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Laser-Induced-Fluorescence Photogrammetry for Dynamic Characterization of Membrane Structures

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Photogrammetry has proven to be a valuable tool for static and dynamic profiling of membrane-based inflatable and ultralightweight space structures. However, the traditional photogrammetric targeting techniques used for solid structures, such as attached retroreflective targets and white-light dot projection, have some disadvantages and are not ideally suited for measuring highly transparent or reflective membrane structures. In this paper, we describe a new laser-induced-fluorescence-based target generation technique that is more suitable for these types of structures. We also present several examples of noncontact noninvasive photogrammetric measurements of laser-dye doped polymer membranes, including the dynamic measurement and modal analysis of a 1 m × 1 m aluminized membrane.

Introduction

GOSSAMER structure research has reached the stage where measurements of the surface profile and dynamic behavior have become an integral part of the design process. Furthermore, measurements of both ground-test and in-flight structures are essential for continued gossamer development. Photogrammetry is the science of calculating three-dimensional spatial coordinates from multiple two-dimensional photographs. It has proven to be a valuable tool for acquiring these types of measurements. It offers the simplicity of taking photographs coupled with high measurement precision of up to one part in 100,000 or higher.[1] Videogrammetry is the extension of still-camera photogrammetric principles to time sequences of images and is useful for capturing dynamic behavior.

Current practices for photogrammetric measurements of gossamer structures use either attached retroreflective targets or white-light dot projection. Retroreflective targets provide excellent high-contrast images, but suffer from disadvantages associated with physically attaching targets to the structure.[2] White-light projection is an alternative that offers the advantage of noncontact measurement, thereby eliminating the problems associated with attached targets. It works well on diffuse material because, by definition, the projected light is scattered in all directions allowing the acquisition of high-contrast images from any viewing angle. However, gossamer structures are often manufactured from highly transparent or specularly reflective aluminum-coated materials that provide little diffuse scattering, which in turn causes difficulties when attempting to photograph projected targets.[2] There are two major disadvantages of white-light projection for these applications. The first is the appearance of hot spots caused by direct reflections of illumination sources. Second, it requires very long exposure times, limiting its use to static measurements.

Laser-induced-fluorescence (LIF) target generation has recently been demonstrated as a viable alternative technique for photogrammetric target generation.[2–4] This method uses LIF to generate diffuse-like scattering that allows image acquisition with fast shutter speeds and high imaging rates and does not suffer from the disadvantages associated with either attached retroreflective or white-light projected targets. To date, LIF target generation has been studied and applied to polymer membranes doped with laser dye to aid the LIF process.

In this paper we first introduce and contrast LIF target generation with traditional retroreflective and white-light projection methods. We then present four demonstrations of noncontact photogrammetric profiling of dye-doped polymer membranes using the LIF targeting technique. Both static small-amplitude wrinkle mapping and dynamic characterization are demonstrated for transparent and aluminized reflective membranes, including a 1 m × 1 m square aluminized membrane. These demonstrations highlight the advantages of the LIF-based technique, and in some cases measurements are performed that have previously been unobtainable.

Photogrammetry and Traditional Photogrammetric Targeting Techniques

Photographic images are the result of a perspective projection of a three-dimensional object onto two dimensions. Consequently, two or more photographic images can be reverse engineered to derive the three-dimensional shape of the original object. This process is called (close-range) photogrammetry, and the solution provides a quantitative relationship between a three-dimensional object and the two-dimensional images acquired by the cameras.[5]

Accurate photogrammetric measurements require the photography of high-contrast surface features that appear in at least two images. However, many objects commonly measured do not naturally exhibit such features. Traditionally, retroreflective targets are painstakingly attached to the object to artificially provide these high-contrast features.

Retroreflective targets work exceptionally well and have very few drawbacks when used on solid structures. However, even though they have been used on gossamer structures providing excellent results,[6–8] they introduce several undesirable effects when used on gossamer membrane structures. The primary concerns are added mass and altered stiffness, which in turn alter and mask the true characteristics of the structures. Furthermore, once affixed, the pattern of attached targets cannot be changed, and the targets are very difficult or impossible to remove because of the delicate nature of the membrane material.[2] An alternative solution is to project the target

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pattern on the structure, thereby providing a completely noninvasive photogrammetric measurement.[2]

Projected dot patterns provide good results with diffuse surfaces because light is scattered in all directions, and the projected pattern can be viewed and photographed over a wide viewing angle.[9] However, when applied to gossamer structures difficulties arise because the membrane material is usually either highly transparent or reflective (aluminum coated). In both cases, there is very little diffusely scattered light because the majority of light passes directly through a transparent membrane or is specularly reflected off an aluminized membrane. Consequently, exposure times as long as 30 s are required to obtain sufficient contrast images from white-light illuminated aluminized membranes.[2] These long exposure times prohibit the use of white-light projection for dynamic studies and limit its application to static measurements. Furthermore, no measurements of white-light illuminated transparent membranes have been reported.

