SAND2019-12755C

Fast Computation of Laser Vibrometer Alignment using Photogrammetric Techniques

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ABSTRACT

Laser vibrometry has become a mature technology for structural dynamics testing, enabling many measurements to be obtained in a short amount of time without mass-loading the part. Recently multi-point laser vibrometers consisting of 48 or more measurement channels have been introduced to overcome some of the limitations of scanning systems, namely the inability to measure multiple data points simultaneously. However, measuring or estimating the alignment (Euler angles) of many laser beams for a given test setup remains tedious and can require a significant amount of time to complete and adds an unquantified source of uncertainty to the measurement. This paper introduces an alignment technique for the multipoint vibrometer system that utilizes photogrammetry to triangulate laser spots from which the Euler angles of each laser head relative to the test coordinate system can be determined. The generated laser beam vectors can be used to automatically create a test geometry and channel table. While the approach described was performed manually for proof of concept, it could be automated using the scripting tools within the vibrometer system.

Keywords: Multi-point; Laser Vibrometry; Photogrammetry; Alignment; Automation

1 Introduction

Laser Doppler Vibrometry (LDV) is a mature technology that has been used to overcome numerous testing challenges [1]. It has the ability to measure dynamic motion without mass-loading the test article, which can be important for small components and high spatial density measurements. It also has a very high frequency range compared to traditional instrumentation. Typically, laser vibrometers have been fielded in single-point or scanning variants, with the scanning LDVs being very successful with their ability to measure a number of points quickly and accurately. Unfortunately, this multi-point data is not obtained simultaneously, which can limit the testing that can be performed. Recently, the Multi-Point Vibrometer (MPV) has been introduced, which can measure multiple channels of laser vibrometer data simultaneously, either in triaxial (three beams per measurement point) or uniaxial (one beam per measurement point) configurations. From a user's perspective, this system is effectively a large number of single-point vibrometers, which need to be positioned and oriented manually. While the scanning systems had feedback with the mirror servos so the laser beam geometry could be automatically generated, the orientation of each laser beam must be given manually to the MPV systems. This paper introduces an approach to quickly generate laser beam orientations for each of

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

the MPV measurement beams using 3D photogrammetric techniques. While the proof-of-concept presented in this paper was performed manually, it could be easily automated using the macro capabilities of the MPV system.

2 Demonstration Experiment

The process described in this paper was validated using the test setup shown in Figure 1 using a Polytec MPV-800 system with 24 laser heads. The test article is a rectangular beam with retro-reflective tape at 18 measurement points. The 24 laser heads were arranged to provide 15 uniaxial and 3 triaxial measurements. Two Canon Powershot G1X point-and-shoot cameras were mounted to tall vertical posts above the test from which they could view the part and laser beams. A stereo camera calibration was performed using a Correlated Solutions 10×14 dot 40 mm calibration target.

3 Laser Beams in 3D Space

A laser beam from an LDV system can be modeled geometrically as a vector in 3D space originating from the laser head and passing through a given measurement location on the object under test. The LDV measures the velocity of the opject at the point where the laser beam intersects the part, in the direction along the laser beam. Therefore, if only uniaxial measurements at each measurement point are obtained, the test geometry can be constructed solely from the point where the laser intersects the part and its orientation in 3D space.

The situation is slightly more complicated for a triaxial measurements where 3 beams intersect the test article at the same point. Each of the 3 beams measures a different component of the 3D velocity at that point. The transformation between the 3D velocity, $[v_x, v_y, v_z]$, in the object's coordinate system and the velocities measured by each laser beam, $[v_1, v_2, v_3]$, is given by

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} l_{1x} & l_{1y} & l_{1z} \\ l_{2x} & l_{2y} & l_{2z} \\ l_{3x} & l_{3y} & l_{3z} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \quad (1)$$

