

Dot-Projection Photogrammetry and Videogrammetry of Gossamer Space Structures

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The technique of using hundreds or thousands of projected dots of light as targets for photogrammetry and videogrammetry of gossamer space structures is documented. Photogrammetry calculates the three-dimensional coordinates of each target on the structure, and videogrammetry tracks the coordinates vs time. Gossamer structures characteristically contain large areas of delicate, thin-film membranes. Examples include solar sails, large antennas, inflatable solar arrays, solar-power concentrators and transmitters, sun shields, and planetary balloons and habitats. Using projected-dot targets avoids the unwanted mass, stiffness, and installation costs of traditional retroreflective adhesive targets. Four laboratory applications are covered that demonstrate the practical effectiveness of white-light dot projection for both static-shape and dynamic measurement of reflective and diffuse surfaces, respectively. Comparisons are made between dot-projection videogrammetry and traditional laser vibrometry for membrane vibration measurements. A promising extension of existing techniques using a novel laser-induced fluorescence approach is introduced.

Introduction

GROUND and in-space testing of future gossamer space structures poses many unique challenges because of their large size and flexibility.¹ Examples of gossamer systems under development include solar sails, large antennas, inflatable solar arrays, solar-power concentrators and transmitters, sun shields, and planetary balloons and habitats.² These structures characteristically contain large areas of thin-film membranes and can be tens or even hundreds of meters in size. They will be compactly folded to fit on existing launch vehicles, expanding in space to many times their launch size.

Photogrammetry is the science of measuring object coordinates with photographs. It offers the simplicity of taking photographs coupled with good to excellent measurement precision.^{3,4} When applied to time sequences of images, it is often called “videogrammetry” instead of “photogrammetry,” although either term is acceptable. Research to develop effective photogrammetry and videogrammetry methods for future gossamer space structures began about three

years ago. Several earlier publications discuss related and complementary aspects of this work.^{5–9}

This paper documents recent experiences at the NASA Langley Research Center (LaRC) using projected dots of light as photogrammetric targets for measuring gossamer systems. These unconventional, membrane-dominated structures can be reflective or transparent, significantly complicating the associated imaging and data analysis problems. References 10 and 11 discuss other applications of dot-projection photogrammetry to more conventional structures, including rigid antennas, door panels, and wind-tunnel models. Dot projection is considered to be primarily a tool for measuring ground test articles, although in-space application is potentially possible as well.

The paper begins by comparing the pros and cons of commonly used retroreflective adhesive targets with those of projected-dot targets for gossamer applications. Next, important membrane reflectivity effects are discussed, followed by brief mention of the equipment used for ground tests. The next section explains what is measured with the dot-projection technique, which can be easily misunderstood. Four laboratory applications are then covered, which demonstrate the effectiveness of white-light dot projection for static shape measurement of both opaque and reflective membranes and for dynamic measurement of opaque membranes, but not reflective ones. (Transparent membranes cannot be measured by standard, white-light dot projection methods.) The paper closes by introducing a promising extension of existing techniques for measuring the shape and dynamics of all types of membranes, including transparent ones, using a novel laser-induced fluorescence approach.

Comparison with Retroreflective Targets

Retroreflective targets reflect light strongly back to the source and appear as bright white dots in images when illuminated from the camera position. They are the “gold standard” targeting method of precision photogrammetry.¹⁰ It is useful to begin by comparing the uncommon dot-projection technique with the commonly used and well-understood retroreflective-targeting technique. Several

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Table 1 Characteristics of retroreflective targets for gossamer applications

Advantages	Disadvantages
<ol style="list-style-type: none"> 1) They are much brighter than other types of targets. 2) They are easily illuminated with a camera flash from long distances and therefore suitable for large structures. 3) They are manufactured to tight tolerances in convenient tape strips or sheets of individual targets. 4) They are suitable for some gossamer spacecraft components, such as support booms. 5) There is excellent contrast between targets and background in underexposed images, which simplifies and improves target centroiding. 6) They are unaffected by test object reflectivity or transmissibility (can measure shiny and transparent membranes). 7) Targets move with the structure, and true three-dimensional deformations at each location are measured. 	<ol style="list-style-type: none"> 1) They add considerable mass and stiffness to ultrathin membranes. (Note: Black borders can add more mass and stiffness than target material itself, but is generally needed for contrast). 2) They are inappropriate for certain delicate measurements such as measuring the size and shape of wrinkles. 3) It is labor intensive to apply, and possibly remove, hundreds or thousands of targets. 4) One cannot change dot size and/or spacing without removing the targets and installing others. 5) Thin membranes can tear if targets are removed. 6) Target thickness (approximately 100 microns) must be accounted for in precision measurement applications.

Table 2 Characteristics of projected-dot targets for gossamer applications

Advantages	Disadvantages
<ol style="list-style-type: none"> 1) They add no mass or stiffness to test article. 2) They require no installation or removal time. 3) One can project 20,000+ targets onto a structure using a single projector and slide (can achieve high dot densities). 4) Dot size and/or spacing can be changed by simply changing slides. 5) One can create custom dot patterns with smaller dots in some regions and larger dots in others. 6) They have no thickness so that coordinates of the dot equal the coordinates of test article. 7) One can measure transparent membranes with special techniques (e.g., laser-induced fluorescence). 8) Projector can be used as another "camera" in data analysis. 	<ol style="list-style-type: none"> 1) They requires exceptionally bright projector for large structures (larger than approximately 5 m). 2) Flash projectors are difficult to use on reflective membranes that might require longer camera exposure settings. 3) Partial dots on membrane edges and folds are marked incorrectly by algorithms assuming an elliptical shape. 4) They might be obscured at certain viewing angles relative to projector. 5) Dot intensity varies with distance and angle from projector. Complicates target centroiding and can reduce accuracy. 6) Targets always move on straight lines either toward or away from the projector. Only can measure this component of motion.

advantages and disadvantages of each method for gossamer applications are listed in Tables 1 and 2. Some of these items are alluded to in this section by example. The others are either self-explanatory or will become clear as four laboratory applications using projected dots are described later in the paper.

