Videogrammetry Using Projected Circular Targets: Proof-of-Concept Test

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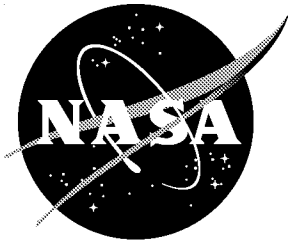
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ABSTRACT

Videogrammetry is the science of calculating 3D object coordinates as a function of time from image sequences. It expands the method of photogrammetry to multiple time steps enabling the object to be characterized dynamically. Photogrammetry achieves the greatest accuracy with high contrast, solid-colored, circular targets. The high contrast is most often effected using retro-reflective targets attached to the measurement article. Knowledge of the location of each target allows those points to be tracked in a sequence of images, thus yielding dynamic characterization of the overall object. For ultra-lightweight and inflatable gossamer structures (e.g. solar sails, inflatable antennae, sun shields, etc.) where it may be desirable to avoid physically attaching retro-targets, a high-density grid of projected circular targets – called dot projection – is a viable alternative. Over time the object changes shape or position independently of the dots. Dynamic behavior, such as deployment or vibration, can be characterized by tracking the overall 3D shape of the object instead of tracking specific object points. To develop this method, an oscillating rigid object was measured using both retro-reflective targets and dot projection. This paper details these tests, compares the results, and discusses the overall accuracy of dot projection videogrammetry.

INTRODUCTION

The science of videogrammetry expands the methods and techniques of close-range photogrammetry and applies them to a sequence of images to generate time history data. Photogrammetry is defined as the process of making precise measurements of an object from photographs of that object [Ref. 1]. Using high contrast retro-reflective targets, static shape characterizations of ultra-lightweight and inflatable (gossamer) test articles, such as solar sails and inflatable antennae, have been achieved in previous work at the NASA Langley Research Center (LaRC) [Ref. 2]. The measurements were used to create three-dimensional models of those gossamer structures. Videogrammetry produces a time-history of these 3D models. The generated time-response data can then be used for such tasks as modal analysis and to track deployment.

The term "gossamer" is applied to a particular class of spacecraft designed to minimize launch weight and volume [Ref. 3]. These structures must therefore be tightly packaged for launch, subsequently deploying or inflating once in space. Many, such as solar sails, will use ultra-thin membranes – three microns in thickness or less – as main components to achieve areal densities of less than 10 grams per square meter [Ref. 4]. The combination of the weight minimization requirement and the inherent fragility of such structures necessitates that alternatives to physically attached retro-reflective targets be explored. Projected circular targets (dot projection) is one of these alternatives. A target pattern created using dot projection instead of physically attached retro-reflective targets eliminates the mass, stiffness, and attachment time of potentially thousands of targets that would be affixed to the inherently large – greater than 60 square meters [Ref. 5] – gossamer structures, while still providing the high contrast required for quality photogrammetric and videogrammetric measurements [Ref. 6]. Projected fields of dots may also be customized to any density or size, providing greater flexibility than attached targets [Ref. 7].

This paper will detail work at LaRC using a simple swinging plate to develop and validate the dot projection

videogrammetry technique by direct comparison with traditional retro-reflective target videogrammetry.

TEST SETUP

Figure 1 shows the setup used to validate the dot projection technique for dynamic measurements. A square 24-inch plate of white, laminated pressboard was suspended by two six-foot-long strings, allowing it to swing freely between two 4 x 24 inch pressboard pieces mounted on stands. The plate was attached via another string to a long-stroke electrodynamic shaker set to approximately a 10-inch stroke with a 10 second period. The plate swung back and forth between the two stationary 4 x 24 inch pieces with the same 10-second period of the shaker. Two synchronized Pulnix TM-1020-15 digital video cameras (CCD: 1008 x 1018 pixels, 9.072 x 9.162 mm, Removable lens: 24 – 85 mm, f/2.8 – f/22, Up to 15 frames per second) shown in Figure 2 mounted on tripods recorded the motion.

