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Reference:

Sels Seppe, Ribbens Bart, Bogaerts Boris, Peeters Jeroen, Vanlanduit Steve.- 3D model assisted fully automated scanning laser Doppler vibrometer measurements

Optics and lasers in engineering - ISSN 0143-8166 - 99(2017), p. 23-30

Full text (Publisher's DOI): <http://dx.doi.org/doi:10.1016/J.OPTLASENG.2016.09.007>

To cite this reference: <http://hdl.handle.net/10067/1466310151162165141>

3D Model Assisted Fully automated Scanning Laser Doppler Vibrometer Measurements.

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Abstract

In this paper, we present a new fully automated scanning laser Doppler vibrometer (LDV) measurement technique. In contrast to existing scanning LDV techniques which use a 2D camera for the manual selection of sample points, we use a 3D Time-of-Flight camera in combination with a CAD file of the test object to automatically obtain measurements at pre-defined locations. The proposed procedure allows users to test prototypes in a shorter time because physical measurement locations are determined without user interaction. Another benefit from this methodology is that it incorporates automatic mapping between a CAD model and the vibration measurements. This mapping can be used to visualize measurements directly on a 3D CAD model. The proposed method is illustrated with vibration measurements of an unmanned aerial vehicle.

Keywords: Pose estimation, Time-of-Flight, 3D camera, CAD model, scanning laser Doppler vibrometer

1. Introduction

The increasing availability of low cost and industrial 3D cameras has increased the research on 3D object recognition and pose estimation. Today object recognition and pose estimation techniques are mainly used in robotics and 3D scanning techniques. In this paper we will combine 3D measurements and processing techniques with an optical vibration measurement system: the scanning laser Doppler vibrometer (SLDV).

The scanning laser Doppler vibrometer is frequently used in the design and testing of products and structures (e.g. automotive, machine or aircraft components) [1, 2, 3, 4]. The scanning laser Doppler vibrometer (SLDV) is an accurate instrument based on laser interferometry that can measure high spatial resolution vibration data by sequentially positioning the measurement laser beam at discrete positions using two scanning mirrors (for the vertical and horizontal deflection of the beam). Commercial scanning laser Doppler vibrometers (see Figure 3) also have an integrated 2D RGB camera in which the position of the laser can be detected.

Although the scanning LDV is an accurate vibration measurement instrument, the measurement procedure involves a lot of user interaction: the user has to manually draw a grid of measurement locations on a 2D camera image of the measurement scene. Furthermore, the user also has to perform a calibration between the 2D image of the test object and the two laser mirror angles. This can be a time consuming and tedious task that has to be repeated every time that the instrument or the test object is moved. Moreover, the manual interaction can lead to uncertainties between different measurements on the same object[5]. Our proposed methodology uses an automated calibration procedure and a 3D Time-of-Flight (ToF) camera to measure the location and orientation of the test-object. The 3D image of the time of flight camera is then matched with the 3D CAD-model of the object in which measurement locations are predefined.

2. State of the art

Currently the SLDV measurement procedure requires a lot of user input. When vibration shapes of an object are measured with a traditional system the user needs to go through the following steps:

1. **Calibration** of the scanning system: in the calibration step the transformation between the image coordinates (x, y) and laser scanning angles $(\theta_{hor}, \theta_{ver})$ are determined. To do this the user points the laser at

minimum three positions on the structure and manually identifies these positions[6, 5]. (see Figure 1a).

2. **Definition of grid points** on the object in the camera-image. In commercial software, polygon drawing tools are used for this purpose (see Figure 1b).
3. **Measure** the selected grid points by scanning over the defined grid points. (see Figure 1c).

During these steps, aiming the laser on a location on a structure is done by changing the angle of two integrated scanning mirrors. In order to be able to point at arbitrary locations on the structure during the measurement a mapping between the position of the laser spot and the angles of the mirrors is needed. This mapping is calculated with a 2D calibration procedure.

When the measurements are ready, they need to be interpreted and/or validated. With the traditional scanning laser Doppler vibrometer, measurements are only visualized on a standard 2D image of the object (see Figure 1c). Measurements are also difficult to compare with values from numerical simulations (e.g. finite element analysis) because no direct geometric relation between numerical and measurements nodes is available.

