spatial coverage. The PMI technique projects a grid of equally spaced parallel lines onto the test article. The basic principle of the method is that any height difference from a reference plane causes a shift in the projection line of light in the image plane of a recording camera.[8] While the technique provides full-field measurement it is not well suited for real-time applications. There are several factors that can affect measurement accuracy for the PMI technique; among them are projected grid pitch, field of view, optical modulation transfer function, and illumination.

The dot projection technique proposed here will seek to find a "middle of the road" in the optical measurement technology spectrum, between the superior accuracy associated with the use of photogrammetric principles and retro-reflective targets (as they have been developed in current videogrammetric systems) and the spatially continuous measurements provided with the PMI technique. The basic goal of dot projection is to apply the same photogrammetric principles used in the aforementioned videogrammetry techniques, but without the use of attached targets. The dot projection technique as presented here is based upon two video cameras, but photogrammetric techniques with more than two cameras would be required to capture extreme 3-D motion where targets may become occluded occasionally.[9]

Experimental Discussion

To evaluate the accuracy of white light projected targets a laboratory experiment was designed to directly compare the three-dimensional photogrammetric accuracy of projected targets against the adopted standard provided by retroreflective targets. Figure 2 shows the laboratory configuration. The hardware configuration included two Hatachi CCD (640x480) progressive scan video cameras with

Sony 25-mm focal length lenses, and a Newport MP-1000 slide projector. The test article for this experiment was a mock-up of the 16 percent scale F18-E/F planform Smart Wing developed by Northrop Grumman and tested at the NASA Langley Transonic Dynamics Tunnel in March 1999.[10]

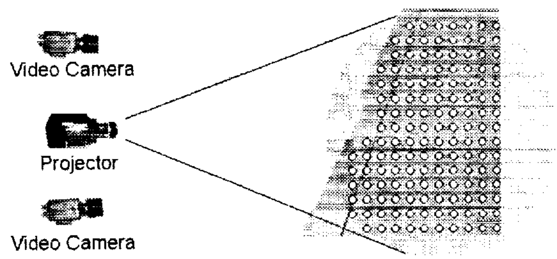

Figure 2: Hardware Configuration

Calibration

Perhaps the most critical aspect of any photogrammetric measurement technique is the camera calibration. The camera calibration determines the camera orientation parameters that relate the 2D image plane and 3D object space. The process is developed with a set of collinearity equations.[11] three-tier calibration target plate, shown in Fig. 3, provided a three-dimensional known target field. The coordinates of the target field, which were independently measured with a 3-D coordinate measuring machine, provide an input for the camera calibration process.

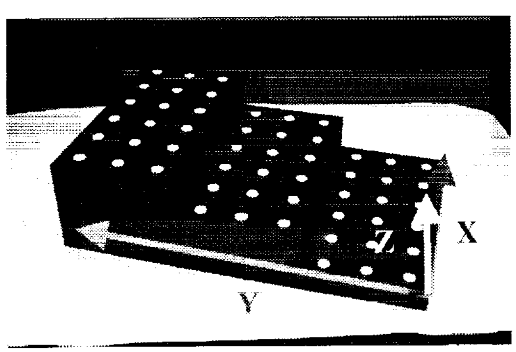

Figure 3: 3-Step Calibration Target Plate

The calibration process establishes a coordinate system in which all measured points are referenced. We aligned the axis of motion defined by a translation table with the Z-axis as established by the calibration plate. For this configuration, the Z-axis represents motion toward the cameras. Once the calibration has been completed, any camera movement will result in erroneous data. Similarly, any vibration or motion of the projector once the initial reference is established will prevent accurate correlation in image sequences.

Projection Hardware

A white-light projector used for the dot projection technique does not have to be calibrated, as is the case with the PMI technique. The projected pattern is imaged simultaneously by two CCD cameras. As with most two-camera techniques an angle of around 90 degrees between the optical axes of the two cameras is desirable to maintain precision in the approximate direction that the cameras are pointed.