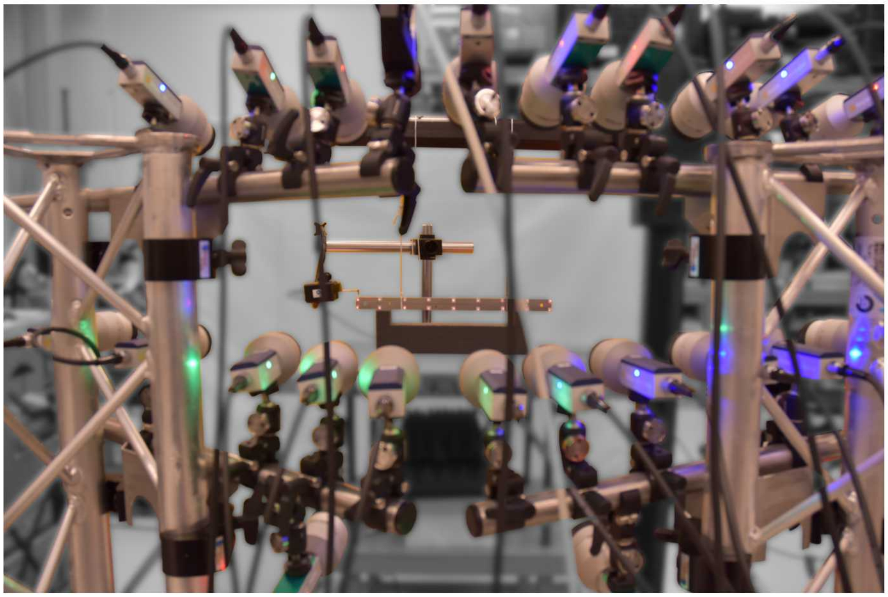
where l_{ij} is the cosine of the angle between the ith laser head and the coordinate direction j. The matrix of direction cosines is simply inverted to compute the 3D velocity in the object's coordinate system from the independent laser beam measurements. Note that each row of the matrix is the unit vector of the laser beam in the xyz coordinate system. Therefore, for both uniaxial and triaxial measurements, the vector formed by the laser beam is the key to creating a test geometry.

4 Determining Laser Geometry using Photogrammetry

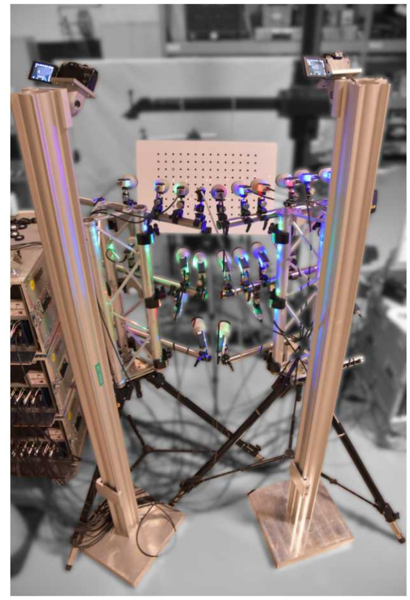
Two points are sufficient to define a vector in 3D space, so for this work, the positions of two points on each laser beam will be found, from which the laser vector can be computed. One of the points will be the position of the laser spot on the part, which will define the measurement point position in space as well as aid in defining the laser orientation. The second point on each laser beam was created by placing a large plane (in this case the calibration target) in front of the part; the position of each laser spot on this intermediate plane provides a second point on the vector. Note that if the part was complex, or there wasn't a camera view that could capture all laser spots simultaneously, the intermediate plane approach could be used twice. However, if test geometry was required, a third measurement would need to be performed to identify the locations of the laser spots on the part, as two planes will not give the location of the measurement point on the part.

There are many methods of measuring geometry. The simplest methods may involve a ruler and protractor. Coordinate measuring machines may also be used for more complex geometry; however they are not easily automated. In the case of this work, geometry of the laser beam will be measured using 3D photogrammetric techniques. 3D photogrammetry involves capturing images of a scene using a pair of stereo-calibrated cameras. The stereo camera pair needs to initially be calibrated so intrinsic and extrinsic parameters of the stereo camera rig, which define the cameras' properties and relative positioning to eachother, can be computed. Individual features in each stereo image pair can be triangulated to determine a point in 3D space [2].

3D photogrammetry was chosen for its ease of automation in software. Once the camera images are obtained, the images can be sequentially loaded into memory, the laser spots can be identified, and triangulation can be performed. The taking of the images can also be automated depending on what kind of cameras are available. A pair of webcams, for example, is easily automatable with the Open Computer Vision (OpenCV) library [3]. For this proof of concept, however, a pair of digital cameras were used and the images were captured manually by pressing the shutter buttons.



(a) Beam test article with retro-reflective tape at laser positions.



(b) Photogrammetry setup

Figure 1: Test Setup showing the test article in front of the MPV system (a), as well as the photogrammetry setup showing calibration target and cameras mounted to the tall vertical posts (b).