On one side of the 24-inch square plate and 4 x 24 inch side pieces, strips of retro-reflective tape (Fig. 3) consisting of 0.25 inch diameter targets spaced two inches apart were affixed to create a 22 x 22 inch grid of 124 dots on the plate and a 2 x 22 inch grid of 24 dots on each of the side pieces (Fig. 4(a)). Fiber optic lights illuminated the targets (Fig. 3) providing the necessary high contrast target field. The opposite sides of the plates were left blank creating an ideal diffuse white surface for the dot projection portion of the experiment, as shown in Figure 1. A consumer slide projector (Fig. 1) projected a grid of dots that covered the square plate and side pieces yielding a 22 x 22 inch grid of 169 dots on the square plate and a 2 x 22 inch grid of 26 dots on each of the side pieces (Fig. 4(b)).

DATA ACQUISITION

The test was repeated for two separate target conditions: one using the retro-reflective tape and the other using dot projection. As stated above, the Pulnix cameras recorded the oscillating plate system, creating sequences of digital images used in the videogrammetric analysis. At a sampling rate of five frames per second, the data acquisition yielded a set of 200 images over 40 seconds (four cycles) for each camera position. Figure 5 shows examples of images taken by the upper right camera. Figure 5(a) was recorded during the illuminated retro-reflective target test and Figure 5(b) during the dot projection test. In both cases high contrast was achieved between the white targets and the measured object, creating an optimum condition for

photogrammetric and videogrammetric measurement [Ref. 6].

Around the perimeter of the square plate in Figures 4(b) and 5(b), several of the dots appear cut-off. In the dot projection portion of the experiment a stationary projector created the field of targets, meaning that the plate moved independently of those targets. As the plate moved, the targets on the edges slipped in and out of visibility depending on the point in the cycle, as is the case with the top row and right column in Figure 5(b). Because these points are not visible in all the images, they were not processed at any time step.

At the time this test was conducted, only two video cameras were available. Acquiring four synchronized image sequences using two cameras required allowing all transient motion to damp out of the oscillating plate system. The resulting data acquisition recorded only the constant and continuous (steady state) forward and back movement. The combination of the plate moving at a constant 10 second period and the data acquisition being computer controlled enabled each capture sequence to be initiated at a precise time (point in the cycle). The two cameras were then moved to different positions and a second synchronized set of data was gathered, initiated at exactly a multiple of 10 seconds (cycle time) after the first, yielding synchronized image sequences from four vantage points. The cameras were spaced approximately 90 degrees apart to provide equal measurement precision in all three coordinate directions [Ref. 6].

VIDEOGRAMMETRY

The videogrammetric processing was performed using a beta version of the PhotoModeler Pro 5.0 software from Eos Systems [Ref. 6]. The software loads multiple sequences of images, associating each with the correction parameters unique to the particular camera with which the images were recorded. The correction parameters were obtained when both cameras used in the data collection were calibrated using the Camera Calibrator supplied with the software. This procedure, described in detail in Reference 8, calculates the focal length, location of the principal point, the radial lens distortion, and the decentering lens distortion of each camera. Using these parameters, the software automatically removes any distortions of the images due to aberrations in the cameras or lenses, enabling accurate measurements.

The initial images for each of the four sequences – corresponding to the initial time step labeled epoch 0 – were

processed exactly as a stand-alone project would have been. The targets were marked to sub-pixel accuracy (see Reference 8) in all the photos, and the corresponding points (i.e. the calculated centers of the targets) referenced (matched) across the photos. After approximately eight targets had been marked and referenced, the bundle adjustment algorithm simultaneously computed the camera locations and orientations as well as the point location and precision values. After the photographs were oriented, an automatic marking tool marked the remaining targets, preceding the use of an automatic referencing tool that matched the corresponding points across all of the photos. The bundle adjustment was subsequently run again, updating and iterating on the orientations and exact 3D locations of the marked and referenced points. Finally, a scale and an axis were defined. All of the steps described above, at any point in the process, may be repeated one or more times to ensure the highest accuracy in the final result, which is a "point cloud" forming a three-dimensional model of the photographed object. Figure 6 shows the generated 3D view of the completed retro-reflective target project. The camera locations and orientations (approximately 90 degrees apart as discussed above) have been correctly calculated by the software, as have the 3D coordinates of the target points. Reference 8 describes in much greater detail the photogrammetric process and the exact functioning and use of the software.