Currently 3D and 2D localization techniques in combination with laser Doppler vibrometry are mainly used for measurements on moving objects. 2D techniques are used to track landmarks of a moving or rotating object and automatically aim the laser beam to a landmark position [7, 8]. Although these methods are fast, the land-mark (white spot, reflective sticker) still needs to be applied manually. With these techniques 3D movements of the target where the landmark is distorted or only partially visible can cause inaccurate results. 3D techniques like photogrammetry are also used to track objects and aim the laser beam [9]. For accurate tracking manually applied or selected landmarks are still needed. None of the methods reported in literature provides a system that can automatically match measurements on a CAD-model and none of them can automatically select (visible) measurement points.

(a)

(b)

(c)

Figure 1: (a) Manual selection of calibration points. The 8 targets on the structure show the locations where the laser spot was placed and where the user clicked. (b) Manual selection of grid points superimposed on an RGB camera image in the Polytec scanning LDV system using a polygon selection tool. (c) Graphical representation of a vibration mode shape measured at the selected grid points.

Object recognition and matching of 3D CAD models with 3D point clouds are key parts of our methodology. Currently, 3D matching techniques exist and are implemented in open source libraries like PCL-C++ libraries [10]. In our work we mainly use viewpoint feature histograms [11] to detect an object in a point cloud and for finding an initial pose estimation. An implementation of the iterative closest point algorithm is used to refine the pose estimation [12, 13]. The pose estimation procedure will be elaborated in the next section.

3. Proposed SLDV method

3.1. Method summary

In contrast to traditional SLDV measurements which use user interaction to select sample points, we use a 3D camera and a CAD-model of the sample object in combination with the SLDV. The 3D camera, 3D CAD-file and pose estimation techniques will replace the traditional user interaction of selecting sample points. The traditional calibration technique is also replaced by an automated procedure.

For the end user our proposed scanning methodology consists of the following steps:

1. Step 1: **Automatically calibrate** the scanning LDV system. This step is explained in Section 3.2
2. Step 2: **Select sample points** (points of interest) on the CAD model and find the corresponding coordinates on the test object. This task is performed prior to the measurements campaign.

This is done by locating the sample-object in the 3D image and estimating the transformation matrix $T_{cad \rightarrow 3D}$ between the 3D image and the CAD-model. Where $T_{cad \rightarrow 3D}$ is a homogenous transformation composed of a rotation and a translation.

3. Step 3: **Measure** the vibrations at the predefined locations of interest.

The key role of the CAD model in our proposed methodology also allows for a more efficient measurement process. When simulations expose certain critical

Figure 2: Link between measurements, CAD-model, 3D camera and scanning LDV. A 3D camera, 3D model and pose estimation is used to find the position of the object and automatically select measurement points. An automated calibration procedure is used to aim the laser to these points.

measurement points these points can be measured and selected directly without measuring an entire grid around them. The link between all the proposed steps is visualized in Figure 2.

As 3D camera we use a Kinect One device. This device consists of a 3D Time-of-Flight (ToF) camera and a normal 2D RGB camera. The Kinect for windows SDK provides a pre-calibrated mapping between the 2D RGB coordinate system and the 3D Time-of-Flight system. The 3D ToF sensor is used for 3D measurements of the object at frame rates up to 30 frames/second. The measurements will be in the form of a 3D point cloud (see Figure 8). Because the ToF sensor is equipped with a band pass near infrared filter, the laser spot is not visible in the 3D image. Therefore, the integrated 2D RGB camera is used in the calibration procedure (Section 3.2) for detecting the laser spot. The Kinect is mounted below a scanning laser Doppler vibrometer (Polytec type psv 300) (see Figure 3). As test-object we used a model of a unmanned aerial vehicle that was developed by the company Nimbus in the framework of the Seventh

Figure 3: Experimental setup. Kinect One 3D camera mounted below a Polytec PSV 300 scanning LDV aimed to the sample-object (a). Sample object mounted on a electromagnetic shaker (c) Kinect One 3D camera and front of scanning LDV.

Framework Program EU project Acheon¹.

3.2. Step 1: Calibration

The new calibration procedure uses the 2D coordinate system of an RGB camera[14] like the traditional techniques but is fully automatic. The 2D RGB camera is used in addition to the 3D camera because the laser spot (wavelength of 632nm) is not visible in the used 3D Time-of-Flight camera image.