4.1 Camera Calibration

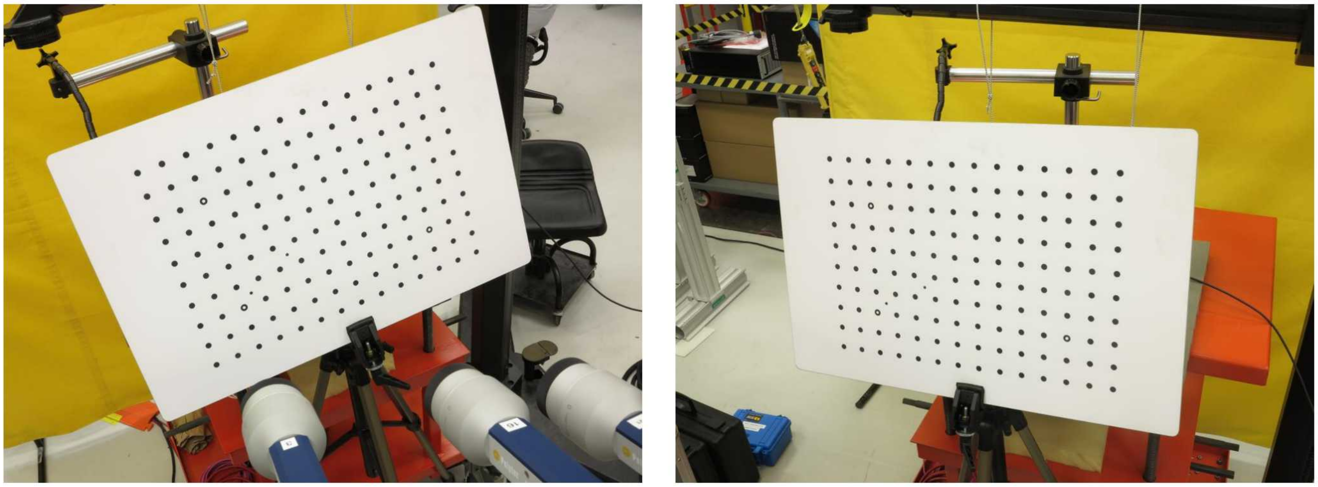
Camera calibration was performed using a Correlated Solutions 10×14 dot-grid calibration target with 40 mm grid spacing. Figure 2 shows the pair of calibration images used for this work. The OpenCV `stereoCalibrate` function was used to calibrate the stereo pair of cameras. Alternatively, a photogrammetry or digital image correlation software package could be used, though it may be more difficult to automate this step if a commercial package is used.

4.2 Laser Spot Identification on Image

The first step to automating the triangulation process is to identify a single laser spot in an image. This was performed by closing the laser shutter for all lasers, capturing an "all off" image, then opening the shutter of just one laser at a time and capturing an image of the updated scene. If the lighting in the room is constant and the scene is static, the only difference between the two images should be the appearance of a laser spot. A simple subtraction of the two images clearly identifies the laser spot in the difference image. Figure 3 shows this process. The difference image is thresholded to produce a binary black and white image. Contours are found in the image using the OpenCV `findContours` function, and the center of the contour is treated as the laser spot center. This process is repeated for each laser head individually. Images are captured for each laser head intersecting the object, and again for each laser head intersection the intermediate plane (calibration target plate).

4.3 Triangulation

With camera matrices from the calibration and laser points identified on each image, the points could be triangulated in 3D space. Triangulation was performed using the OpenCV `triangulatePoints` function, which uses the Direct Linear Transform algorithm from [2]. After triangulation, a vector representing each beam can be computed in 3D space using the point triangulated on the intermediate plane image and the point triangulated on the part image. To verify the triangulation, the extracted laser beams can be projected back into image space using the OpenCV `projectPoints` function, which projects 3D points to the image plane. Figure 4 shows this verification step. Note that the vectors produced by triangulation will likely be defined in an arbitrary coordinate system defined by the camera calibration (Figure 5), so it will be useful to transform them to the part coordinate system.



(a) Left calibration image **(b)** Right calibration image

Figure 2: Calibration images captured by the digital cameras.