The above paragraph describes the photogrammetry procedures for an entire static project. As stated previously, however, this is only one step in the videogrammetric process. After the static photogrammetric calculations of the first time step (epoch 0) are successfully completed, it is necessary to expand those same calculations to the remaining time steps. PhotoModeler Pro 5.0 contains a "Tracking" function that tracks the marked targets in the first epoch through all of the subsequent epochs. Essentially, the program overlays the point coordinates from the previous epoch onto the current epoch in the tracking process. Around each of the point locations from the previous epoch it searches for another target in a user-specified radius. When a new target is located and marked, the algorithm assigns to the new point the same identification number as the point in the previous epoch, thereby creating motion of the target from one epoch to the next. Continuing in this manner, the tracking algorithm searches through all the epochs, automatically locating, marking, and matching targets while maintaining point numbers identical to the original epoch. The result is a single set of points with three-dimensional coordinates for each of the recorded time steps. These coordinates can then

be exported in ASCII format as a list of points with corresponding X, Y, and Z coordinates at each time step.

VALIDATION

The ASCII time history data for both conditions were animated using the ME'Scope commercial software to show the square plate swinging past the two stationary rectangular pieces as displayed in Figure 7. To allow for better visualization, the images have been rotated 90 degrees. The bottom image shows the plate at its closest position to the cameras, the middle image shows the plate at the mid-point of its cycle, and the top image shows the plate at its farthest position from the cameras. The animation captured in Figure 7(a) was generated using data from the retro-reflective target condition. For comparison, Figure 7(b) shows the same animated sequence using projected dots.

A graphical validation of the dot projection method may be accomplished by visually comparing the two animation sequences generated from the time series data. Figures 7(a) and 7(b) show the same three time steps from the two animations, which appear virtually identical. This is sufficient to demonstrate that the overall 3D shape of an object, in this case a flat plate, can be tracked over time as it moves relative to a stationary field of projected targets without knowledge of the exact location of any specific point on that object.

Figure 8 provides another form of graphical validation. The two images show the movement of the left-most column of points plotted over the entire test. As expected, the individual points form lines that trace the paths followed by the targets over the cycle. It would also be expected that the physically attached targets would move with the plate in an arced manner through the sequence of images, similar to the path of the tip of a pendulum. Careful examination of Figure 8(a) reveals that the paths of the retro-reflective targets are, in fact, curved upwards as expected. Conversely, it would be expected that, in the case of the plate oscillating approximately parallel to a field of stationary projected targets, the displacement of the points in the X-Y plane created by the image (image plane) would be much less than the displacement of the points in the Z-direction (normal to the image plane, toward or away from the projector). Imagine holding a piece of paper in front of a projector. The image on the paper will displace in the Z-direction with the paper as it is moved toward or away from the projector; however, moving the paper up, down, right or left in the X-Y plane will not change the location of the image. It will remain stationary as the paper moves.

Therefore, it would be expected that the plotted paths of the points in Figure 8(b) would be straight lines. Examination confirms the fact that each point only moves along the straight line from the point to the projector, not along a curved path with the plate.

Figure 9(a) shows the motion of two points over time in the retro-reflective test condition. The first graph (left) describes the lower left point on the swinging plate. Its motion over the image sequence is as expected: a sine wave that repeats four times, corresponding to the shaker input. The second graph (right) shown in Figure 9(a) is a stationary point on the left sidepiece. Figure 9(b) graphs the same two points using dot projection data. The lower left point on the swinging plate (left) again moves in the same periodic sine wave as the shaker, and the stationary point (right) remains still. The scatter displayed in the graphs of the stationary points in Figures 9(a) and 9(b) provides an indication of the random noise and uncertainty of the measurement method. In both conditions, the videogrammetric method is precise to less than one-tenth of a pixel.