Figure 1a shows a 5-m inflatable parabolic reflector with 550 6-mm-diam retroreflective circular targets. They were installed on this ground test article several years ago to measure the reflector shape with photogrammetry. The rms deviation of the surface from an ideal parabolic shape was measured with these targets to be about 1 mm. The targets have never been removed, and it would be difficult to do so now without destroying the reflector. For this reason retroreflective adhesive targets are generally not appropriate for measuring thin-film membranes whenever the targets must be removed afterward. Figure 1b shows two quadrants (one-half) of a 10-m square solar sail with 80 28-mm-diam retroreflective circular targets. It is a pathfinder solar-sail model used for analytical and experimental research and development. Mode shapes of the structure at the target locations were measured with a scanning laser vibrometer. Dynamic response measurements using videogrammetry can also be made with these targets. The static shape of the structure, however, would be inadequately characterized using photogrammetry with these targets because the targets are too large and sparse relative to the wavelength of the wrinkles.

Projected dots of light are an attractive alternative to retroreflective targets for measuring thin-film membrane structures. Figure 2 shows an example of approximately 4000 circular dots projected onto a freely hanging strip of frosted plastic membrane. By taking photographs from two or more directions, the three-dimensional coordinates of the center of each dot can be accurately calculated by photogrammetry. (Reference 7 describes the 10 steps of close-range photogrammetry consistent with the commercial software product that was used for all analyses presented in this paper.¹²) Videogrammetry methods can also use these 4000 targets for dynamic measurements, but generally a subset of the targets would be selected for calculation of motion time histories.

Projected dots offer some obvious advantages over adhesive targets for shape and dynamic measurements of membranes (e.g., thousands of targets can be used without adding mass or stiffness),

but there are some disadvantages as well. For example, on shiny membranes the majority of the projected light will specularly reflect from the surface and not enter cameras located at most viewing angles relative to the projector. This causes significant light intensity variation in the images across the area of the projected dots, complicating the photogrammetric analysis and limiting the attainable measurement accuracy. Modifying the membranes with diffuse coatings or adding laser-induced fluorescent dyes (discussed later) are two possible solutions to this problem.

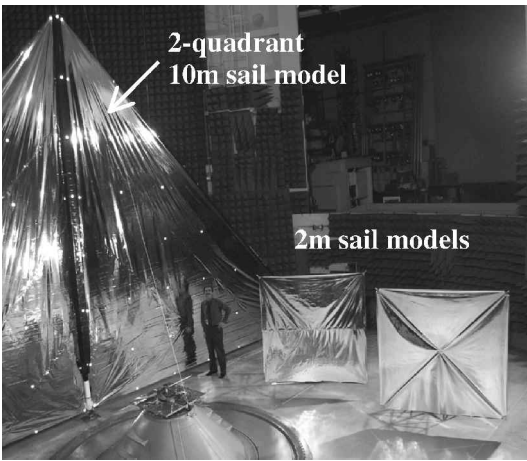
Membrane Reflectivity Effects

Not surprisingly, the reflection characteristics of membrane surfaces directly affect the quality of images measured with the dot-projection technique. Diffuse surfaces are generally best for photogrammetry because light scatters in all directions resulting in more uniform contrast in the images. But in many cases gossamer structures will require reflective or transparent membranes. Reflective surfaces are more difficult to measure than diffuse surfaces for the reason just stated. Transparent membranes are the most difficult of all because projected light passes directly through the material. Note that all membranes have some degree of each of these optical characteristics, that is, membranes are never totally diffuse, totally reflective (specular), nor totally transparent.

Figure 3 shows images obtained by simultaneous dot projection on both shiny and diffuse surfaces using side-by-side pieces of aluminized Kapton® and matte-white Mylar® films. Figure 3a shows the test configuration. The three images in Figs. 3b–3d were recorded using camera exposure times ranging from 2.5 to 20.0 s. For this test the projector was located directly in front of the membranes and the camera was about 30 deg to the left. The target contrast is clearly superior on the matte surface for all exposure settings. On the aluminized surface the target contrast varies significantly within each image and with changes in the exposure time. Variable target contrast of this magnitude complicates, but does not preclude, accurate photogrammetric analysis. With shiny membranes the dot intensity is greatest in the images where the angle of reflection off the membrane is closest to the angle of incidence from the projector. Although both films are tensioned similarly, the Kapton film



a) 5-m inflatable parabolic reflector



b) Scale-model solar sails

Fig. 1 Retroreflective targets on two large gossamer structures.

shows more wrinkling in Fig. 3a than the Mylar film because it is thinner (50 vs 100 microns), but this small difference in surface topology has only a secondary effect on the reflected light patterns in Figs. 3b–3d.

Projectors and Cameras

Figure 4 shows four projectors used during the course of this research. The images presented in Figs. 2 and 3 were obtained with the consumer-gradeslide projector shown in Fig. 4a. It is bright enough for dot-projection photogrammetry of relatively small objects only (e.g., under 2 m). Figure 4b shows a modified projector with a much brighter lamp suitable for slide presentations in auditoriums. This unit will adequately illuminate shiny membranes up to about 3 m in size and diffuse ones up to about 10 m in size. The projector in Fig. 4c is a consumer-grade, 1200-lumendigital projector useful for projecting custom patterns of dots, allowing computer-controlled selection of target sizes, spacing, and positioning. A disadvantage of digital projectors is the pixelation that occurs in the projected dots, causing some reduction in target centroiding accuracy. Figure 4d shows a professional stroboscopic projector manufactured specifically for dot-projection photogrammetry.¹⁰ It uses a high-intensity flash tube that is fired by the camera. Slides with up to 22,500 dots are available for this unit.

Figure 5 shows three principal types of digital cameras used in this research. In Fig. 5a is a consumer-grade, 5-megapixel color camera with a nonremovable zoom lens. Most of the photogrammetry work conducted over the past year used this type of camera. In Fig. 5b is a professional, 6-megapixel monochrome camera that uses interchangeable lenses designed for 35-mm film cameras. This camera was recently acquired and has not been used much to date. In Fig. 5c is a scientific-grade, 1-megapixel monochrome video camera that also uses interchangeable lenses. Images captured by the camera, at up to 15 frames per second, are stored in computer memory during a test and then transferred to individual files or combined into one movie file. Most of the videogrammetry work conducted over the past year used this type of camera. For tests with retroreflective targets, the cameras can be equipped with ring flashes or fiber-optic ring lights to provide uniform target illumination. Each test typically uses two to four cameras of any one type simultaneously.