A series of slides with different dot sizes were produced, from which the best projection pattern was selected depending on the object surface properties and the desired resolution. The slides used stainless steel screens that were photo-chemically machined using a photochemical etching process.[12] The material is commercially available in sheet-form. Because they are photochemically etched, the metal is not mechanically perforated; resulting is greater material integrity, and a cleaner, burr-free perforation. Using the metal screen as a projection medium produces maximum contrast in the pattern as well as high thermal stability compared to a film slide. The slides were cut to fit a standard slide projector. For the results presented here a Newport MP-1000 Moiré projector fitted with a 50 mm Nikon lens was used in place of a standard slide projector.

Experimental Configuration

To generate out-of-plane motion of the wing in this experiment, it was attached to a Velmex 12 inch linear translation table. The table provided measurement accuracy of 0.001 inch as verified with electronic dial gauges accurate to 0.0001 inch. The projector axis was aligned with the translation axis of the table to ensure the wing remained in the field of projection throughout the range of motion. A perspective of the wing under dot projection is shown in Figure 4.

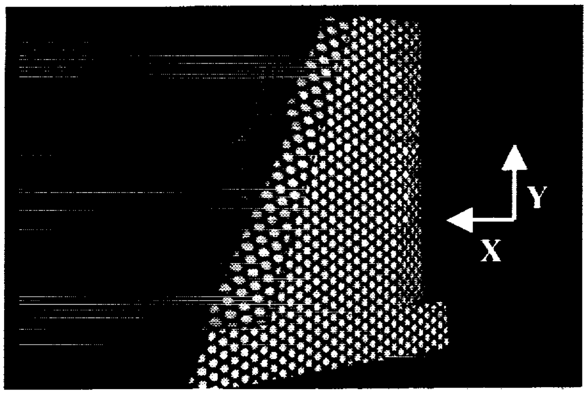

Figure 4: Test Article with Dot Projection (Simulated Image)

Four retro-reflective targets were positioned at two spanwise locations along the wing. This comparative analysis used 38 of the projected targets. The tracked retro targets are identified in green (most extreme targets) and the projected targets in white (middle set of targets) in Figure 4. The wing translated over a ten-inch range with image sequences acquired at one inch increments. The axis of motion was along the Z-axis as defined by the camera calibration process.

Results

As expected, the retro-reflective targets tracked the motion of the wing with high accuracy and very small scatter over the measured range. Using the retro data to check for possible error in the alignment of the photogrammetric axis (Z) and the axis of translation identified a slight misalignment of 0.42 degrees. It was determined this small misalignment would not significantly affect the data over the measured range. Figure 5 highlights the delta change for the retro targets over the measured range and identifies a mean of 0.9997 inches with a standard deviation of 0.0048 inches. The standard deviation for both the X and Y-axis was approximately 0.001. The better precision in the XY plane was due to the small convergence angle between the two cameras that led to reduced precision in the Z-axis.

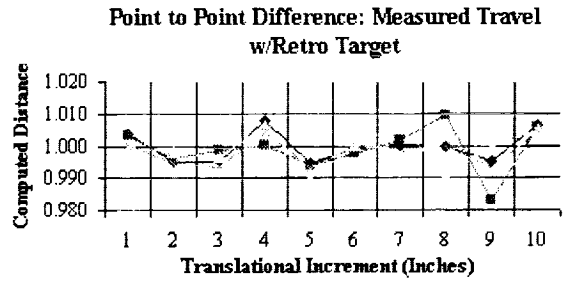

Figure 5: Retro Target Incremental Change

Figure 6 shows the scatter in the Z component between the two targeting methods over the measured range.