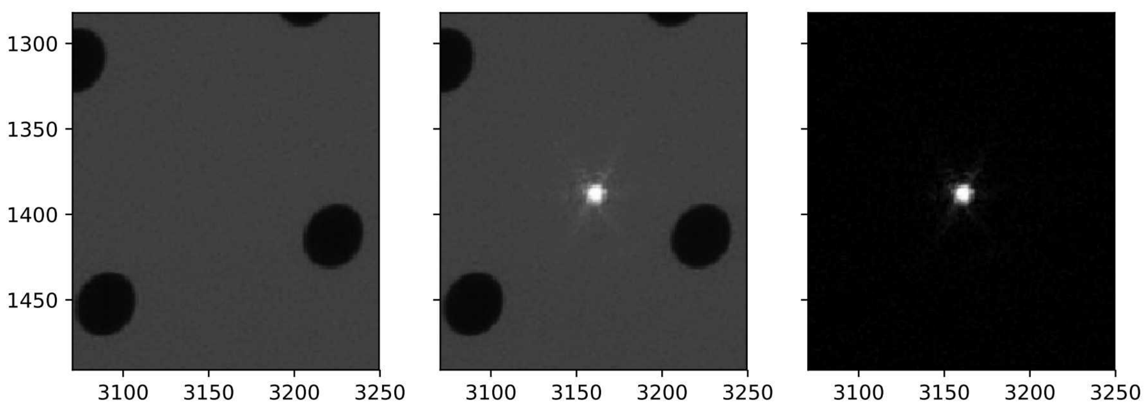


Figure 3: Identification of the laser spot through differencing the laser-on and laser-off images. The left image shows a crop of the "all off" image, the middle image shows the laser spot turned on, and the right image shows the difference between the two images.

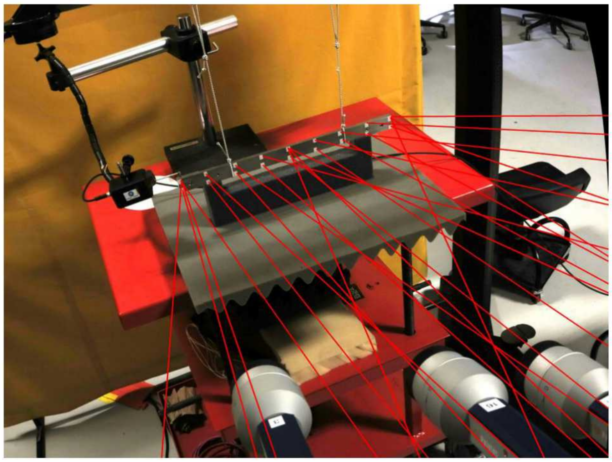


Figure 4: Laser vectors projected back onto the camera image showing approximate path of laser beam from laser head to part.

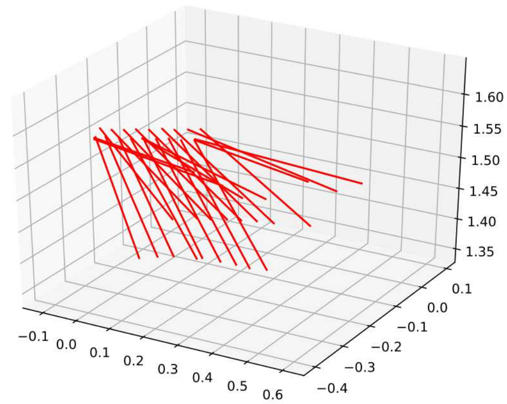


Figure 5: Raw laser vectors computed from the triangulation. They are defined in the left camera coordinate system, which is arbitrarily defined with respect to the part.

The measurement points have just been triangulated in a camera coordinate system, so if the (x,y,z) coordinates of the measurement points are known in the part coordinate system, a transformation between those sets of points can be directly solved for via e.g. [4,5] or a similar method. If the measurement point coordinates are not known in the part coordinate system, some other features can be used. In the present case, the coordinates of the beam corners are known, so they are used in the transformation. The corner coordinates in the camera coordinate system can be triangulated using the same approach that was done for the laser spots, and then the rigid transformation can be solved for. After transformation, the laser vectors should align with the part. Figure 6 shows the laser beams aligned with the part model after transformation into the part coordinate system.

The vector definition should be sufficient to create a test geometry consisting of measurement point locations and directions; however, some users may wish to import the laser geometry into other software, which may involve specifying Euler Angles to define the orientation. Euler angles can be readily computed from rotation matrices (see e.g. [6]). However, the unit vector formed by the laser beam consists of only one row or column of the rotation matrix, so it may not be clear how to proceed. One solution to this is to form a reference vector v_{ref} that is meaningful to the part or measurement system coordinates. For example if Euler angles are defined using a yaw and pitch rotation, an "up" direction may be meaningful, as it will be the vector about which yaw is defined. If the laser vector v_l is defined as the first axis of the coordinate system, the third axis of the coordinate system $v_\perp$ can be defined using the direction of the vector resulting from the cross produce of the laser vector and the reference vector, as the cross produce will produce a vector that is perpendicular to both reference and laser vectors. The laser vector may not be perpendicular to the reference vector, so to produce the true second coordinate system axis, the reference vector should be redefined as the cross product of the third vector and the laser vector $v_{ref\perp}$. This will result in three orthogonal directions based on the direction of the laser vector, shown schematically in Figure 7, which can be assembled into a rotation matrix. Euler angles can then be computed from this matrix.