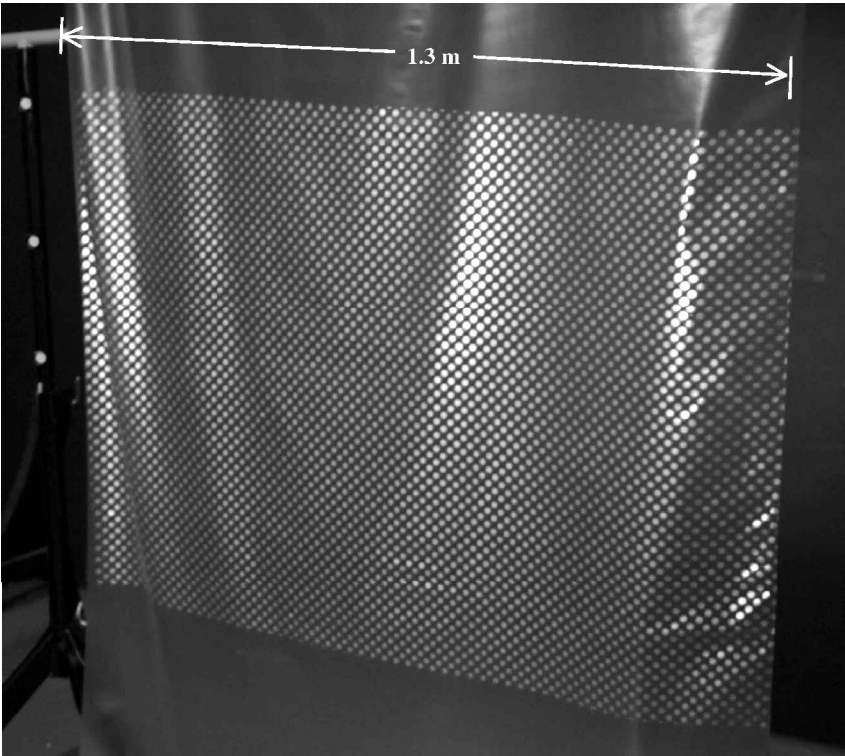
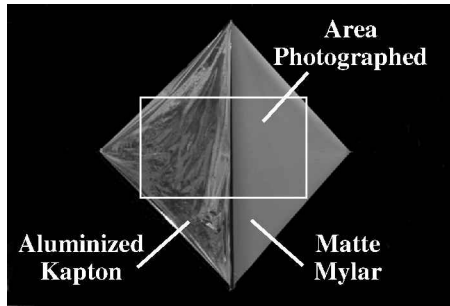
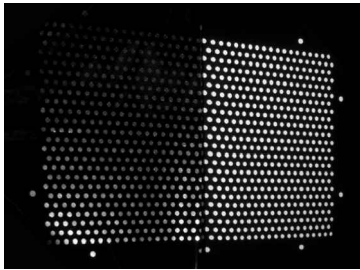


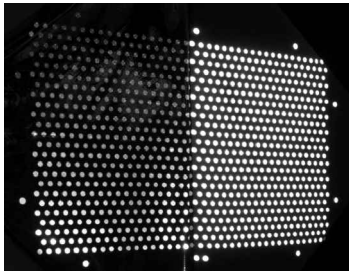
Fig. 2 Approximately 4000 projected dots on a thin-film opaque membrane.



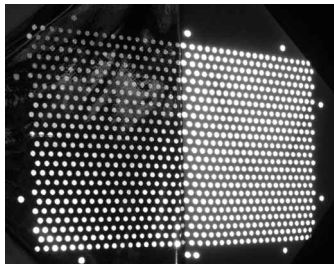
a) Test configuration



b) 2.5-s exposure



c) 8.0-s exposure



d) 20.0-s exposure

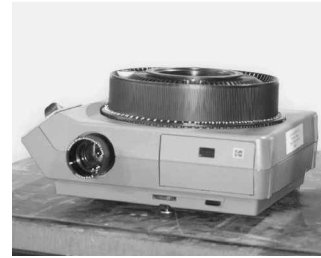
Fig. 3 Comparison of projected dots on adjacent shiny and matte-white membranes at various image exposure settings.

What Is Measured?

It is easy to misunderstand exactly what is being measured with the dot-projection technique. This is particularly true for dynamic measurements made with videogrammetry. This section will clarify any confusion on this topic.

Clearly, the location of each projected dot on a structure matches the location of the underlying surface. The photogrammetric process accurately computes the three-dimensional coordinates of the center (centroid) of each dot at each instant of time.⁷ Thus, photogrammetry generates a set of three-dimensional points, a so-called “point cloud,” defining the shape of the structure at the target locations at any instant of time. For static shape measurements this calculation is performed once. For dynamic measurements the target coordinates are tracked vs time, generating a series of point clouds, and each of these point clouds also accurately defines the shape of the structure at the corresponding instant of time.

However, projected dots do not move with the structure when it vibrates or changes shape in the same way as attached targets do, which



a) Standard Kodak carousel



b) High-intensity carousel



c) Digital projector



d) Stroboscopic projector

Fig. 4 Projectors used in this research.

is typically the point of confusion. This is an important fundamental difference between attached and projected targets for dynamic measurements. An attached target will move in all three coordinate directions with the structure. Videogrammetry calculates x -, y -, and z -direction time histories for each attached target that match the motion of the underlying structure in all three directions. A projected dot, however, can only move along a straight line either toward or away from the projector regardless of how the structure moves. Note that a projected dot on a surface represents the intersection of the surface and a stationary ray of light from the projector. Regardless of how the structure vibrates or changes shape, the intersection point for that dot will always lie somewhere on the same ray of light. With projected-dot targets videogrammetry will again correctly measure the dynamic three-dimensional movement of each target, but in this case the path of each target always follows a straight-line course moving either toward or away from the projector.