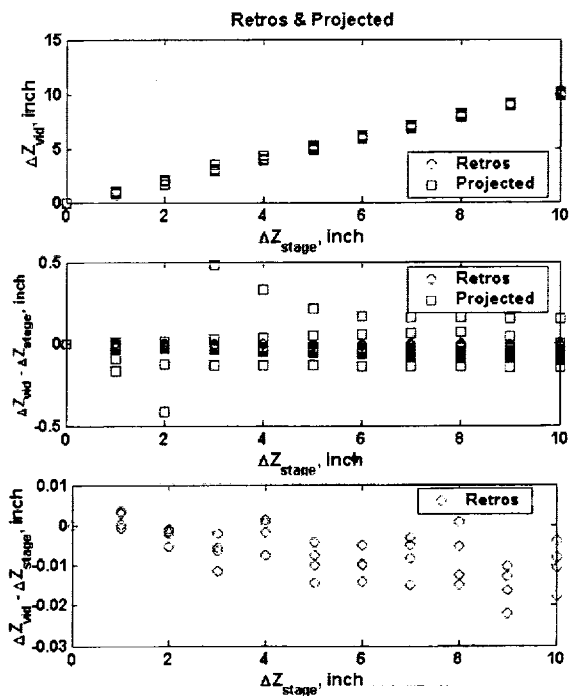

Figure 6: Comparison Retro vs. Projected

A closer inspection of the results indicates a substantial variation in the XY plane for the projected targets while the attached retro targets show only small variations in that plane over the same range of motion. Figure 7 highlights the recorded motion of the projected targets over the measured range. With the motion of the model along the Z-axis the projected targets appear to move closer together. As would be expected the motion of the projected pattern appears to converge toward a point of symmetry for the projection. This convergence is seen to be a point in the upper left quadrant of the plot.

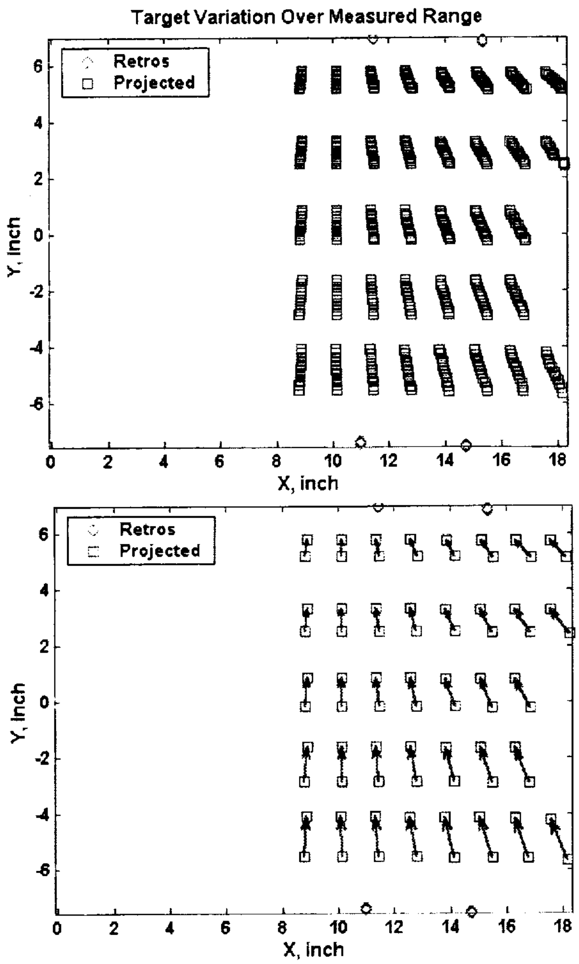

Figure 7: Retro/Projected Motion in XY Plane

To interpret the true surface motion as defined by the projected targets, a fixed reference point would need to be included in the data set. The repeating dot pattern of projected targets can be exported to a CAD environment to generate splines along various regions of interest. An obvious shortcoming of projected targets is the inability to provide time histories of a specific point of interest on the test article.