$$v_\perp = v_l \times v_{ref} \tag{2}$$

$$v_{ref\perp} = v_\perp \times v_l \tag{3}$$

5 Conclusions

This paper presented a technique to more accurately estimate laser angles from a MPV test setup. It involves highly-automatable photogrammetry process that could be seamlessly integrated into the MPV workflow via software macros. As the authors only had a limited time with an MPV system, a quick proof-of-concept was instead performed. The technique was demonstrated on a beam test setup, and laser beams were accurately reproduced and plotted with a model of the part.

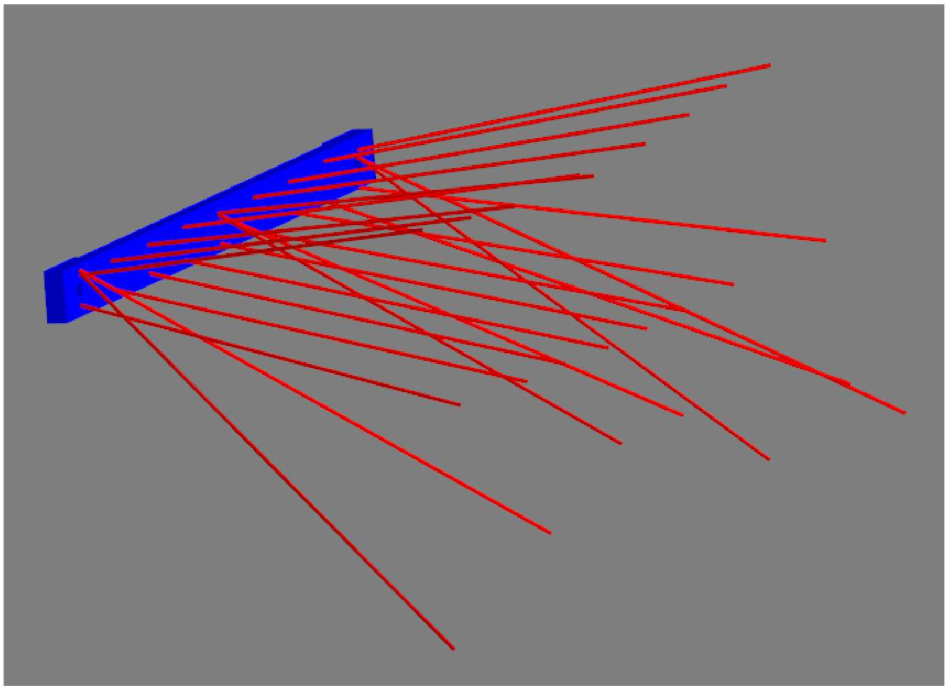


Figure 6: Laser beams aligned with the part.

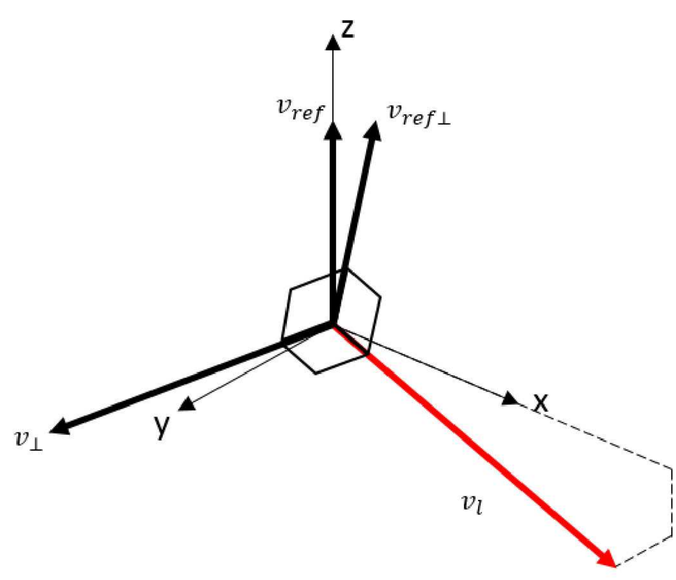


Figure 7: Coordinate systems reconstructed from a laser vector.

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