A further complication arises with photogrammetric observations of reflective structures, using either the retroreflective or projected targets method, is the appearance of glints or hot spots. These hot spots are areas of bright illumination on the image that is generated as a direct reflection of the camera flash or other unrelated source such as room lights. Hot spots act to reduce the contrast of targets, or in many cases completely occlude the targets, in a localized region of the image rendering these targets unusable.[8]

Laser-Induced-Fluorescence Target Generation

LIF is a process of inelastic scattering in which a portion of incident laser light is absorbed by a material (solid, liquid, or gas) and is then emitted at a longer wavelength. (In optical physics, inelastic scattering is the scattering process in which there is a change of photon energy and hence wavelength. This is opposed to elastic scattering where there is no change in energy or wavelength.) Many materials exhibit the phenomenon, but some are explicitly designed to utilize and optimize it. One example of such an optimized material is laser dye, which is usually dissolved in methanol and used as the optical gain medium in dye lasers.

To utilize LIF as a mechanism to generate diffuse-like scattering in transparent polymer membranes, small quantities of Rhodamine 590 laser dye (Exciton, Dayton, Ohio) have been added to the membrane during their manufacture. When these dye-doped polymer membranes are subjected to laser radiation at or near 532 nm, they fluoresce and emit light in all directions, allowing high-contrast images to be obtained from almost any viewing angle.

Our previous research investigating the photophysics of laser-dye-doped membranes has proven their suitability for photogrammetric target generation.[4] In particular, the fluorescence emission pattern was found to afford a wider viewing angle than diffuse scatter from white-light projected targets. The laser-dye doped into the membrane was also found to have a substantial useful lifetime, specifically in excess of 200 min of continual operation at a frame rate of 25 Hz. In addition, the fluorescence temporal decay time was found to be in the order of nanoseconds. This is several orders of magnitude faster than high-speed photography exposure times and hence well within the limits required for dynamic videogrammetry.

To generate a fluorescing photogrammetry target pattern, an array of laser beams is projected onto the structure being studied, as shown in Fig. 1. A diffractive optical element (DOE) (Stocker Yale, Montreal, Canada) is employed to split a single laser beam source into the required beam array. The resulting fluorescing target pattern is then photographed by two or more cameras and processed with standard photogrammetry software. We use the term laser-induced-fluorescence photogrammetry (LIFP) to describe this procedure.

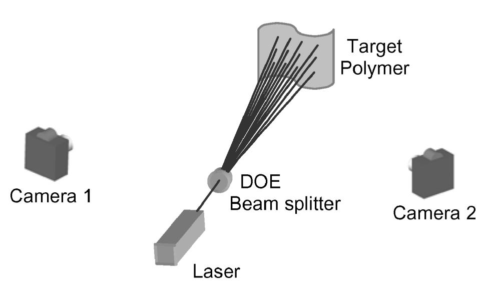


Fig. 1 LIFP principle.

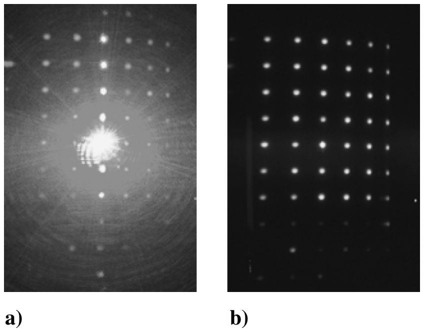


Fig. 2 Transparent dye-doped polymer membrane fixed to a reflective cylinder simulating an aluminized membrane illuminated with a laser dot pattern. Photographed without a filter showing a glint (a), and the same illumination with filter blocking laser light, eliminating the glint, and showing only laser-induced fluorescence (b).