An interesting parallel can be drawn with conventional laser vibrometry. In fact, the dynamic information measured by videogrammetry with projected-dot targets is equivalent to that measured by laser vibrometry if the vibrometer is located at the projector position and its “cosine correction” feature is turned off. A laser vibrometer is a universally accepted instrument for measuring dynamic characteristics of thin plates and other structures that vibrate predominantly in

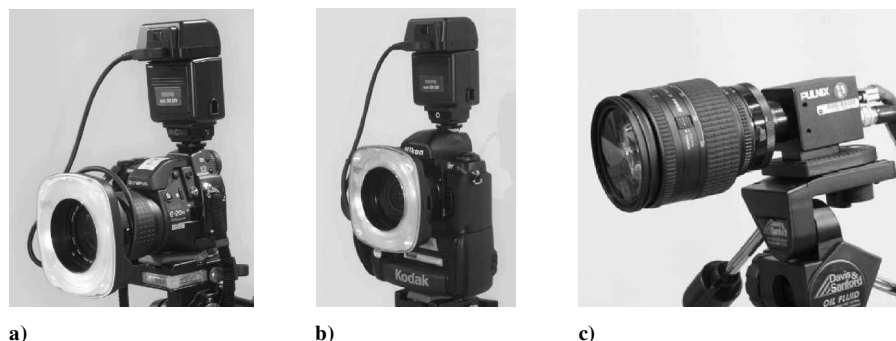


Fig. 5 Digital cameras used in this research: a) consumer digital camera, 2560×1920 pixels, eight units available; b) professional digital camera, 3024×2000 pixels, four units available; and c) scientific video camera, 15 fps, 1008×1018 pixels, four units available.

one direction only (out of plane). A vibrometer also only measures motion along the stationary ray of light extending from the instrument to the intersection point on the surface. A significant difference between laser vibrometry and videogrammetry with projected-dot targets, however, is that vibrometry measures only one point at a time, whereas videogrammetry measures them all simultaneously. Furthermore, laser vibrometry measures only dynamic data (cannot measure the static shape), whereas photo/videogrammetry measures both the static and dynamic structural characteristics.

Application Examples

This section covers four laboratory applications of the dot-projection technique that show the practical effectiveness of this approach. The first two examples illustrate static shape measurement of reflective membrane surfaces (one large measurement area and then one small measurement area) with photogrammetry, and the last two examples illustrate dynamic measurement of diffuse white surfaces (one swinging rigid structure and then one flexible membrane structure) with videogrammetry. Static shape measurement of diffuse (opaque) structures is not covered because it is the simplest case of all, and excellent results are routinely obtained with dot-projection photogrammetric measurement of diffuse objects. Dynamic measurement of reflective surfaces with projected-dot targets has not been successfully accomplished.

Three-Meter Hexapod Membrane Reflector

Figure 6 shows the first of two application examples of dot-projection photogrammetry. The test article is a 3-m-diam, reflective membrane research structure developed for active shape and vibration control experiments.¹³ It is not an actual spacecraft concept, but contains components of proposed inflatable gossamer observatories. Figure 6a shows a front view of this hexapod test article. Both the front and rear surfaces of the tensioned membrane have a shiny aluminum coating. Recall that reflective surfaces are difficult to measure because most of the projected light reflects away from the camera positions. Only a fraction of the light is scattered into the cameras by surface imperfections.

This test used a high-intensity carousel projector designed for auditorium presentations. Two 5-megapixel digital cameras, one on each side and somewhat lower than the projector, photographed the back of the membrane. Figure 6b shows the images obtained of approximately 550 dots projected onto the back surface. Although the surface is shiny, sufficient contrast was obtained in a darkened room using an image exposure time of 30 s. Note that this approach would be inadequate for dynamic tests where much shorter exposure times are required.

Figure 6c illustrates the nonuniform contrast typically encountered with reflective membranes. To calculate the centroid of each dot, photogrammetry software must differentiate the region of the dot from its surrounding area. One way to differentiate is by manually selecting an intensity threshold that is below the intensity of all targets in a specified region of the image but above the intensity of the background. The intensity of each pixel in the image ranges from 0 (pure black) to 255 (pure white). The images in Fig. 6c show

the photograph from the left-hand camera position displayed with binary intensity thresholds of 100, 75, and 50. At a threshold setting of N , all pixels in the image with a gray-scale value (intensity) of N and greater are displayed as white, and all others are displayed as black. These results more clearly show the uneven distribution of light intensities in the image, ranging from the highest intensity in the white regions to the lowest intensity in the black regions.

Nonuniform contrast complicated this step of the data analysis process, but did not prevent an accurate analysis. In this case three successively smaller thresholds were selected, and at each setting additional targets were identified and centroided correctly. Figure 6d shows the resulting three-dimensional point model obtained using the two images in Fig. 6b, viewed from both the front and top of the membrane. The overall static shape was accurately measured, and postprocessing of the data showed an rms deviation from a best-fit plane of approximately 1.0 mm. The dot size used in this experiment is appropriate for measuring the overall shape, but is much too large to characterize any wrinkling that occurs, such as near the tensioned boundary or along seams.

The rms measurement precision in this application was 0.289 mm, corresponding to one part in 10,380 for a 3-m test article. Calculation of photogrammetric measurement precision is a standard byproduct of the least-square bundle adjustment algorithm used to process the images.^{3,4,12}

Two-Meter Aluminized Kapton Solar Sail

Figure 7 shows the second application of dot-projection photogrammetry. This example demonstrates the capability of close-range photogrammetry to measure distributed, small-amplitude wrinkles on a lightly tensioned reflective membrane. The exact shape of the wrinkles can change easily with slight air currents or other environmental disturbances, and so it would be exceedingly difficult to measure this information by any other means. The test article is a 2-m square solar sail model (the length of each side is 2 m) shown in Fig. 7a. This sail model, also seen near the center of Fig. 1b, is one of several pathfinder gossamer structures at LaRC used for analytical and experimental research and development.¹⁴ The membrane for this structure consists of two strips of aluminized Kapton, similar to the hexapod reflector material in the previous example, seamed together horizontally. Membrane wrinkling, caused by the discrete corner tension loads, the seam, and gravity, is abundant.

A grid of approximately 5000 dots was projected onto the area indicated in Fig. 7a, which is about 1.0×0.5 m in size. Four cameras photographed the dot pattern simultaneously in this test. The cameras were located approximately at the corners of the area of interest pointing toward the center of the area. The orientation angle between cameras was about 90 deg in both the horizontal and vertical directions. Several sets of photographs were taken in a darkened room at different shutter speeds. The set selected for processing used a 30-s image exposure time, which provided the best contrast between the projected white dots and the aluminized Kapton background.

