Use of Photogrammetry for Sensor Location and Orientation

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In this article, two photogrammetric methods are used for performing 3D digitizing of test objects for modal testing applications. The performance of both systems is evaluated by discussing the operation of each and by digitizing two different structures using both.

Currently, several digitizing commercial photogrammetric systems are available. Most are directed at obtaining solid models, which can be used in virtual modeling applications, reverse engineering, and/or CAE applications, such as generating and rendering 3D models. This article evaluates two systems that have applications for locating measurement points on a structure and for determining the orientation of sensors mounted on the test object. The first is a classical photogrammetry system[1] that uses a digital camera and image processing software. The second system is a roving digitizer[2] that uses the photogrammetry technique in reverse – a calibrated panel is used to determine the camera position at each digitized point. This photogrammetric digitizer uses circular barcodes for automatic orientation of the image for the vision algorithm.

Camera Photogrammetry System

The photogrammetry program used in this article has been in use for roughly the past 10 years. It has been used in a large number of application areas for digitizing items both large and small. Very high accuracy is possible with quality photographs.

The authors have used this program for the past 5 or 6 years on a number of projects, but primarily as a backup digitizing system. For most projects a large number of photographs are taken for documentation purposes and these photographs can be used to check on the locations and orientation of various components in the test system. In the past, using this program to digitize a test article was rather time consuming, so other, faster means were normally employed. For experimental modal analysis, a large number of points are not used in a modal survey primarily due to limitations in the number of sensors available. These points are normally scattered over a wide area and a large number of photographs are required to locate the points. Points are located in areas inside, under, behind and generally out of view. Very often a large number of points were simply added to stitch the photographs together. Locating and referencing these widely scattered points between the photographs was sometimes difficult and time consuming. A number of newer features have been incorporated over the past several years which have automated the process for digitizing a structure, thereby making the process more attractive.

Photogrammetric Digitizer

The photogrammetric digitizer system uses a roving probe (Figure 1) that contacts the structure at each digitized point. At each location, the user triggers data acquisition with a push button on the probe. The data acquisition starts with an infrared flash by the probe, which illuminates the viewing area for an infrared camera (also in the probe). The CCD is located behind the black lens in the center of the circular opening of the handheld probe, shown in Figure 2.

As the probe is roved about the structure, the camera is pointed toward an array of retroreflective targets mounted on a flat panel. Two types of targets are used on the panel – circular barcodes and simple circular dots. After the image of the panel is passed to the image processing algorithm in the PC, the barcodes are used for calculation of the gross orientation of the probe, and the more numerous dots are used to provide redundant data to refine the solution. Each panel is associated with a calibration file that documents the precise locations of each target. The target panels vary in size from a fraction of a meter to 1.5 meters on a side (Figure 3).

The 2D digital image acquired by the probe is transferred to the host PC and processed almost instantaneously when using a 300 MHz processor. The 3D coordinates are collected, and processed into commonly used Universal File Format ASCII files for use in structural dynamics analysis software.

6 DOF Sensor Locations

In addition to 3D coordinate digitizing, the system software for the photogrammetric digitizer expands to calculate Euler angles of the sensor as it is installed. By digitizing 3 separate points on the surface of the sensor, we calculate the normal plane of the structure at that point. We re-machined standard sensors in 3 different locations (such as the one shown in Figure 4) to create holes that serve as the digitizer probe targets.

When acquiring 6 DOF geometry, the software acquires the 3 consecutive 3 DOF points and calculates the mounting plane for the sensor. The software maintains a database of sensor model numbers and the relative location of the associated digitizer holes. Once the system software recognizes the sensor type being used, it calculates the mounting point of the accelerometer. The digitizer holes are designed to be non-equidistant, so the 3 points can be digitized in any order.

TEDS Update

The system software also exploits the capabilities of TEDS (Transducer Electronic Data Sheet) sensors. Since their commercial introduction 5 years ago, TEDS sensors have seen a steady rise in popularity with test labs that do multi-channel structural testing.[3,4] The mixed-mode (analog and digital) design uses the high fidelity characterisitics of IEPE (Integrated Electronics PiezoElectric) sensors and a standardized inverse excitation technique to switch the sensor into digital mode. During digital operation, the sensor communicates with a TEDS capable host signal conditioner for the purpose of self-identification. The memory of the sensor's digital circuitry is very limited (the current commercial units carry only 320 bits of memory), but this is enough to carry model number, serial number, and calibration information. In addition, binary encoding of the data allows for the inclusion of geometry data.