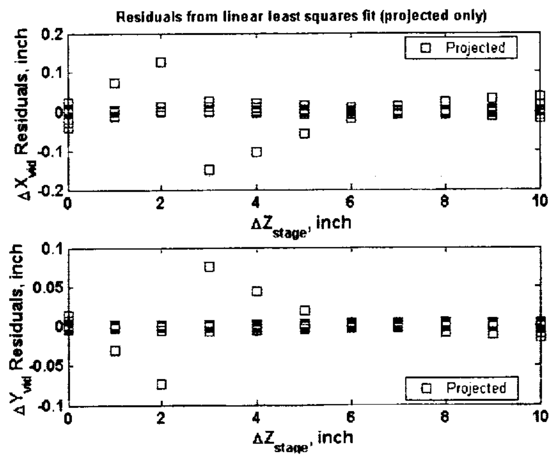

Figure 8: Linear Least Squares Fit (Proj)

Plots of the computed residuals for the projected targets for both the X- and Y-axes are shown in Figure 8. One of the targets has a significantly larger residual variation over the range. Manual inspection of the image sequences identified the target in question as an edge target with an incorrect background calculation. This discrepancy is discussed in the next section.

Discussion - Target Recognition

A factor in achieving maximum accuracy with either retro-reflective or projected targets is the image plane diameter of the target. During test planning, the user should consider the necessary field of view and the resolution of the cameras. For best centroiding accuracy, the diameter of targets in the camera image plane should be approximately 5-7 pixels. In the case of larger structures such as proposed solar sails, this requirement may dictate the need for targets several inches in diameter. A noted benefit of using projected targets is the ability to quickly change projection slides to adjust from larger to smaller targets when the research focus changes to an individual component of a larger model.

Target recognition can be achieved in several ways. Several of the systems currently in use at NASA Langley require initial manual identification of each target for each camera. It is obvious that such an effort for a system using hundreds of closely spaced projected dots would be excessively labor intensive and prone to human error. It is therefore desirable that the identification of targets be automated. A useful algorithm for matching the projected dots between two images is based on the epipolar geometry. Epipolar geometry can help establish correspondence between dots for each camera view. As shown in Figure 9 for object point P, the projection centers of the two images, O1 and O2, form a plane (the epipolar plane) that intersects the two image planes. As a result, two epipolar lines (one for each image) are created. Corresponding points fall on these lines. Once the camera positions and orientations are determined from calibration, the equations of the epipolar lines are known.[13] Since there are many points that may fall on this line the approximate distance from the camera to the test article is used as an additional constraint for the algorithm.

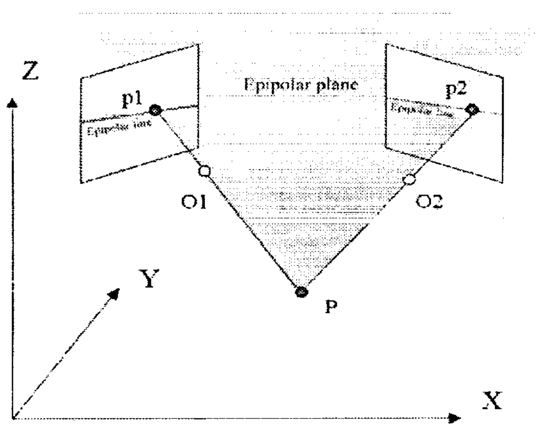

Figure 9: Epipolar Geometric Model[14]

Several factors may contribute to mistaken correspondence of targets. Object features such as slots, edges or holes will often cause a projected dot to appear as two distinct targets from one camera perspective, but appear as a normal ellipse from another. Figure 10 shows the same region of interest on the model but from opposite camera positions. Note that the edge between the wing and the flap creates several erroneous targets that must be detected and discarded by the software during image processing. This type of error is also more likely when the separation angle between cameras is large, however reducing this angle negatively affects sensitivity in the Z-axis. Automating the process of false target discrimination for large target fields is difficult.