An accurate model of the membrane surface was obtained by analyzing these images. The results, consisting of over 5000

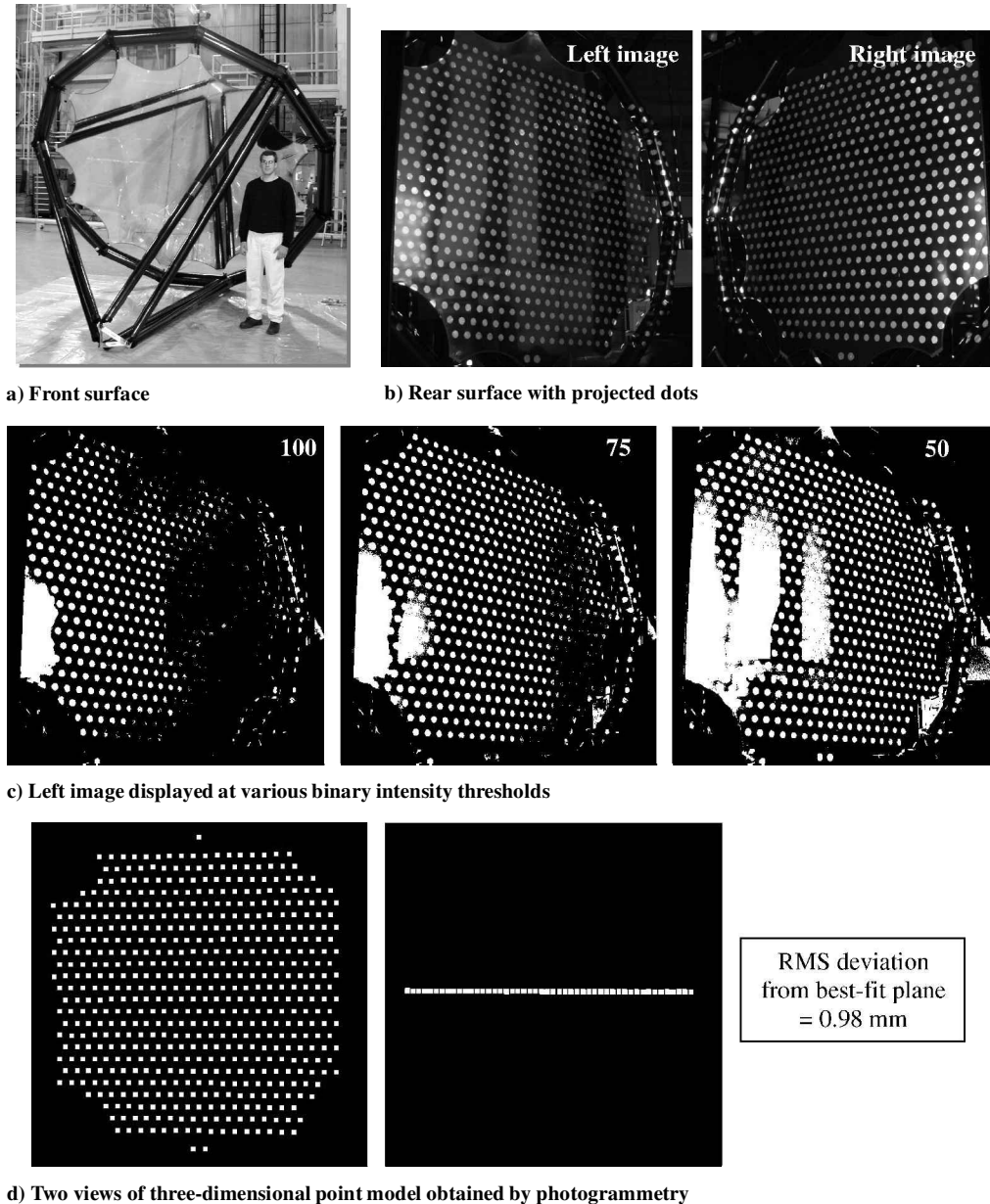


Fig. 6 Photogrammetry of 3-m hexapod membrane reflector using approximately 500 projected dots.

three-dimensional points, are displayed as a relief map in Fig. 7b and as a corresponding contour plot in Fig. 7c. These maps, normally used for displaying topographic land features, clearly illustrate the visible wrinkles in the Kapton membrane and the seam cutting horizontally across the center. The maximum wrinkle amplitude was approximately 1 mm zero to peak, and the rms photogrammetric measurement precision (calculated by the software) was 0.096 mm.

0.6-Meter Oscillating White Plate

Figure 8 shows the first of two application examples of dot-projection videogrammetry. This application is a proof-of-concept test conducted to compare videogrammetry results for the same structure using both projected dots and then retroreflective adhesive targets.¹⁵ Figure 8a shows the test article, which is a 0.6×0.6 m rigid plate of white, laminated pressboard suspended by two 2-m-long strings. The strings allow it to swing freely between two stationary reference plates mounted on stands. A long-stroke shaker connected to the bottom edge of the plate by another string slowly moved the plate back and forth sinusoidally at 0.1 Hz (10-s period). A repetitive, steady-state motion of approximately 12-cm zero-to-peak amplitude was achieved before any image acquisition occurred.

A grid of dots was projected onto both the swinging and stationary plates with a small Kodak slide projector. Two synchronized digital video cameras mounted on tripods recorded the motion, and Fig. 8b shows a typical pair of images. Excellent target contrast was obtained with both cameras by underexposing the images. A sequence of 200 frames was recorded at a sampling rate of five frames per second, corresponding to four cycles of the repetitive motion. These images were processed using commercial videogrammetry software.¹²

Figure 8c shows the videogrammetrically determined out-of-plane motion of a target located near the bottom of the swinging plate. These results are exactly as expected. The plot shows four cycles of steady sinusoidal motion with a zero-to-peak amplitude of about 12 cm. Recall that videogrammetry with projected-dot targets accurately measures the true three-dimensional shape of the test object at every instant of time, but that each target will always move on a straight-line path either toward or away from the projector. Consequently, the dots "slide over" the structure if it has any in-plane component of motion. Therefore, from the perspective of each camera (i.e., in the image planes) the observed path of motion of every projected dot is always a straight-line segment, and this is exactly what was measured in this test of a swinging plate.¹⁵ For structures such as this (i.e., move primarily in one direction),