Figures 7, 8, and 9 demonstrate that dot projection data produces results that are qualitatively comparable to retro-reflective target data. Figure 10 demonstrates the validity of dot projection videogrammetry at a quantitative level. The swinging plate used for these tests was chosen for its ease of characterization, not for its flatness. Figure 10 shows that, in fact, the plate is slightly bowed in the middle by approximately 0.035 inches. Estimates calculated by the software indicate the videogrammetric data is precise to approximately 0.0015 inches; therefore, a curvature of 0.035 inches is, while not easily visible to the eye, accurately characterized by both photogrammetry and videogrammetry. Figure 10(a) was generated using data from the retro-reflective test while Figure 10(b) used dot projection data. To enable both test conditions to be run in succession, opposite sides of the same plate were used. It was simply flipped over after one set of data was completed. Therefore, if the plate is bowed 0.035 inches during the retro-reflective test, the same bow should be visible in the opposite direction when it is flipped for the dot projection test. The dot projection data in Figure 10(b) does show an inverse curve to the retro-reflective data in Figure 10(a) of the same magnitude. This indicates that the dot projection results are in excellent quantitative agreement with retro-reflective target results. Given the accuracy and the capacity of dot projection videogrammetry to define and model the overall 3D shape at a particular time step (Figure 10(b)), those 3D shapes can then be animated over all of the

time steps to produce the desired time-response data [Ref. 9].

CONCLUSIONS

Videogrammetry is an important tool in the dynamic characterization of ultra-lightweight and inflatable space structures. Traditional videogrammetry relies on physically attached retro-reflective targets that may not be suitable in gossamer applications due to the added mass, stiffness, and attachment time of the targets. The experiment detailed above validates videogrammetry using projected circular targets (dot projection) as an alternative to retro-reflective targets by directly comparing the two methods. Dot projection measured the same 0.035 inch curvature of an oscillating plate as was measured using retro-reflective targets, and proved capable of tracking the three dimensional shape of that plate over time. The resulting dynamic data was identical to that generated using retro-reflective targets. Specific, but certainly not limited, to gossamer structures with predominantly out-of-plane dynamics, dot projection videogrammetry proved a robust and flexible alternative to traditional retro-reflective target videogrammetry.

ACKNOWLEDGEMENTS

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Figure 1 – Test Setup

Figure 2 – Pulnix TM-1020-15 monochrome digital video camera

Figure 3 – Retro tape and targets un-illuminated (top) and illuminated (bottom)
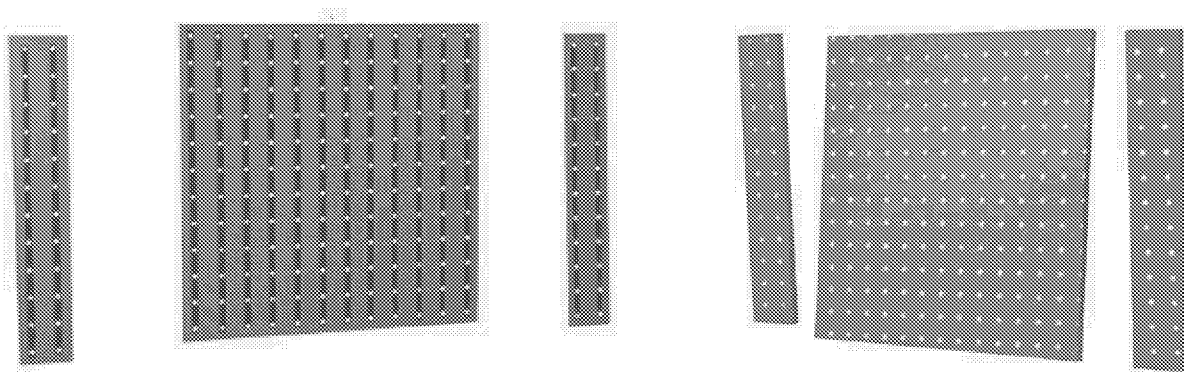
(a) Retro-reflective targets   (b) Projected dots