An optical filter is used in front of the camera to remove any stray laser light and prevent any hot spots that might otherwise be observed. The effectiveness of this filter is clearly illustrated in Fig. 2, which shows a dye-doped polymer membrane attached to a reflective surface illuminated with a 7×7 laser spot pattern and photographed with and without the optical filter. In the unfiltered image a reflection of one laser beam enters the camera directly causing a massive hot spot that renders the image completely useless. With the filter installed, the hot spot is eliminated, and all targets are visible. For a more in-depth discussion regarding filter selection and photophysics of the dye-doped polymer membranes, see Dorrington et al.[4]

Measurement Demonstration

To illustrate the effectiveness of laser-induced-fluorescence-based photogrammetric profiling, several measurement examples will now be presented. These demonstrations include both a high-spatial-resolution static measurement and a larger-scale dynamic measurement for the two cases of transparent and aluminized films.

Static Wrinkles in a Transparent Membrane

Transparent membranes have so far proven impossible to measure with white-light projection techniques, which fail to generate sufficient diffuse scatter from the membrane to provide suitably high-contrast images. LIF target generation can, however, provide noncontact target generation in dye-doped transparent membranes. Our group has recently reported an experiment designed to demonstrate the ability of LIF-based photogrammetry to measure small-amplitude wrinkles in a transparent membrane.[3] This experiment will now be summarized here for completeness.

The experimental setup closely follows the principle shown in Fig. 1. The article being measured is a 12-in. (304-mm)-diam circular transparent dye-doped polymer membrane, manufactured by SRS Technologies (Huntsville, Alabama), stretched over a hoop to provide near uniform tension. This hoop has been compressed in one direction to induce small wrinkling.

A low-power, 2-mW green (543.5 nm) helium neon (He–Ne) laser was used as the illumination source. Its beam passes through a diffractive optical element producing a 19×19 grid over the surface of the membrane. Figure 3 shows a typical image of this dot pattern on the membrane. The image is slightly overexposed to clearly show the membrane and support ring. Images used for photogrammetric processing are optimized for highest-contrast dot pattern. The size, density, and arrangement of the target pattern can be easily adjusted to fit any test article, with additional optics. Furthermore, the lower-intensity second- and higher-order diffractive dots visible around the edges of the 19×19 pattern can be eliminated with spatial filtering if required.

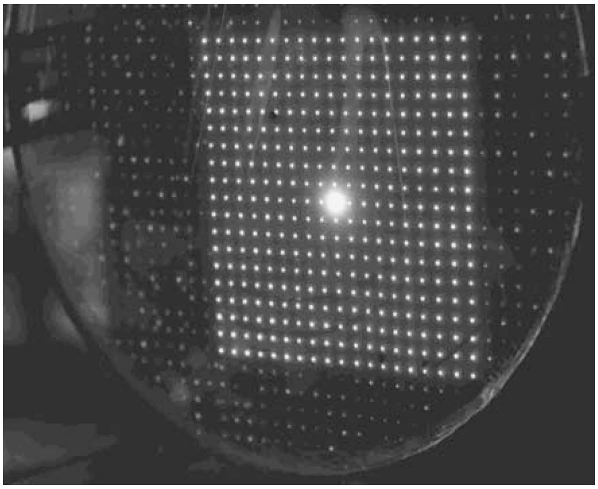


Fig. 3 Fluorescent target pattern on tensioned transparent dye-doped membrane.[3]

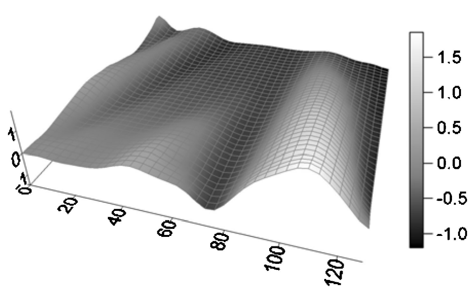


Fig. 4 Shaded relief map overlaid with wire-frame model of wrinkles in compressed membrane. Note the clearly visible nature of the wrinkles despite the low amplitude in the order of 2 mm (all dimensions in millimeters).

In this example, the target has a high-intensity center spot (180 times brighter than any other spot) that is a result of using an inexpensive off-the-shelf DOE that was designed for operating at a different wavelength (670 nm). Some of the experiments described next use similar DOEs, but later experiments use a custom-manufactured DOE designed for the correct wavelength. Our custom-manufactured DOEs include patterns with either a center spot of the same intensity as the rest of the pattern, or three times brighter for identification purposes.