The digitizer system software uses the PC serial port to communicate with TEDS sensors. First, the system software automatically detects the presence of TEDS circuitry on the serial port. Next the system software uses the TEDS model number information to query the system database for the expected locations of the 3 indented marks on the sensor. This also returns the correct transformation matrix used to calculate the location and orientation of the sensor.

After the points are digitized and the 6 DOF transformation is made, the system software goes back to the TEDS interface and writes the updated geometry data back into the sensor. At this point, the sensor is installed on the structure and holds the unique identification, calibration and geometry data for this sensor. The subsequent connection of the sensor array to a TEDS capable signal conditioning system allows this information to be mapped to the data acquisition channel for the test.

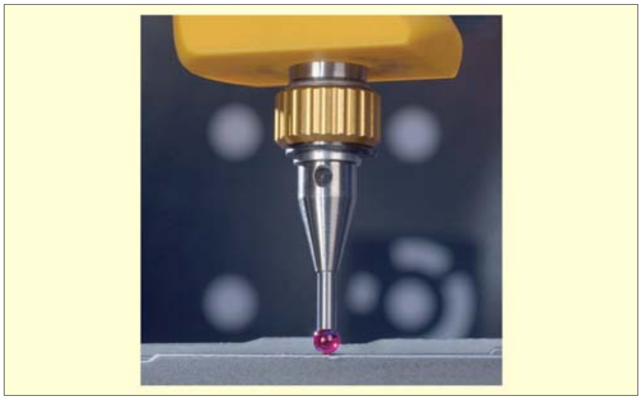

Figure 1. Digitizer probe tip locates the sensor position on the structure.

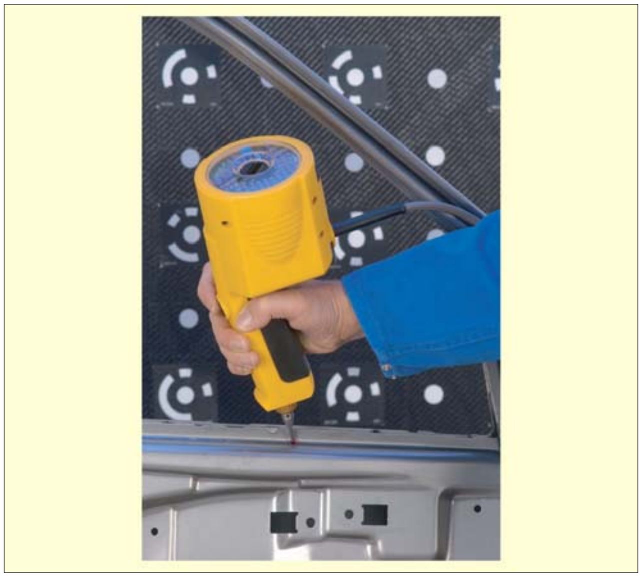

Figure 2. Infrared camera is embedded in the digitizer's handheld probe.

Case Study – Passenger Car (160 Points)

The authors identified 160 points on a late model sedan that would be typical of the points used for a modal test, and digitized the vehicle using both the camera-only system and the photogrammetric digitizer. The experience of using both is described in the following sections.

Camera Photogrammetry Case. An automotive example is presented where a set of typical test points were defined and digitized. The procedure for using the camera-only system is summarized as follows.

First, two sets of points were defined on the test auto (see Figure 5 for a photo of the auto used in this example).

- Points where modal measurements would be made.
- Points used to stitch photographs together, located on the ground surrounding the auto along with extra points taken on the wheels for this purpose.

Removable, 3/4 in. white circular optical targets were located at the points of interest. The targets were picked to provide contrast with their background so that automatic target marking could be used. Light targets are used on a dark background and dark targets can be used on a light background. In software, the photos are converted into single bit black and white images for automatic marking. The automatic marking is optimized for circular targets of a predefined diameter and sub-pixel algorithms are used for locating the centroid of the circle. Retro-reflected targets, where flash photography can be used to illuminate the targets, provide the best contrast for marking. However, due to flaring of the image from these targets, they do not provide the best overall accuracy. Regions of the photo can be selected and the black and white threshold can be adjusted to optimize the marking.