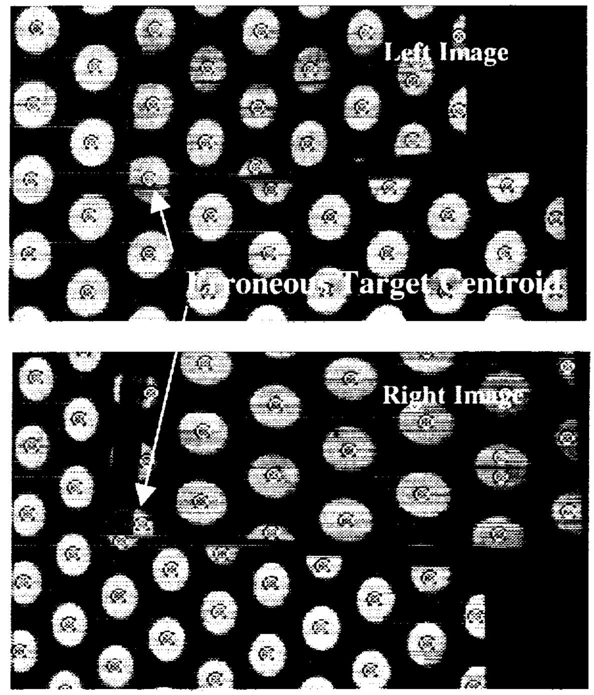

Figure 10: Target Recognition Errors

Discussion - Target Tracking

There are three widely adopted techniques used for target tracking. They are centroid, edge, and correlation tracking. Centroid tracking is a brightness based segmentation technique that computes the centroid for the segmented area. Edge tracking seeks to define the target with an edge segmentation scheme that is followed by a centroid calculation. The correlation technique identifies a template to track from frame to frame. For our experiment a centroid tracking technique was applied.

There are a number of methods that have been developed to find the subpixel location of a target.[15] Among the various techniques available are Binary centroid, Gaussian Distribution Fitting, Ellipse Least Squares, Perimeter Average and Squared gray scale centroid.

With projected dots several issues can affect the accuracy of the subpixel algorithm. An accurate determination of the target background is necessary. With dot projection, the combination of a high-density dot pattern and a model that covers a wide depth of field can negatively influence the definition of background. In many applications the search window for the targets edge is defined as some factor times the largest target diameter found on the object. For our experiment the depth of field of the projected pattern created targets that ranged from 21 to 45 pixels over the full span of the model. When using a high-density projection pattern, adjacent targets only a few pixels away may negatively influence target centroiding when a general search window based on the diameter of the largest target is used to define the background. With our experiment the 38 projected targets were selected over a region that minimized their size variation and thereby avoided this issue of background definition.

As simulated in this paper using a linear stage to move the entire wing in the out-of-plane direction, the technique could support a wide range of dynamic motion. A reconstructed rendering of the model surface created using all of the projected targets from a single image set of the experiment is shown in Figure 11. With the use of external control targets (i.e. stationary background targets) a rigid frame of reference could be established to reference sequential renderings of the model.

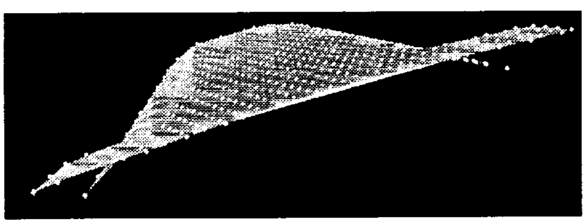

Figure 11: Surface Rendering of Wing

The step from capturing static surface contour measurements to dynamic motion may require additional hardware. One possibility is a configuration using a pulsed light source as the projector. The pulsed light output would freeze the motion to prevent blurring of the projected dots. To ensure the light pulse occurs during the camera open shutter period an external synchronized trigger will be required.

Model Surface and Lighting

To take advantage of the full dynamic range available with a standard 8-bit digital video camera the settings should be optimized with the combination of shutter speed and aperture to remove extraneous light. Due to the variations in ambient lighting in many wind tunnel facilities a higher power projector may be necessary to ensure adequate contrast. Since the distance between the retro targets and the light source is not critical, the projector was positioned 10 feet from the test article to ensure sufficient intensity

When considering the use of white-light dot projection over the more common retro-reflective targets, consideration must be given to the reflective nature and surface finish of the test article. Typically wind tunnel models have surface finishes ranging from highly polished steel to painted diffuse white panels. As demonstrated in Figure 12, the contrast in target and background is very low for a highly reflective model surface due to the substantial reflection of light away from the cameras. In cases where the specular reflection direction is toward one of the cameras, the light source may create bright spots that prevent target recognition in the immediate area.