Photographs were taken from four different viewing angles with a professional grade six-megapixel Kodak DCS 760M camera fitted with a Kodak #22 Wratten Gelatin filter to block the laser light. This camera was calibrated to determine all camera parameters and lens distortions prior to performing the measurements. The images were processed in Photomodeler® (EOS Systems, Vancouver, British Columbia, Canada) software to calculate three-dimensional coordinates for each target in the pattern, which were plotted in Fig. 4 using the Surfer® software package (Golden Software, Inc., Golden, Colorado).

This surface plot clearly shows the ability of the system to distinguish small-amplitude wrinkles in the membrane, in the range ± 1.5 mm, with a good signal-to-noise ratio. Noncontact photogrammetric measurement of wrinkles in aluminized membranes has been demonstrated before at a similar level of detail,[8] but no such measurements of transparent membranes have been reported.

Dynamics of a Transparent Membrane

The preceding example demonstrated the ability to perform static measurements on a transparent membrane, which were previously unobtainable using white-light projection techniques. This capability is now developed one step further, and a demonstration of a dynamic measurement is presented.

For dynamic measurements the preceding experimental setup is changed in several ways. The illuminating laser was replaced with a Nd:YAG pulsed laser source producing 10-mJ pulses at variable repetition rates up to 30 Hz. For dynamic studies, the pulsed laser is much more appropriate than the continuous-wave (CW) laser because of its very short pulse time and high peak power output. The pulsed laser also provides more average power than the CW laser, but this is not its primary advantage. During the static measurements, exposure times of several seconds could be used to combat low fluorescence intensity levels. For dynamic studies, however, short exposure times and short laser pulses are needed to avoid motion blur.

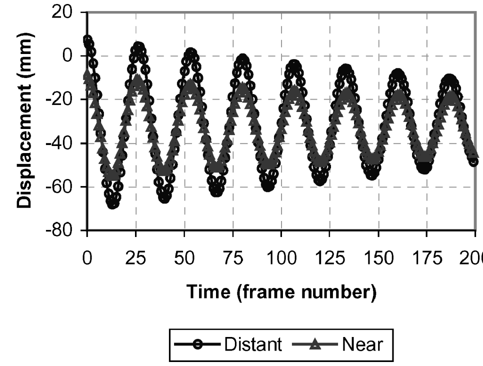


Fig. 5 Displacement of targets along the axis of pattern projection.

The Nd:YAG laser used in this experiment achieves these goals with a 10-ns pulse time, which also allows the camera shutter time to be set at a level that rejects background room light illumination. For comparison, one pulse from the Nd:YAG laser contains an the same number of photons found in a 5-s exposure using the He-Ne laser described earlier.

The still camera used in the previous experiment was replaced with two Pulnix TM-7610 video cameras attached to a PC computer fitted with digital video acquisition cards. The laser pulse rate and video camera acquisition rate were controlled and synchronized with a Stanford Research Systems (Sunnyvale, California) pulse generator Model DG535.

The test structure was formed by mounting a dye-doped transparent polymer membrane on a card frame suspended from a bar. Weights were attached to the bottom of the frame, and the membrane was allowed to swing back and forth freely. Just prior to initiating image acquisition, the weights were lifted and released to induce a swinging motion. Two-hundred images were then acquired at a rate of 25 fps, covering approximately seven full swing cycles and processed in the Photomodeler Video software.

Figure 5 shows the computed displacement along the axis of pattern projection for two targets over time. The exponential swing amplitude decay can be seen on this plot, along with the differences in amplitude between two targets; one near the pivot axis and one at the maximum distance from the pivot axis.

From a modal analysis perspective, a more interesting motion is observed when the membrane and frame are excited by an impulse at the bottom center between the weights, and more than one vibration mode can be observed. Such an excitation was employed in a second experiment using this setup. As with the first experiment, 200 image frames were acquired using the same equipment and processed in the same way.

Figure 6 shows the displacement of one target in both the time and frequency domain, which clearly shows two dominant modes. The first is a short-lived bending oscillation at 3.18 Hz that settles into a more steady 0.94-Hz swinging mode. The reasons for the bending and swinging labels is apparent in Fig. 7, which shows a plot of displacement amplitude at these specific frequencies. The bending mode has a maximum amplitude in the bottom center of the structure and is induced directly from the impulse excitation at that location. However, this mode decays leaving a swinging mode that has an amplitude that varies in the vertical direction only and is proportional to the distance from the pivot axis.