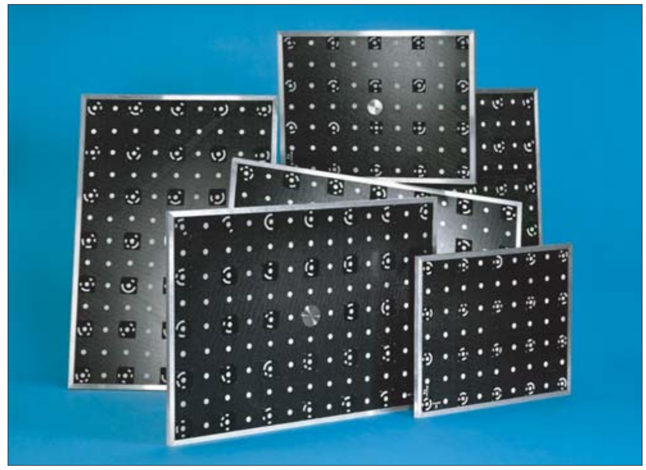

Figure 3. Calibrated target panels serve as reference images in calculating the position of the handheld probe.

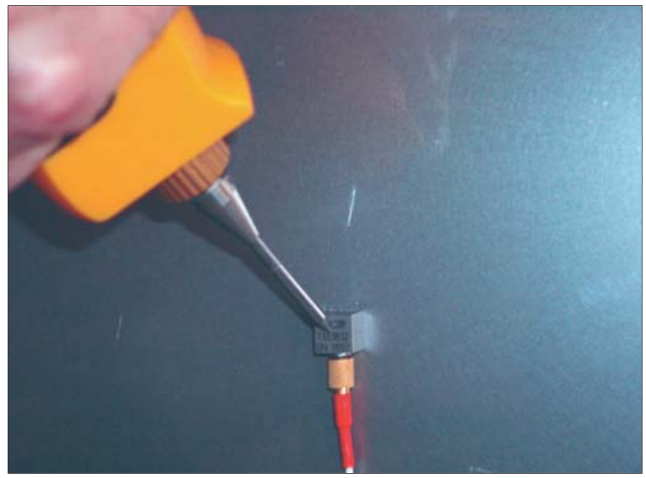

Figure 4. TEDS sensor with precision machined locator holes for digitizing 6 DOF coordinates.

Figure 5. 3/4 in. circular targets placed on car.

Second, photographs were taken of the automobile from eight locations in a ring around the auto. The best accuracy is achieved if the angle to a given point is approximately 90 degrees from the different camera locations. Four other photographs were taken to aid in the location of points located on the rocker panels, which were not clearly visible from the initial eight photographs. In general, more photographs yield more accurate results.

- Camera calibration – For best results, the lens on the camera should be calibrated. The commercial software has a simple procedure to calibrate the lens, which was performed before the photos of the auto were taken.
- Camera – A 6 megapixel Canon digital camera was used for

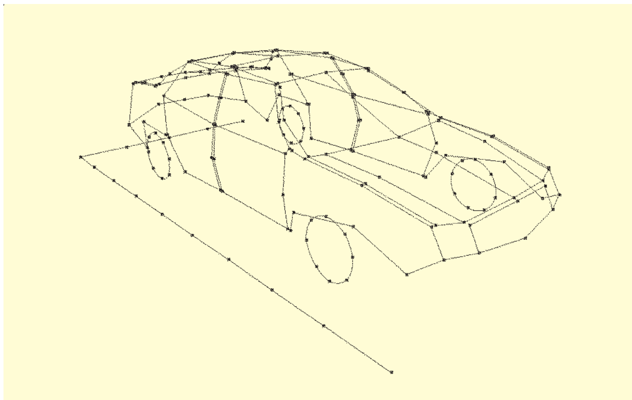

Figure 6. Solid model of automobile from camera based system.

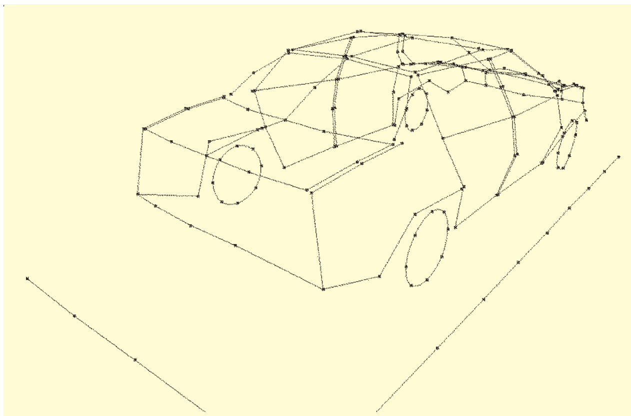

Figure 7. Solid model of automobile from camera based system.

this project. It was a single lens reflex camera with all of the exposure and flash adjustment options typically found on a high-end 35 mm film camera.