Deformation measurements at the National Transonic Facility (NTF), where model surfaces are always highly polished, routinely require the targets to be painted on the model surface.[16] The polished paint diffuse targets are typically 0.0005 inch thick with a surface roughness of less than 10 μinch. Ordinary lights (non-laser) can provide sufficient illumination. While this technique has been demonstrated to be effective for deformation measurements at the facility, the procedure for painting the targets is detailed and time consuming. Similarly, repair time for damaged targets can be substantial. Ambient lighting can also create reflections on a painted target model. Since a laboratory investigation of the use of projected targets on highly reflective model surfaces yielded poor results due to the low contrast and surface reflections of the source projector, further developments will be necessary before the dot projection technique is suitable for high Reynolds number facilities such as the NTF.

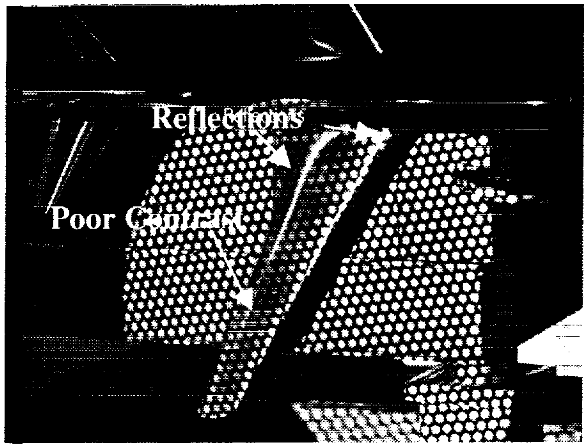

Figure 12: Highly Polished Metal Surface

Laser Projected Targets

There are advantages and disadvantages to using a laser as a replacement source for projecting the dot pattern. A suitable laser will provide a concentrated diffraction limited beam that is generally visible above the ambient lighting in most environments. This high intensity beam may be able to provide comparable signal-to-noise ratios commonly found with the use of retro targets. In addition, a laser could also be chosen that would operate in the near infrared. A pulsed laser diode emitting in the near infrared similar to that used in the aforementioned PMI systems, coupled with suitable wavelength filtering, may supply sufficient contrast to allow lights-on operations in most research facilities.

Among other advantages noted is the narrow spectral bandwidth of the laser, which provides the user the unique ability to remove most of the extraneous light with an interference filter on the camera. Diode lasers are another option that compare favorably to available white light projectors. A diode laser offers a small (few inches) and self-contained package that operates with low power requirements. When coupled with a diffractive pattern dot generator the combination is routinely used in laser machining, laser marking, alignment systems and computer vision. However, note that safety considerations will be a factor when using a laser as the projection light source.

As part of the evaluation of the centroiding accuracy using retroreflective, laser, or white light projected targets, a micro air vehicle (MAV) test article was mounted on a precision rotary index head approximately perpendicular to the laser beam and optical axis of a camera. The A.G. Davis index head has an accuracy of better than 1 arc second. For this experiment a 5mW HeNe laser was selected. The MAV model wing section used was made of latex and provided a consistent contrasting background for target comparison. The model was placed 48 inches from the laser and camera station. The camera optical axis and the projected beam axis were aligned by sight. The setup is shown in Figure 13. A stationary Kodak DCS 460 6 megapixel (3060x2048) camera acquired the image sequences. The camera was stationary during the image sequences. The camera focal length and aperture settings remained constant for all images. The camera electronic shutter was varied to obtain approximately the same relative exposure for each trial. All targets were approximately 0.25 inches in size.