Although this modal analysis is very basic, it suffices for the purposes of demonstrating the capabilities and potential of the

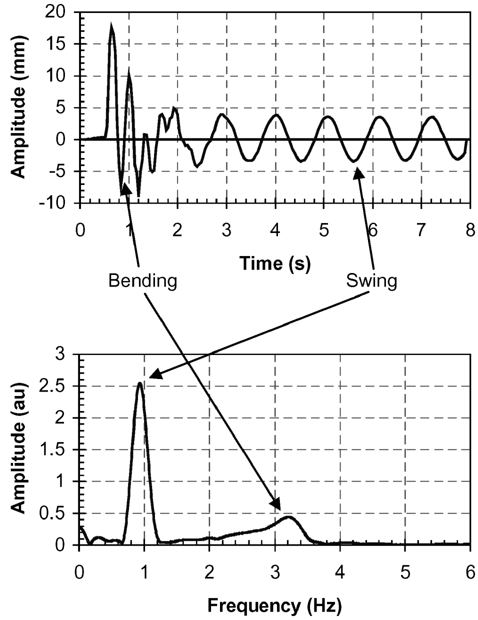
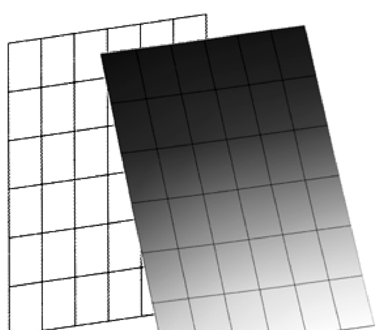
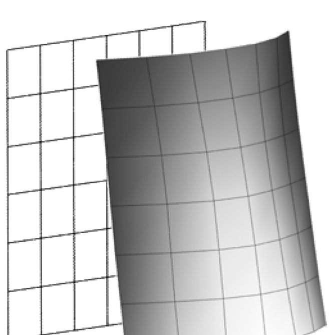


Fig. 6 Displacement of impulse excited transparent polymer membrane in time and frequency domains. Notice the short-lived bending mode and the slowly decaying swinging mode.



a) 0.94-Hz swinging mode



b) 3.18-Hz bending mode

Fig. 7 Mode shapes across the measured area of the transparent membrane with reference to the stationary (planar) shape.

measurement system. A more sophisticated modal analysis could be performed with the same acquired data, but it is not warranted in this case because we are not attempting to learn anything relating to the structure's properties.

Static Wrinkles in an Aluminized Membrane

Because many gossamer space structures are aluminized for radiation protection, and in the case of solar sails, for thrust generation, the just-demonstrated measurements must be adapted for aluminized membranes. If the membrane is aluminized on only one side, LIFP measurements can be performed from the noncoated side. This actually offers the advantage of increased fluorescence intensity when compared to a transparent membrane (for a given illumination power and dye concentration).[4] The increase in observable fluorescence intensity for aluminized membranes is caused by reflections of both the laser and fluorescence light off of the membrane's aluminum back coating. Firstly, after passing through the membrane once the laser is reflected by the aluminum coating and passes through the membrane a second time. This effectively doubles the illumination intensity causing a corresponding increase in generated fluorescence. Secondly, the fluorescence that would normally propagate in the direction of illumination and away from the observer is reflected by the aluminum coating back toward the observer, causing a further increase in detected fluorescence.

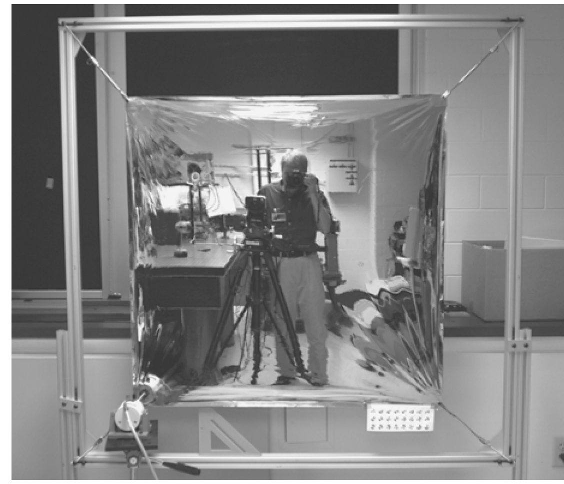


Fig. 8 Photograph of 1-m dye-doped polymer membrane suspended in tension frame.