The third step was establishing marking points. The initial effort was to try the auto marking feature. Since the photographs were taken of the automobile outside on a bright sunny day, the automatic marking feature never worked well because it was difficult to locate large areas where the threshold for detection could be set properly for large areas of the photographs. Small areas could be marked like the tires and ground points, providing a significant time savings since those are important points used primarily to determine the location of the cameras. However, the majority of the points were marked manually. Sub-pixel marking was performed on the points where the targets were clearly visible, and the rest of the points were marked using a manually centered cursor.

Fourth, the reference points were established by using two photographs to reference the points on the tires and on the ground. Referencing consists of marking common points on the two photographs. The points on the ground and the points on the wheels were the first points referenced along with a couple points on the top of the car. These points were used to locate the cameras for the two photographs. These are points where coded targets would have been useful to automatically reference these points. Once these initial points were referenced, the data were processed and the cameras were oriented and located. Once the cameras were located, then the rest of the marked points in the photographs could be theoretically auto-referenced, which would save tremendous amounts of time. However, in this example, auto referencing did not work very well becuase the initial lens calibration was performed on a small close-calibration target. Focusing the lens on a large distance target changed the characteristic of the lens such that the errors in the digitized points were large enough to render auto-referencing only partially successful. This was corrected by using a field calibration taken from data collected using the

Figure 8. Using the photogrammetric digitizer to collect geometry on an automobile.

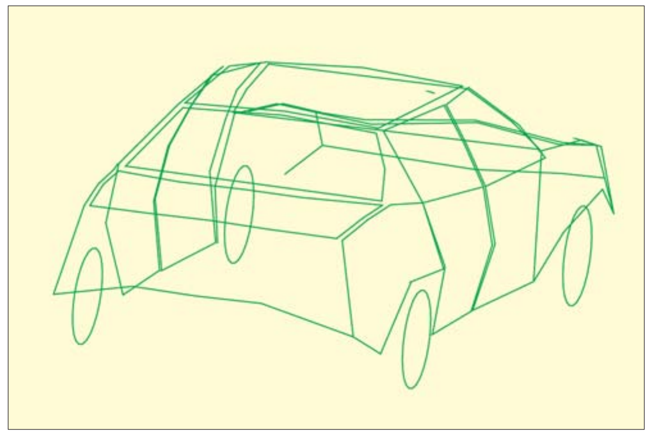

Figure 9. Photogrammetric digitizer results from automotive case study.

same camera on another project. A field calibration is when the characteristics of the lens are adjusted to minimize the errors in a project; the calibration taken from the field can be used in other projects using the same camera-lens combination. It should be noted that errors in the referencing process are very time consuming to fix. As a result, working in a systematic fashion by incrementally adding a small number of photographs saves time by reducing errors in the referencing process.

Fifth, the initial 3D model was constructed from four photographs, which took about 1.5 hours. There were a number of points that were not visible from the four photographs so additional photos were added, for a total of 11. It took about three hours to develop the final model.

Through these steps, the final model was developed. Statistically, the largest error was on the order of 0.18 in., with most errors being approximate 1/32 to 1/16 in., more than adequate for modal testing. The model consisted of 160 points located on the car and 14 points located on the ground near the car. Figures 6 and 7 present views of the solid model created with the camera photogrammetry system.

Very good results were obtained for the model and it is clear that improvements in the automatic marking and referencing could speed up the process significantly. NASA has performed a test on a large space structure using retro-reflective targets with auto marking and referencing using this software.[5]

Photogrammetric Digitizer Case. The same 160 points were measured using the digitizer system. Due to the size of the structure and limited focal length of the infrared camera, the calibrated panels were moved several times during the measurement process. In all, 4 panel locations were used to digitize the entire vehicle. In each case, the panel was positioned about 4 feet away from the corner of the vehicle at a height of about 5 feet. The face of the panel was aimed at a 45 degree angle to capture as many points as possible in the visible field.

From the start of the digitizing project to the end, the entire

Figure 10. The photogrammetric digitizer uses an array of probe tips to measure hard-to-reach places.