Figure 4 – 24 inch plate and side pieces
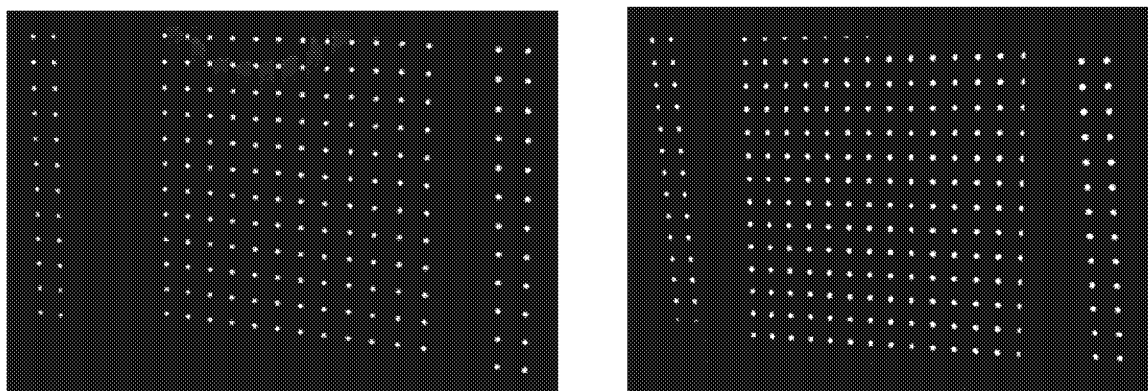
(a) Retro-reflective dot pattern   (b) Projected dot pattern
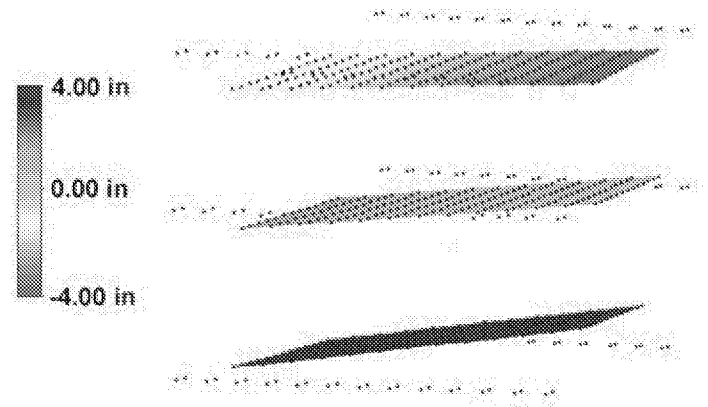
Figure 5 – Upper right images used in processing
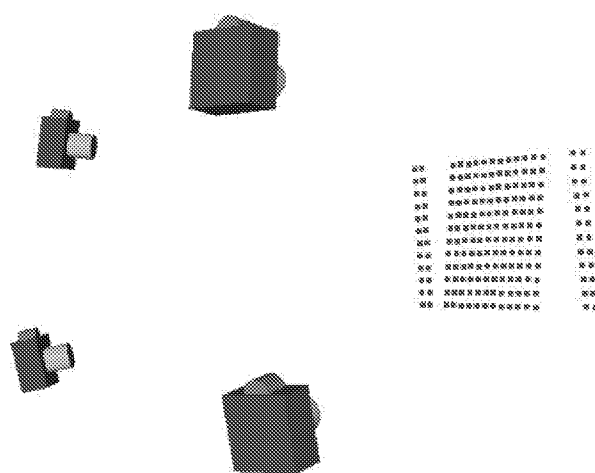
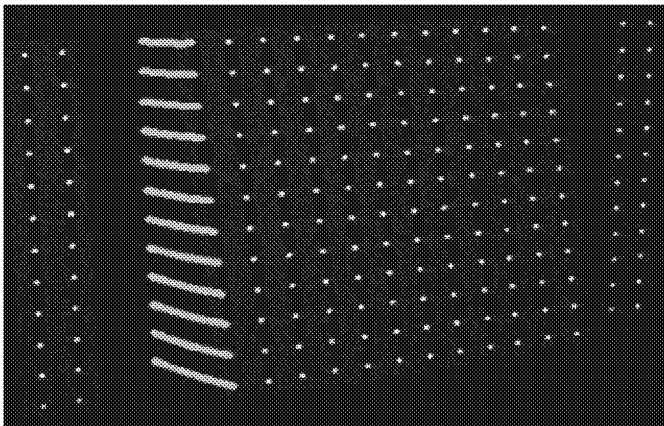Figure 6 – 3D view of camera stations and marked points
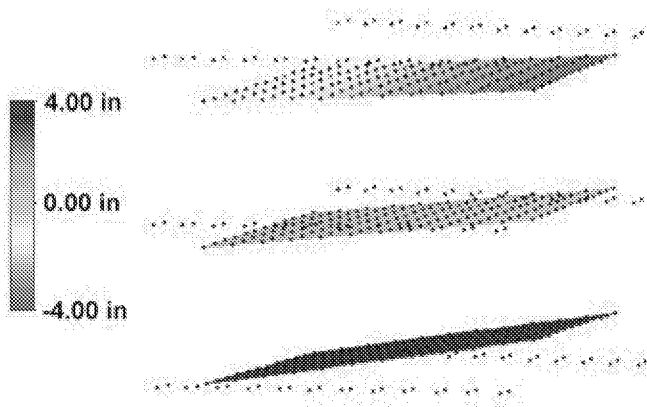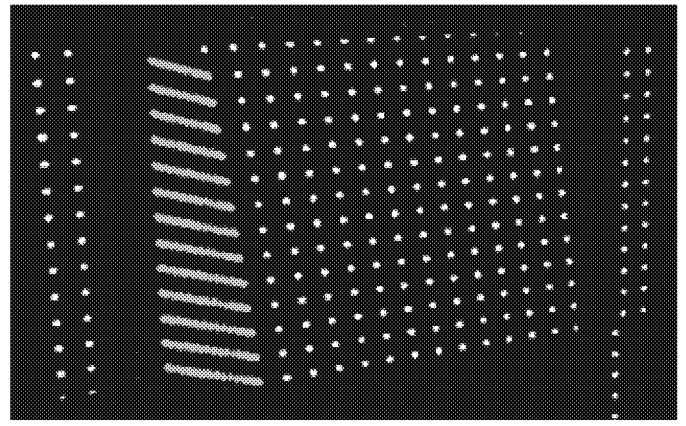
(a) Retro-reflective target data   (b) Dot projection data