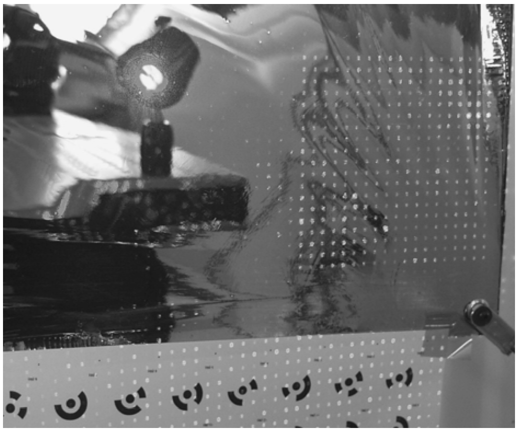
To demonstrate the LIFP technique on aluminized membranes, we used a 1 m × 1 m membrane made from dye-doped CP1™ polymer and aluminized on one side only (SRS Technologies, Huntsville, Alabama). The membrane was reinforced on the edges, and eyelets were placed in the corners to allow suspension in a tensioning frame, as illustrated in Fig. 8. Tension was applied unevenly in the diagonal directions to encourage the formation of wrinkles in the corners. These wrinkles were then measured with a similar experimental setup described earlier for the transparent membrane wrinkle measurements.

The area of measurement coverage can be seen in Fig. 9a, which also shows part of the projection setup reflected in the membrane. The fluorescence is not evident in this image because it is swamped by the ambient light and incident laser light. It is also apparent from this image that the laser-projected spots are of insufficient quality (because of inconsistent shape and contrast) to be used as photogrammetric targets. An image of the same area viewed through an optical filter (and with the room lights off), Fig. 9b, shows the significantly superior quality of the fluorescent targets. In these images, a set of coded targets is also visible below the membrane, which were used to help automate the photogrammetric processing and provide a scale reference. As always, the cameras were calibrated with the laser-blocking optical filter in place.

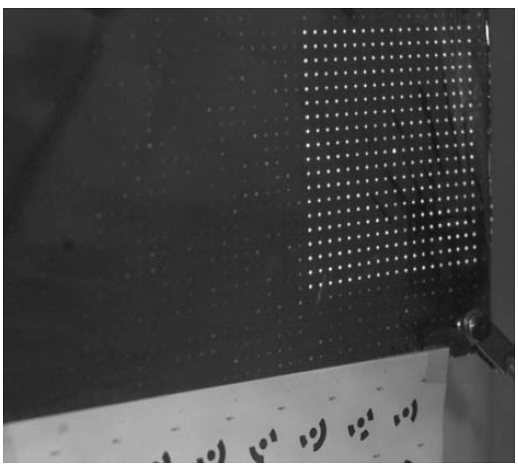
Six images were acquired and processed to generate a three-dimensional model representation of the wrinkled surface, shown in Fig. 10. The model agrees qualitatively with observations of the membrane surface and is of sufficient quality to clearly show wrinkles with amplitudes as low as 200 μm peak to peak. These results demonstrate the potential of LIFP to perform high-precision detailed examinations of (dye-doped) aluminized polymer membranes.

Dynamics of an Aluminized Membrane

To demonstrate the capability of LIFP to be used for dynamic characterization of aluminized structures, the 1-m membrane was also the subject for dynamic measurements using a slightly modified version of the experiment setup used for the transparent membrane



a)



b)

Fig. 9 Photographs of the 19 × 19 laser array projected onto the corner of the 1-m membrane. Both a) an unfiltered image and b) a filtered image showing only LIF are shown.

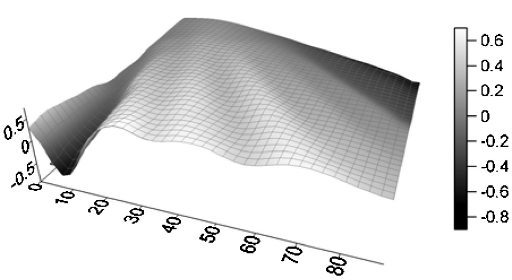


Fig. 10 Computer model of the surface wrinkling compiled from laser-induced fluorescence photogrammetric data (scale in millimeters). The back corner was nearest to the eyelet.

dynamic measurements. The membrane was then excited with a shaker driven by a random signal, and video data were acquired at a rate of 20 frames per second.