The calibration-procedure consists of the following steps:

1. **Position** the scanning LDV-laser at random locations ($N = 100$) within the 2D camera-view.
2. **Find laser spot** xy-coordinates in (RGB) image at different mirror-angles
3. **Calculate mapping** between $(x, y)_{rgb}$ coordinates of the RGB-camera and scanning mirror angles $(\theta_{hor}, \theta_{ver})$.
4. **Calculate mapping** between $(x, y)_{rgb}$ coordinates and scanning mirror angles $(\theta_{hor}, \theta_{ver})$. Where (θ_{hor}) defines the angle of the horizontal mirror and (θ_{ver}) the vertical mirror (the vertical mirror is visible in Figure 3).

The calibration calculates d and d_0 from Equation 1 and Equation 2 with singular value decomposition. The procedure is based on work of[14]:

$$x = d \tan(\theta_{hor}) \quad (1)$$

$$y = d_0 + \frac{d \tan(\theta_{ver})}{\cos(\theta_{hor})} \quad (2)$$

The laser spot is detected by background subtraction of a reference frame F_{ref} (where no laser-spot is seen) and a frame F_{spot} where the laser spot is visible. The highest values of this differentiated image ($F_{diff} = F_{spot} - F_{ref}$) will indicate the position of the laser spot. The error on the positioning of the laser is shown in Figure 4c. This error is caused by the fact that the calibration procedure is a 2D procedure. Because 3D measurements are available, the methodology could be extended to a 3D calibration procedure.

¹<http://acheon.eu/nimbus-develops-innovative-uav-configuration-for-the-acheon-experiments/> for more information.

(a)

(b)

(c)

Figure 4: Illustration of the accuracy of the automated calibration procedure. (a) Example image with detected laser spot where the blue dot is the target point and the red dot is the real midpoint of the laser spot. The distance between the two points is 4mm and the diameter of the laser spot is 10mm. (b) Comparison between true (applied) angle and calculated angles (only horizontal angles are shown). Some outliers exist due to erroneously detected sample points. (c) Positioning error of laser spot for five validation points. The distance between (new) input coordinates and coordinates of the aimed laser spot is shown.

Figure 5: Object transformation pipeline. The pipeline is divided in a global and a local pipeline. The global pipeline searches for clusters (segments) that belong to the object and finds a first approximately view of the point cloud. The local pipeline uses local point features to describe points in both the captured cluster and the synthetic view from the training set. After matching of these features, ICP is used to refine the results.

3.3. Step 2: Finding the 3D sample points

3.3.1. Pose calculation

To accurately aim the SLDV, the 3D position of the sample-object is needed. This position is calculated in the 3D camera coordinate system with a 3D pose calculation technique. The proposed pose calculation technique is built on work of [15, 16, 10, 11]. The procedure can be divided in two main steps:

1. **Object detection.** In this step measured 3D points that describes the sample object are searched. This step is summarized as 'global' pipeline in Figure 5.
2. **Object pose estimation.** In this part the transformation $T_{cad \rightarrow 3D}$ between the CAD model and the measured point cloud is calculated. This step is summarized as 'local' pipeline in Figure 5.

These steps are explained in Sections 3.3.2 and 3.3.3. Section 3.3.5 explains how the pose calculation is used to automatically select sample points.

Figure 6: (a) Partial (1/4) set of training-views. Virtual cameras are located in a sphere around the CAD model. The generated point clouds, VFHs and transformation-matrices are saved. (b) Example of a (segmented) point cloud. Different detected clusters are visualized in different colors

3.3.2. Object detection (global pipeline)

In the proposed procedure, the 3D point cloud generated by the 3D camera is segmented into different clusters (see Figure 6b). Each of these clusters are described by a Viewpoint Feature Histogram (VFH) [11]. This histogram is unique for every object and also has bins which describe the camera position (viewpoint). The Viewpoint Feature Histograms are called global features because they describe all points of a point cloud (cluster) in one histogram. These histograms are compared with a synthetic training set. This set is generated with a virtual camera (see Figure 6a) and the CAD model of the sample object. The cluster with the highest similarity to a certain synthetic point cloud in the training set will be the cluster which contains points from the sample object.