Figure 7 – Sequence of three images from animation of swinging plate
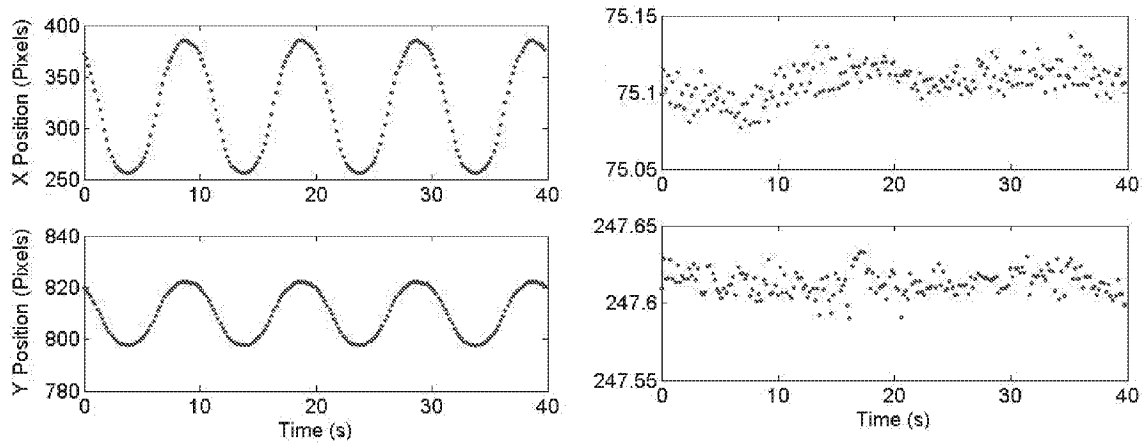