The captured video data were processed to provide out-of-plane displacement data, which were then processed further to determine vibrational modes. A spectral plot of the displacement averaged over every measurement point, shown in Fig. 11, reveals several vibration modes. Four of the modes were chosen for further examination, and their mode shapes (shown in Fig. 12) were reconstructed from the phase and amplitude information obtained from a fast Fourier transform of each measurement point. A more rigorous modal analysis could be performed, but in this case is not warranted because the purpose is once again to demonstrate the measurement capability and not to obtain specific information about the structural characteristics.

Although noncontact static measurements of aluminized membranes have been performed in the past,[8] no dynamic measurements have yet been reported. This is because the long exposure times required for white-light dot projection methods prohibited dynamic measurements.

Measurement Precision

The precision obtained can be estimated by observing the apparent movement of stationary targets. In the dynamic measurement of the aluminized 1-m membrane, several stationary laser-induced-fluorescent targets (both attached to and independent from the support frame) were used to establish a coordinate reference and scale. The image plane centroid data for these targets have been analyzed to determine the scatter in centriod determinations, which can be compared to other target generation techniques.

Table 1 details the 3σ uncertainty (99% confidence level) in the image space for each static target viewed by each of three cameras in the three-dimensional object space. The majority of these uncertainty values are well below one-tenth of a pixel. Furthermore, the average uncertainty in the X dimension is 0.055 of a pixel and in the Y dimension 0.068 of a pixel, ignoring the outlier of target 1 on camera 3. These values are comparable with other targeting techniques[10]; hence, the laser-induced-fluorescence target

Table 1 3σ standard deviations of static target image plane coordinates (in pixels for both X and Y dimensions, and millimeters for three-dimensional displacements) measured in the aluminized 1-m membrane dynamic experiment

		Target number				
Dimension	Camera	1	2	3	4	5
X dimension, pixels	1	0.045	0.072	0.077	0.051	0.042
	2	0.045	0.069	0.062	0.041	0.038
	3	0.044	0.043	0.095	0.064	0.043
Y dimension, pixels	1	0.037	0.169	0.069	0.042	0.030
	2	0.041	0.038	0.057	0.077	0.040
	3	1.319	0.109	0.117	0.098	0.034
Three dimensions, mm	——	0.702	0.312	0.241	0.582	0.354

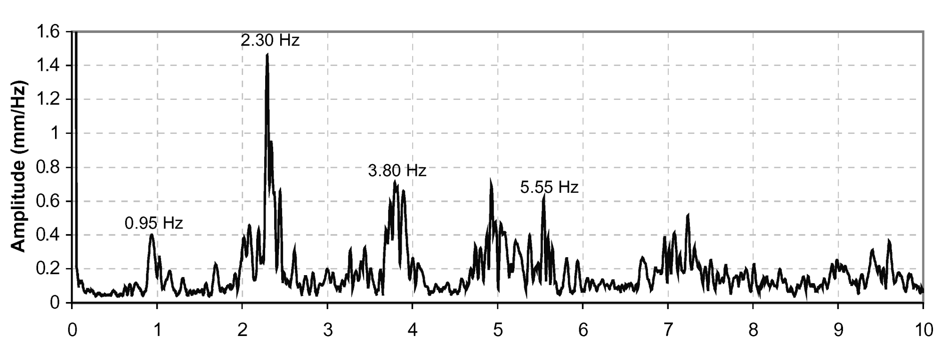


Fig. 11 Spectrum of out-of-place displacement for randomly excited 1-m membrane averaged over every measurement point.

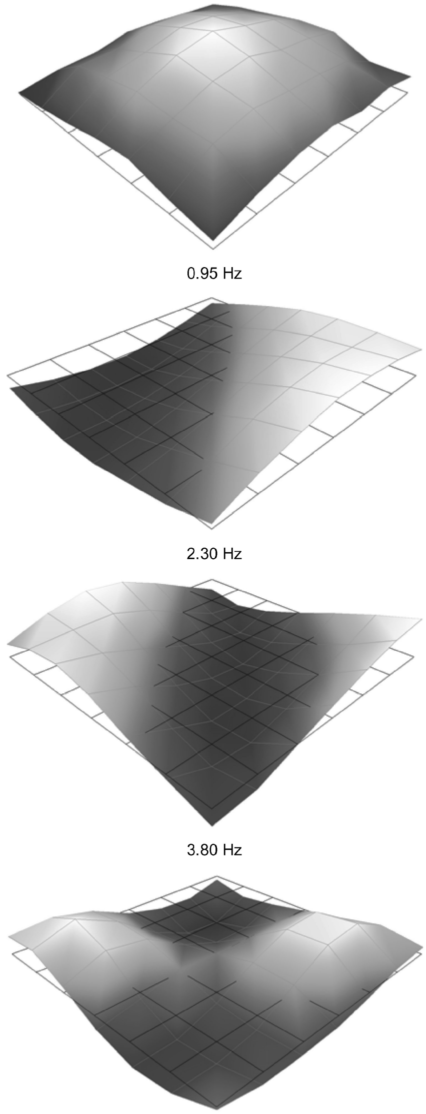


Fig. 12 Selection of mode shapes obtained from random excitation of the 1-m aluminized dye-doped polymer membrane. The membrane was driven from the left corner.