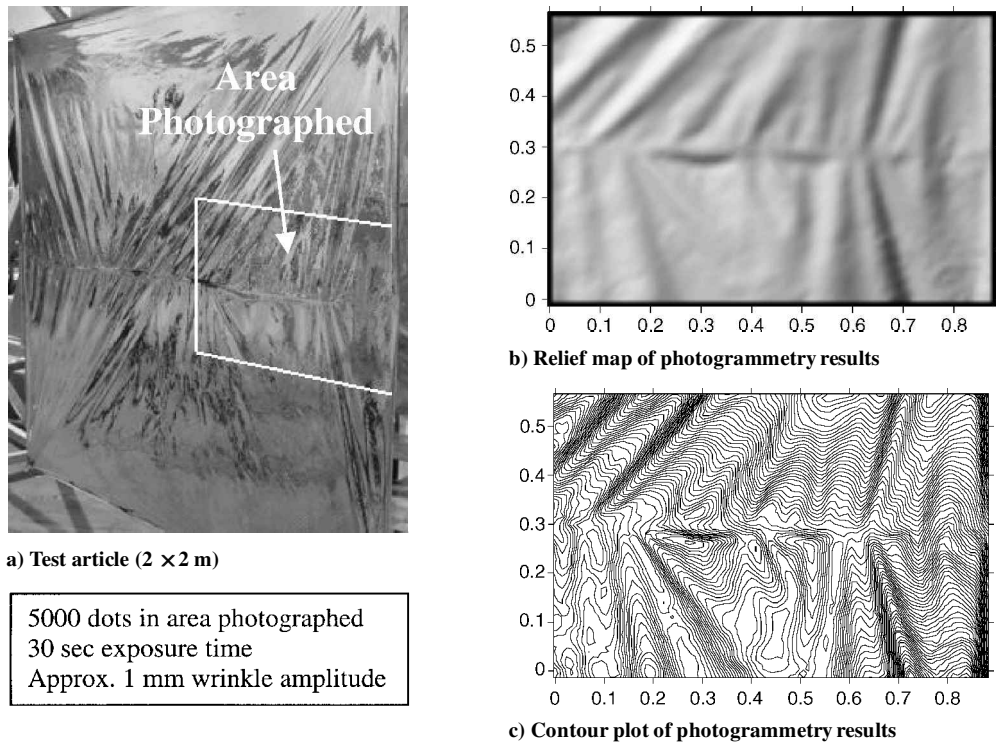


Fig. 7 Photogrammetry of 2-m aluminized Kapton solar sail using approximately 5000 projected dots.

there is little difference between the measured straight-line target trajectories and the true curved trajectories of the object.

Figure 8d shows the videogrammetrically determined time history of a projected-dot target located on one of the stationary sidepieces. These results have an rms value of 0.01 mm, which indicates the measurement noise floor achieved in the test. Therefore, the signal-to-noise ratio of the measurement shown in Fig. 8c is 12,000:1 or 82 dB.

Reference 15 provides a detailed comparison of videogrammetric three-dimensional measurements of the 0.6-m oscillating plate using traditional retroreflective targets (on the front side of plate) vs projected-dot targets (on the back side of the plate). Figure 8e shows the measured motion of the plate at three instances of time using both types of targets, indicating excellent quantitative agreement of the two sets of results.

Two-Meter Matte Solar-Sail Quadrant

Figure 9 shows the second application of dot-projection videogrammetry. The test article is one quadrant of a four-quadrant 2-m solar-sail model constructed with matte-white Mylar (vellum) membranes. The test objective was to compare laser vibrometry and videogrammetry results for this flexible membrane structure using the same set of measurement points. Vellum is not a realistic solar-sail material, but was installed here solely to simplify making comparative measurements with these two optical techniques. Figure 9a shows the test article, the grid of approximately 50 targets measured by both techniques, and the location of the scanning laser vibrometer. The projected dot pattern was designed by computer to match the vibrometry measurement locations, and it was displayed using a digital liquid-crystal-display projector. There are also 10 retroreflective targets located on the two adjacent support rods that were also measured in both tests.

The laser vibrometer was positioned approximately 3 m back from the structure with its axis perpendicular to the membrane surface. It was aligned to point at the center of the quadrant in its zero position (i.e., where the elevation and azimuth angles of the steering mirrors for the laser beam were both zero). A standard vibration test was then conducted using random excitation of the lower-right corner of the sail with an attached electrodynamic shaker. Frequency response functions (FRFs) from 0 to 10 Hz

between the membrane surface velocity measured with the vibrometer and the applied force were computed by the vibrometer system for all measurement points. Using six ensemble averages, each FRF measurement required about four minutes to obtain, so that the total test duration to measure all points was about four hours. Figure 9b shows the mode at 3.34 Hz calculated by processing these FRFs with commercial modal analysis software.¹⁶

Immediately after the vibrometry test finished (with the shaker still running at the same operating level), the digital projector was turned on, and a sequence of images was acquired using two video cameras. This videogrammetry test recorded 384 frames of data at 15 frames per second for a total test duration of about 25 s. All measurement points are recorded simultaneously with videogrammetry rather than sequentially as with scanning laser vibrometry, so that the test duration can be much shorter. These images were processed with the same videogrammetric analysis software used in the preceding oscillating-plate application. From the resulting time histories response spectra were computed instead of FRFs because the current video system could not make a synchronized force measurement. Figure 9c shows the mode at 3.47 Hz calculated by processing these spectra, and it shows good agreement with the corresponding vibrometry result.

When animated, the two modes in Figs. 9b and 9c look nearly identical, so that they are clearly the same flexible mode of the structure. There are some small amplitude differences, however. Three known factors contributing to these differences are as follows: First, the long duration of the laser vibrometry test (four hours) gave the opportunity for small changes in room temperature or humidity to affect the tension in the test article. Out-of-plane membrane stiffness depends largely on the in-plane stress distribution, which might have changed somewhat over this time interval. Second, for modal analysis the vibrometry test used traditional response/force FRFs, whereas the videogrammetry test used (time-synchronized) response spectra instead. This difference caused some variation in the corresponding estimated modes. Third, the laser vibrometer system performed a standard cosine correction of all measurements made at nonperpendicular directions to the membrane surface, whereas the videogrammetry measurements are uncorrected (but could be in future tests if the projector location relative to the test object is quantified either in a separate photogrammetric test