3.3.3. Pose estimation (local pipeline)

In the next phase a Fast Point Feature Histogram (FPFH)[15] will be calculated for each point in the matched cluster and synthetic point cloud (see Figure 7). The feature-histograms are called local features because they describe only one point in a point cloud. The FPFHs are invariant to transformations and therefore can be used to find similar points in point clouds which are translated and/or rotated compared to each other. Each FPFH of the synthetic point cloud

Figure 7: Visualization of feature matching. For each point in both the measured and simulated point cloud features are calculated and matched. (image based on [17]) (Note: colors of the point clouds are only added for a better visualization)

is matched with a FPFH of the cluster. Next the transformation between the two point clouds is calculated. The matching uses a sample consensus algorithm to test multiple matching hypothesis because some points might look similar to points at different positions. For example the histograms of points in a plane will all look the same. After FPFH-matching the iterative closest point (ICP) is used to refine the results. The ICP algorithm refines the results by minimizing the distance between the measured point cloud and the synthetic point cloud (where the synthetic point cloud is transformed with the previously found pose estimation). The result of the last step is the transformation $T_{synt \rightarrow clust}$ between the synthetic point cloud and the measured point cloud.

3.3.4. Discussion pose calculation

In our experiments, the mean euclidean distance between the measured point cloud and the transformed synthetic point cloud is 2mm. This error indicates that the mean position error of the measurement points is 2mm.

The two different stages (global and local) of the pose estimation combines the power of viewpoint feature histograms (global) and fast point feature histograms (local). Viewpoint feature histograms are very good for object recognition but

since they are camera roll independent they can give wrong pose estimations. Fast point feature histograms are very good at finding the transformation between two similar point clouds[18]. Therefore, we compare the FPFHs from the cluster with the features of the similar synthetic view obtained from the VFH-matching. Note that there are other techniques available like CVFH, OUR-CVFH, camera-roll histogram, Hough-voting, that use only global features to find a pose estimation[19, 20, 21].

3.3.5. *Select Points of interest*

When the transformation $T_{synt \rightarrow clust}$ between the synthetic point cloud and the cluster is known, the transformation $T_{cad \rightarrow 3D}$ between the CAD model (which uses the same coordinate system as the synthetic point cloud) and the measured point cloud is known (see Figure 8b). In the next phase visible points of interest are selected on the measured point cloud. These points of interest can be predefined in the CAD model, or they can be obtained from a mesh from e.g. numeric simulations. Using a mesh from numeric simulations provides a direct mapping between measured points and simulated points. To find visible points of interest (sample points) a visibility analysis in combination with the calculated object-transformation is used to select visible sample points (see Figure 8c).

3.4. *Step 3: Measurements*

After step 1 (Calibration) and step 2 (Pose calculations), the 3D position of the visible sample points will be converted to the 2D coordinate system of the RGB camera. Next these 2D coordinates will be converted to the corresponding mirror angles of the SLDV (see equations 1 and 2). After aiming the laser with these mirror angles, the selected points of interest will be measured by the SLDV.

Figure 8: (a) Example of a simulated point cloud. (b) Example of the matched CAD model (yellow, lines) and a measured 3D point cloud (blue, points). (c) Example of visible sample points (red) of the left wing plotted on top of the measured point cloud.

Figure 9: Comparison between (a) our new 3D method and (b) the original output from Polytec. Note that the Polytec viewer filters (smooths) the output where our visualization shows the real (unfiltered) results.

4. Results and discussion

With our methodology it is possible to correlate the LDV measurements directly with the CAD model. As a result it is easier to compare real measurements with numerical simulations. In Figure 9 we compare the result of a traditional scanning method (using Polytec software) with the result of the proposed procedure. The measurements are mapped on a 2D view of the object. With our procedure (Figure 9a) the scanning grid is directly mapped on the CAD file.

Although the concept of the procedure works, further work is possible. An extension of the calibration procedure from 2D to 3D can be used to increase the

accuracy with which the laser can be aimed in the case of complex 3D shaped objects. In our experiments the error is approximately 4mm. Which is in the same order as the size of the laser spot in the 2D RGB image (+- 10mm).

5. Conclusion

Scanning laser Doppler vibrometers (SLDV) are accurate instruments based on laser interferometry that can measure high spatial resolution vibration data. Current techniques require a lot of user interaction during the calibration of the SLDV-system and setup of the measurement. Our methodology eliminates this user interaction with an automated calibration procedure and the detection of the test-object using a the 3D model of the test-subject and a 3D camera. The methodology also incorporates automatic mapping between a CAD model and the vibration measurements. This mapping is used to directly visualize measurements on a 3D CAD model. Also this mapping can be used to directly compare measurements and numeric simulations.

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