(a) Retro-reflective target data (curved paths)   b) Dot projection data (straight-line paths)

Figure 8 – Point movement plotted over entire dataset in the upper left image
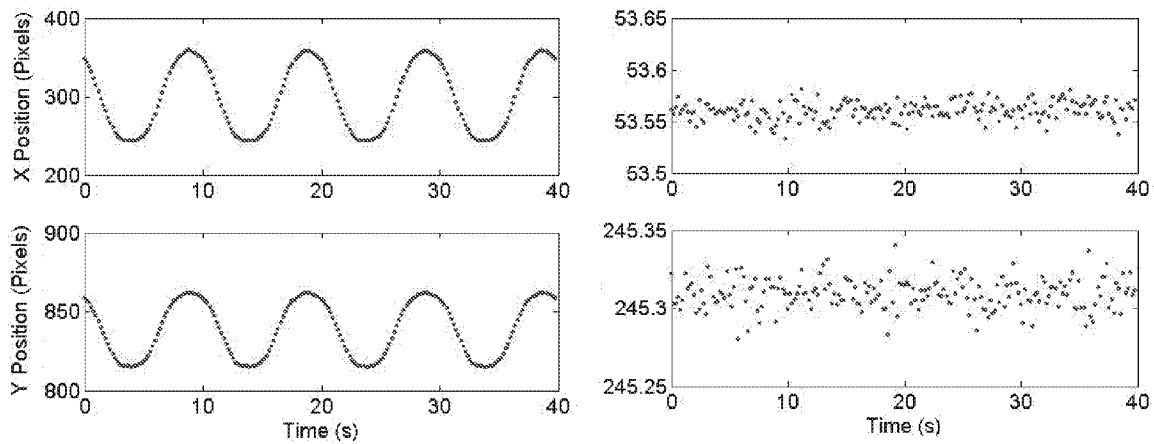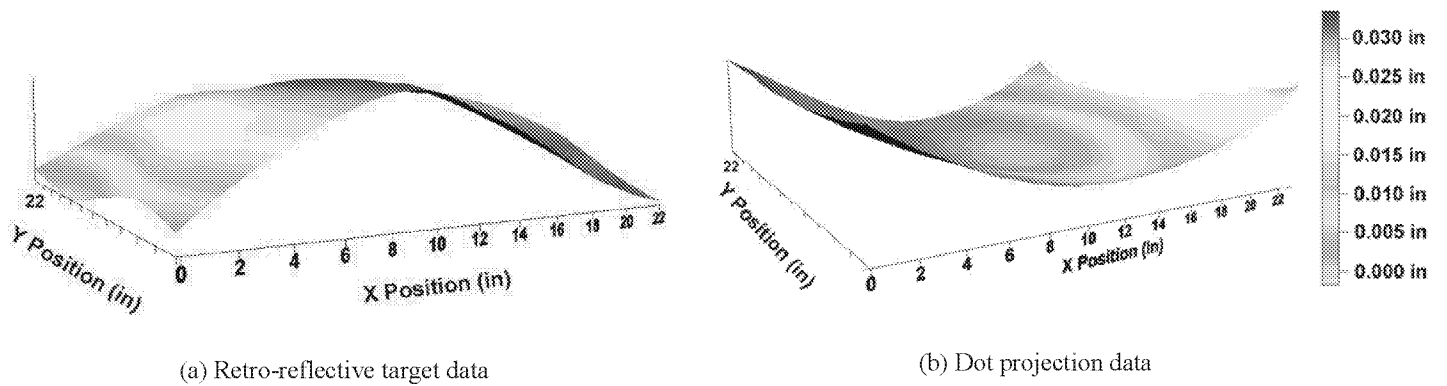
(a) Retro-reflective target data

(b) Dot projection data

Figure 9 – Position of lower left swinging plate target vs. time (left) and position of stationary sidepiece target vs. time (right)

(a) Retro-reflective target data

(b) Dot projection data

Figure 10 – Contour surfaces of swinging plate showing slight bow in the middle

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13. ABSTRACT *(Maximum 200 words)*

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