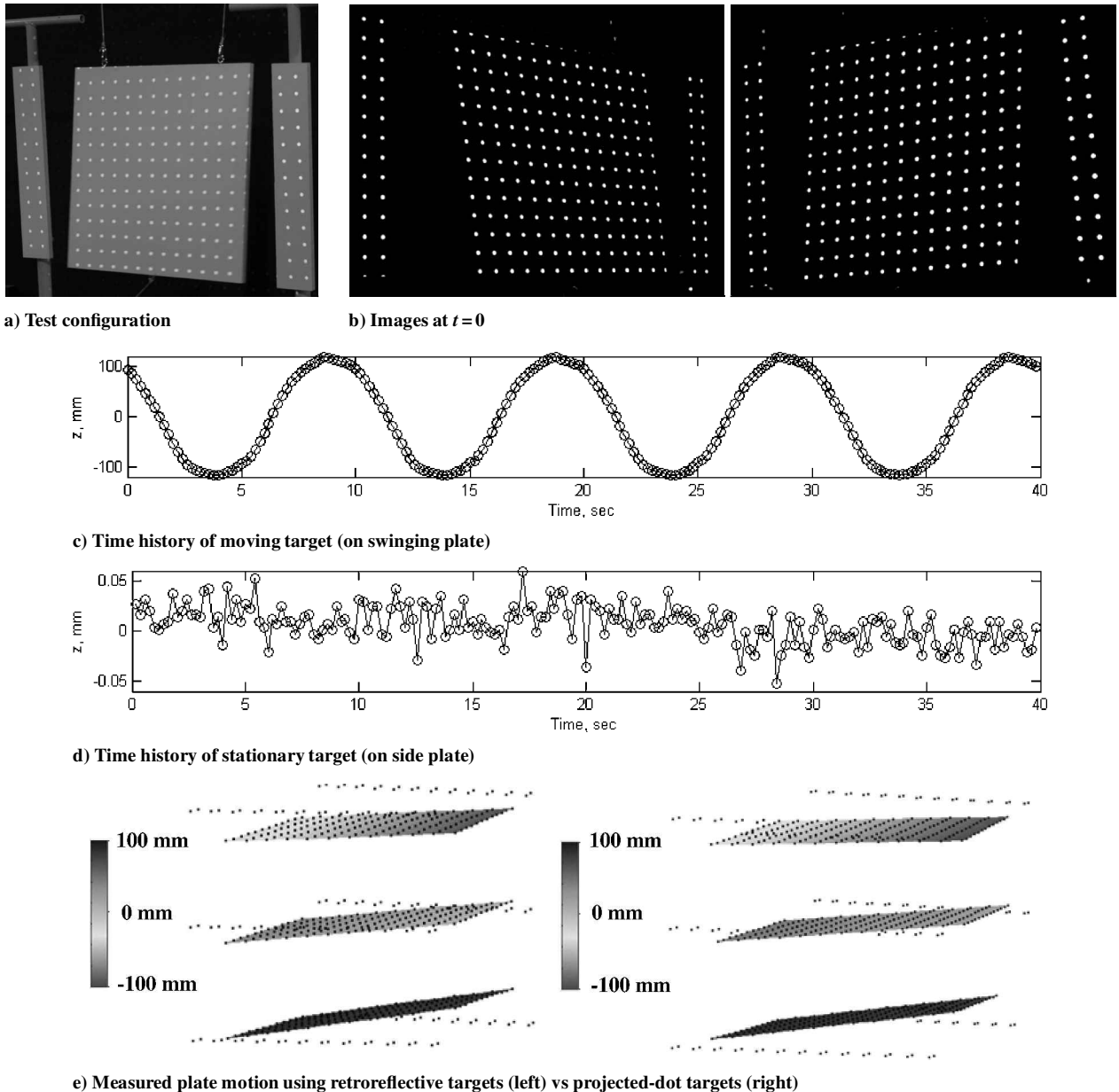


Fig. 8 Videogrammetry of 0.6-m oscillating white plate using approximately 200 projected dots.

or by treating the projector as an additional camera within the photogrammetric procedure).

Laser-Induced Fluorescence

As already discussed, transparent and reflective membranes are difficult or impossible to measure with standard white-light-dot projection because the majority of the projected light passes directly through the membrane (in the transparent case) or is reflected in undesirable directions (in the reflective case). Consequently, images with sufficiently high contrast are difficult to obtain. The images recorded to date with dot projection on reflective membranes required long image exposure times, making dynamic measurements impossible. To overcome these problems, transparent membranes have been manufactured containing a small quantity of fluorescent laser dye. When excited with a laser light source, the dye absorbs a fraction of the laser energy and consequently fluoresces at a longer wavelength. This fluorescence is emitted in all directions providing a significantly more predictable and repeatable dot pattern that can be viewed from any angle.¹⁷

Figure 10a shows the test configuration for a proof-of-concept demonstration of this proposed new approach for dot-projection

photogrammetry and videogrammetry of membranes. Figure 10b shows the test article, which is a small sample of dye-doped CP-2 polyimide membrane wrapped around the top of a white cardboard tube. Note the almost transparent nature of the material. The membrane was illuminated with a laser-generated dot pattern using a 2-mW green (544-nm) helium-neon laser and a diffractive beam splitting element. Figure 10c shows a typical digital photograph taken with a low-pass optical filter placed in front of the camera. The filter blocks the reflected green laser light but allows the orange fluorescence light from the membrane dye to pass through. Note that laser speckle is not a problem because photographs are taken of the self-generated (orange) dots of light and not the directly reflected (green) dots of light from the laser.¹¹ Using several images taken at other viewing angles, an accurate three-dimensional model of the membrane, shown in Fig. 10d, was obtained.