Camera calibration yielded an estimated sensitivity of 0.0055 inches/pixel. The calibration scheme employed for the Kodak DCS professional series camera was based on a photogrammetry technique known as "bundle adjustment." The scheme utilizes multiple camera stations, multiple convergent views, and different camera angles to determine accurately the interior orientation parameters. Using the commercial Photomodeler® software, from EOS Systems Inc., the process requires the user to manually identify a series of control points on each of the calibration images. The bundle solution then computes the interior orientation and distortion parameters of the camera.

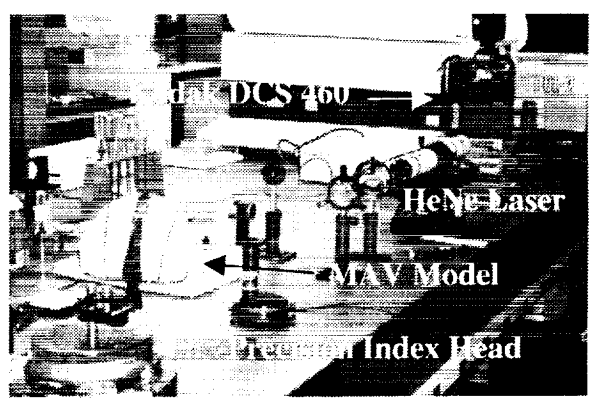

Figure 13. Laser Target Experiment Configuration

Visual observations indicated that laser speckle might adversely impact centroid determination. Due to the concentration of light for the laser the target saturated (255) on an 8-bit grayscale reading. A comparison of the variation in grayscale readings across the retro target and laser target shows a more well defined threshold transition for the retro target. A graph of the typical cross sectional intensity for each type of target is illustrated in Figure 14. The centroid calculation requires an accurate determination of the target background for a defined search area. The three graphs on each figure represent the Red-Green-Blue content of the target. As expected with a HeNe laser, the saturated signal is mostly red.

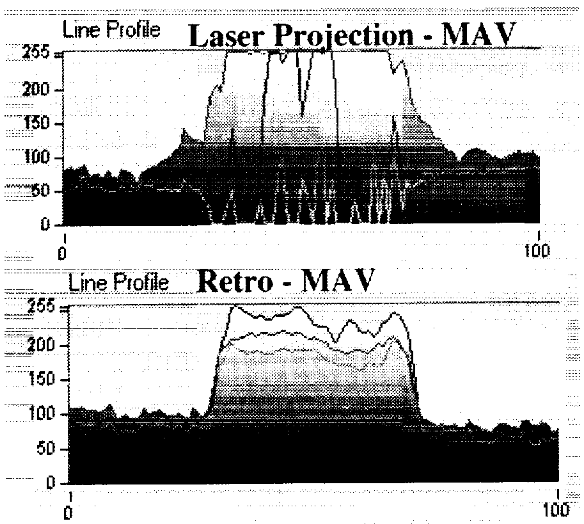

Figure 14: Cross Sectional Comparison of Laser and Retro Targets

The targets were positioned on the test article so the center target was aligned with the rotation center of the index head. The target alignment was verified by rotating the object 180 degrees and verifying the edges were overlapping on each view. The index head and the laser were leveled using a precision 3-axis accelerometer package.

To investigate the effect of laser speckle on the centroid computation, a series of images were taken at incremental rotation angles. The images were shot over a ±40 degree range in 5-degree increments. The calculated mean for the centroid of each target data set was used as the reference for comparing the scatter between the targets. As indicated by the charts in Figure 15, there are much larger variations in the centroiding accuracy for the laser-projected target than for the retro target.