generation process itself does not appear to contribute any significant additional uncertainty. In the object space, the average uncertainty of the stationary targets is 0.44 mm, which equates to a depth accuracy of approximately 1/6000th of the average sensor to object distance. This three-dimensional precision is comparable to the 1 in 10,000 depth accuracy previously published.[1]

Conclusions

We have summarized a new laser-induced-fluorescence photogrammetric target generation technique that has significant advantages over traditional targeting techniques when applied to gossamer space structures. Several demonstrations of the new target generation technique have been presented that illustrate its capability to perform both dynamic measurements and detailed high-resolution surface profiling with precisions comparable to other photogrammetric measurements. The capabilities to measure transparent membranes and the ability to perform noncontact dynamic measurements of both transparent and aluminized membranes have not been previously reported and are significant advantages of the new techniques over traditional techniques. Beyond the requirement for the structures to be manufactured with embedded laser dye and the need for a relatively bulky laser source, there are no disadvantages of the new technique compared to traditional dot projection. Further development and refinement of the technique is required for application to larger structures, but no fundamental limitations are envisaged for structures an order of magnitude larger.

Acknowledgment

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References

[1]Gruen, A., "Development of Digital Methodology and Systems," *Close Range Photogrammetry and Machine Vision*, 1st ed., Whittles Publishing, Caithness, Scotland, U.K., 2001, Chap. 4.

[2]Pappa, R. S., Black, J. T., Blandino, J. R., Jones, T. W., Danehy, P. M., and Dorrington, A. A., "Dot-Projection Photogrammetry and Videogrammetry of Gossamer Space Structures," *Journal of Spacecraft and Rockets*, Vol. 40, No. 6, 2003, pp. 858–867.

[3]Jones, T. W., Dorrington, A. A., Brittman, P. L., Danhey, P. M., "Laser Induced Fluorescence for Photogrammetric Measurement of Transparent or Reflective Aerospace Structures," Instrumentation, Systems, and Automation Society, 49th International Instrumentation Symposium, Paper IIS03-P024, Research Triangle Park, NC, May 2003.

[4]Dorrington, A. A., Jones, T. W., and Danehy, P. M., "Laser-Induced Fluorescence Photogrammetry for Profiling Gossamer Space Structures," Optical Society of America, Conf. on Lasers and Electro-Optics 2003, Paper CThR2, Washington, DC, June 2003.

[5]Burner, A. W., and Liu, T., "Videogrammetric Model Deformation Measurement Technique," *Journal of Aircraft*, Vol. 38, No. 4, 2001, pp. 745–754.

[6]Pappa, R. S., Giersch, L. R., and Quagliaroli, J. M., "Photogrammetry of a 5m Inflatable Space Antenna with Consumer-Grade Digital Cameras," *Experimental Techniques*, Vol. 25, No. 4, 2001, pp. 21–29.

[7]Dharamsi, U. K., Evanchik, D. M., and Blandino, J. R., "Comparing Photogrammetry with a Conventional Displacement Measurement Technique on a Square Kapton Membrane," AIAA Paper 2002-1258, April 2002.

[8]Pappa, R. S., Jones, T. W., Black, J. T., Walford, A., Robson, S., and Shortis, M. R., "Photogrammetry Methodology Development for Gossamer Spacecraft Structures," AIAA Paper 2002-1375, April 2002.

[9]Jones, T. W., and Pappa, R. S., "Dot Projection Photogrammetric Technique for Shape Measurements of Aerospace Test Articles," AIAA Paper 2002-0532, Jan. 2002.

[10]Black, J. T., and Pappa, R. S., "Videogrammetry Using Projected Circular Targets: Proof-of-Concept Test," *Proceedings of the 21st International Modal Analysis Conference* [CD-ROM], edited by A. L. Wicks and R. Singhal, Society for Experimental Mechanics, Bethel, CT, 2003.

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