Note that the bottom portion of the membrane with the white cardboard backing produces spots in Fig. 10c that are almost four times brighter than for the membrane without a backing. This is because the laser energy is scattered by the cardboard and passes through the polymer a second time, effectively doubling the laser (and hence fluorescence) intensity. The fluorescence emitted backward is also scattered by the cardboard and becomes visible from

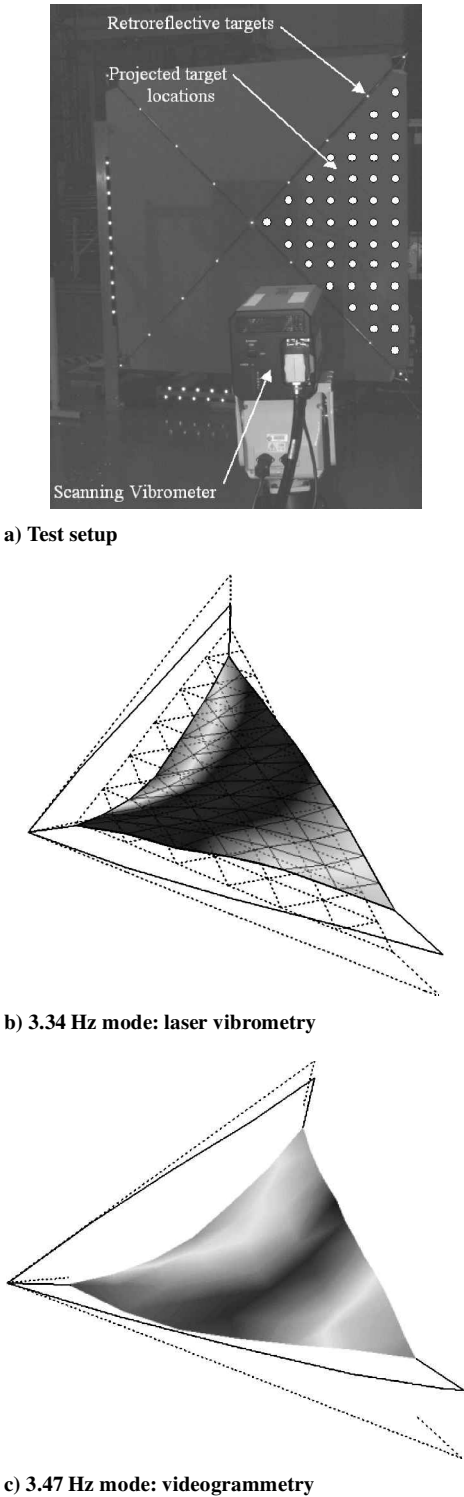
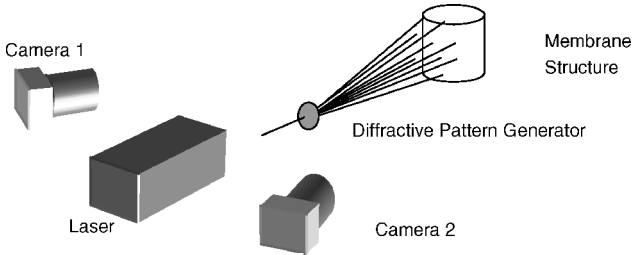


Fig. 9 Videogrammetry of 2-m matte-white solar sail quadrant with approximately 50 projected dots and comparison with corresponding laser vibrometry mode.

the front. A similar increase in brightness is expected for doped transparent membranes that have a reflective back coating, such as a solar sail. The bright spot in the center of the pattern is caused by the nondiffracted zero-order laser energy from the diffractive beam splitter.

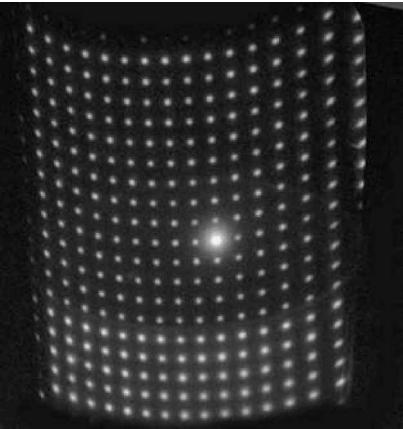
Experimentation continues with pulsed laser systems that will potentially allow acquisition of images at video frame rates and hence will provide the capability to make dynamic measurements of dye-doped transparent and reflective membranes that are currently impossible with white-light dot projection systems.



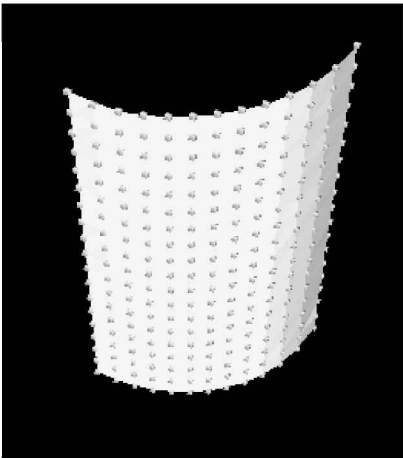
a) Test configuration for proof-of-concept experiment



b) Transparent CP-2 + dye



c) Fluorescence from laser dot projection



d) Three-dimensional surface by photogrammetry

Fig. 10 Laser-induced fluorescence for dot-projection photogrammetry of transparent membranes.

Conclusions

Commonly used retroreflective adhesive targets provide high-contrast images for photogrammetry and videogrammetry. However, when attached to delicate, thin-film membranes of gossamer structures, their mass and stiffness can significantly alter the structural properties. Furthermore, retroreflective targets are time consuming to apply, cannot be easily moved, and are potentially damaging to the structure, especially if they must be removed after testing. On the other hand, using projected dots of light as targets has no effect whatsoever on the structure. Dot projection also has the advantage that the location, density, and size of the dots can be easily and quickly changed, enhancing measurement capability.

This paper gave a comprehensive summary of the technology of dot-projection photogrammetry and videogrammetry, especially as it applies to the measurement of membrane structures. A detailed comparison of projected-dot targets and retroreflective adhesive targets for gossamer applications was provided in summary tables. The paper also explained what is measured with the dot-projection technique, something that is easily misunderstood especially for structural dynamic measurements. An important conclusion is that the dynamic information measured by videogrammetry with projected-dot targets is the same as that measured by scanning laser vibrometry if the vibrometer is located at the projector position and its cosine correction feature is turned off. Four laboratory applications demonstrated the effectiveness of white-light dot projection for static shape measurement of both opaque and reflective membranes and for dynamic measurement of opaque membranes.

A novel laser-induced fluorescence approach was introduced that complements and in some ways exceeds the proven capabilities of the white-light dot projection method. This approach requires doping the membrane material with a small amount of fluorescent laser dye during its manufacture (or perhaps spraying or painting it on afterward). When illuminated with a laser, the fluorescing dye emits light in all directions at a lower frequency than the light source. By using an optical low-pass filter on the camera, high-contrast targets are obtained even on transparent membranes. Coupled with the use of high-power pulsed lasers, this approach can be an enabling technology for making both static and dynamic measurements of the largest anticipated gossamer ground test articles (perhaps up to 30–50 m in size) that will be built in the foreseeable future.

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