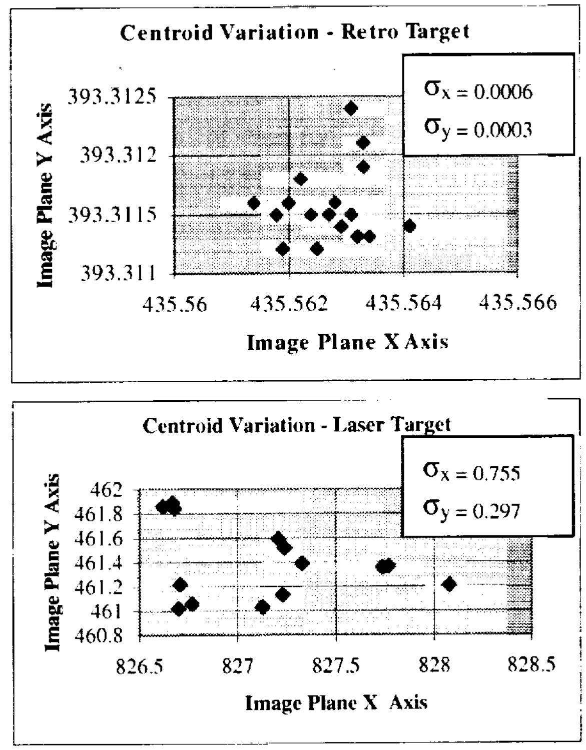

Figure 15: Centroid Variation Laser/Retro

The major disadvantage of laser projection is speckle. While there are several optical techniques for minimizing this effect, the error contribution when calculating the centroid can be significant.[17] Note that the coherent nature of the HeNe laser and the diffuse nature of the surface are the primary cause of the speckle noted in this experiment. It would be expected that the effect of speckle on centroid calculation could be reduced using a multi-mode, low coherence length laser diode with limited spatial coherence. Further investigations are planned with alternative laser sources.

Conclusions

Initial experimental investigations were conducted to evaluate the benefits of dot projection as an alternative to attached targets for shape characterization of various types of model surfaces. Several issues have been discussed with regard to using projected dots from either white light or laser sources. Regardless of the source, the projected dots must have high contrast to achieve accurate measurement. We were able to achieve good contrast for the projected white light targets by adjusting the aperture at a cost to depth of field. The depth of field can also create problems in target centroiding when provisions are not made for the variable dimension of targets over the field. Our investigation selected a target pattern to avoid this issue. While the experimental investigation was not set in an actual wind tunnel, the flexibility associated with the use of a projector and a variety of projection slides should be adequate for any model tested in NASA Langley wind tunnel facilities. While the technique seeks to include the strengths of conventional videogrammetry and PMI, it has several weaknesses regarding target recognition that would prevent its rapid acceptance in real-time applications. Targets near an edge generally require manual intervention for target recognition. Complex model surfaces that contain a significant number of lines, breaks, and holes create a higher probability of inaccurate target matching between images.

Overall, the benefits identified using projected targets are significant when a measurement task requires a completely non-contacting technique. Among the chief benefits noted is the ability to generate full field coverage and to quickly change projection patterns to meet changing test requirements. From a productivity standpoint, the use of dot projection would require a minimum of preparation time. From a data analysis standpoint, the most significant shortcoming of projected targets is the inability to provide time histories of a specific point of interest. However, with the use of external control points the data could be exported to a CAD environment that supports the generation of 3D models with the use of splines created from the photogrammetric data.

Disadvantages of retro-reflective targets are that they must be placed on the test article in prescribed places to describe the motion or position of the surface under observation and the requirement for a closely aligned light source. Often this process can be time consuming or the coverage would be less than desired to fully describe the surface motion without interpolation. While material properties may preclude the use of attached targets for research in various new aerospace programs it is likely that retro targets will remain the standard for conventional model testing in most wind tunnel facilities.

Future Plans

A more detailed investigation of the constraints associated with the use of white light projection on Micro Air Vehicles is planned for the Basic Aerodynamic Research Tunnel at NASA Langley in February 2002. A parallel effort for shape characterization of a 10m solar sail will be conducted in March 2002 in the 16m Vacuum Chamber at NASA Langley. Further laboratory experimental investigations are planned with the use of pulsed light projection sources.

Acknowledgements

The contributions of Mr. Al Burner and Mr. Scott Sealey, NASA Langley Research Center, in the experimental testing of dot projection on the various test articles are greatly appreciated.

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