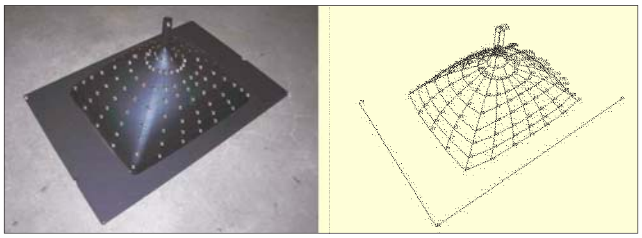

Figure 11. TV tube test setup and solid model.

task took about 1 hour for 160 points (Figure 9). The task of transforming the 4 data sets to a common coordinate system took about 3 min. by specifying the common points between each and using the system software's capability to perform a least-squares fit of the overlapping points to a single coordinate system.

The effective range of the camera from the panel was between 10 and 12 ft. Although multiple panel positions were required to cover the entire vehicle, this operating range enabled many points to overlap between positions, which aided the least squares transformation of the geometry. For example, the initial panel position at the front driver's side proved effective in collecting data from the center point of the hood to the rear tire on the driver's side.

The system software's database also accommodates the use of a variety of probe tips (Figure 10). Various probe tips are available to allow the user to reach around obstacles and position the camera to allow viewing of the panel. In this project, we swapped out the shorter probe for a larger, angled probe, which avoided the obstacle presented by the side mirrors as we proceeded down the side of the car.

Case Study – Television Tube

The second example was a TV tube, the test object being used in a master's thesis project where modal testing is being explored as a method for detecting small cracks formed during the manufacturing process. Changes in the eigenvalues (frequency and damping) are used as a measure of the damage. The tube is very lightly damped and should be very sensitive to small changes in damping. Previous studies on lightly damped structures indicated that cracks in areas with a large change in the local curvature of the modes results in a measurable change in the damping of those modes. As a result, the change in damping can be used as an indicator of damage and the mode that is damped gives information about the location of the damage. An FEM model and experimental modal analysis was performed to gather the modal data on the TV tube. An impact test was performed, and the impact points digitized using the methods evaluated in this article.

Camera Photogrammetry Case. The procedure for using the camera-only system is the same as in the previous example. However, for this case the application of the automatic marking worked better. The tube was painted black and small,

Figure 12. Total data acquisition time on the TV tube with the digitizer was 10 minutes.

Figure 13. Calibrated rooms eliminate the need for temporary panel positioning.

bright, circular yellow 1/4 in. targets were mounted at 161 points on the tube and three points on the ground to scale and orientate the axis for the coordinate system. A total of eight photographs were taken in a ring around the tube. A flash was used to illuminate the points. In approximately one minute, 95% of the points visible on a given photograph were automatically marked. The points not marked were at the extreme edges of the visible regions. These points were left unmarked in the model estimates. However, they were later manually marked to make final improvements to the model. The test setup for the TV tube is shown in Figure 11.

Two photographs taken 90 degrees apart were used to start the referencing process. The three points taken on the ground and 12 points taken on the TV tube were manually selected and used to locate and orient the cameras. Automatic referencing was then tried to reference the remaining common points on the photograph. Very close tolerances were set on the criteria for selecting the reference, necessary to reduce errors in the referencing. Correcting error is one of the more difficult and time consuming processes. As a result, approximately 10% of the points were not referenced and were left to be referenced in the audit phase. The data for the photographs were processed and the camera position and the points updated. A new photograph was then added and the process of referencing the points on the new photograph and processing the data was performed. The results were saved as each photograph was processed into an intermediate file so that it would be possible to go back and start at that point if a large number of points were referenced incorrectly. It is easier to restart than it is to troubleshoot the referencing process.

Photogrammetric Digitizer Case. The same digitizer equipment used for the automobile was used for the television tube. The same technique of roving the probe was also used. Although, with this smaller structure, only one position of the panel was required as shown in Figure 12. In addition, since no obstructions required the use of an additional probe, the entire 161 point data set was acquired in about 10 min. The only post processing required was to export the data to a common ASCII file.

Conclusions

These two applications of photogrammetry show potential for its use in structural test labs. The accuracy of either system is well within the needs of locating sensors for modal testing. In certain situations, the use of the camera-only technique has the potential to be faster, because the repositioning of the calibrated panels of the digitizer can be time consuming. However, there are established applications for calibrating entire rooms (Figure 13), rather than just a single panel. In these cases, moving the calibrated panel becomes unnecessary.

Either of these techniques could be used to bring more automation to a modal test lab. The integration of TEDS sensor technology in the photogrammetric digitizer enables further exploitation of smart sensor technology to reduce human errors in the test setup process.

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