



Chapter 10

Advanced Mesh Reconstruction with Low-Budget RGBD Hardware for Modal Analysis

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Abstract To perform modal analysis, a digital 3D reconstruction of the structure under investigation is required. The acquisition and creation of such reconstructions is very time-consuming and cost-intensive, especially for performing simulations, and is mainly created manually using CAD software. Measurement-based approaches often use much simplified reconstruction models, such as line models, because of this problem. Due to the rapid development of inexpensive RGBD scanners, such as the Intel RealSense or ZED depth cameras, it is obvious to use them also for the field of modal analysis.

In this publication, the performance of these depth cameras and of algorithms for semiautomated post-processing of the 3D scans is investigated, especially for use as a reconstruction basis for finite element analysis. In addition, the 3D reconstructions are also used and evaluated in experimental modal analysis applications. Especially for the algorithms to interpolate unmeasured nodes of the reconstruction, the quality of the reconstruction plays a special role.

The whole acquisition and analysis process consists of three steps and is integrated in the WaveImage software. It starts with the acquisition of the Intel RealSense and ZED depth information (RGBD) and the following online 3D reconstruction. After the acquisition of the reconstruction, the post-processing is performed, which is applicable for beginners as well as experts. Finally, the processed reconstructions are used and validated in the software WaveImage both in the finite element and in the experimental modal analysis.

Keywords Computer vision · Depth camera · 3D reconstruction · Modal analysis · FEA

10.1 Introduction

Creating triangle meshes is a basic requirement for many finite element analysis (FEA) software packages. This is due to their simple geometric description and associated numerical properties. Usually, these triangle meshes are generated from computer-aided design (CAD) models. Creating these models is very time-consuming and requires a lot of expert knowledge.

In this work, we show how a triangle mesh of a given structure can be created with relatively inexpensive RGBD (red, green, blue, depth) sensors and a simple workflow.

10.2 Background

CAD are common practice in the engineering field. Unfortunately, their creation is very time-consuming and requires the use of expensive, specialized software. CAD programs are dedicated technical drawing programs and require exact dimensions of the individual components of the object to be measured.

Measuring the structure is often a labor-intensive process fraught with various sources of error, such as incorrectly assigned or forgotten dimensions. Errors may not be noticed until later, and the need to repeat the measurement makes it even more time-consuming. The procedure is therefore very cost-intensive.

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Reverse engineering for CAD models is offered as a service, using special laser scanners or strip projection scanners. These generate enormous amounts of data in the form of 3D point clouds, which are then used as templates to reconstruct the underlying object with points, lines, and geometric surfaces.

10.3 Technical Implementation

The general workflow for performing FEA includes data preparation in addition to the actual simulation; this essentially creates the volumetric triangle mesh from a surface geometry. We put another step ahead: data acquisition (see Fig. 10.1). The data acquisition phase serves to create a surface model so that the preprocessing for the simulation can be carried out successfully.

10.4 Data Acquisition

The data acquisition with RGBD sensor is comparable with recording a normal video, with the difference that the device is connected to a computer where the data from the RGBD sensor is read and stored by a software. A pure RGBD sensor delivers only RGB images and a corresponding depth image. A sample frame is shown in Fig. 10.2.

Commercial as well as freely available software solutions exist to create 3D meshes from captured RGBD frames. In this work we used RecFusion (commercial) and Open3D (open source).

Open3D is an open-source library aimed at developing software that processes 3D data [1]. The Open3D front end provides a set of data structures and algorithms in both C++ and Python. It contains ready-to-use tools for offline and online reconstruction. Since the Intel RealSense SDK [2] is directly integrated, Intel RealSense sensors can be used without additional effort. The code is maintained through a clear code review mechanism.

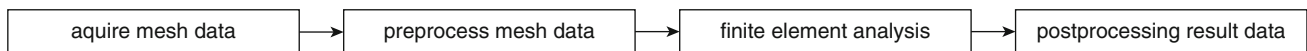


Fig. 10.1 Adding a data acquisition step (most left) to the usual FEA workflow

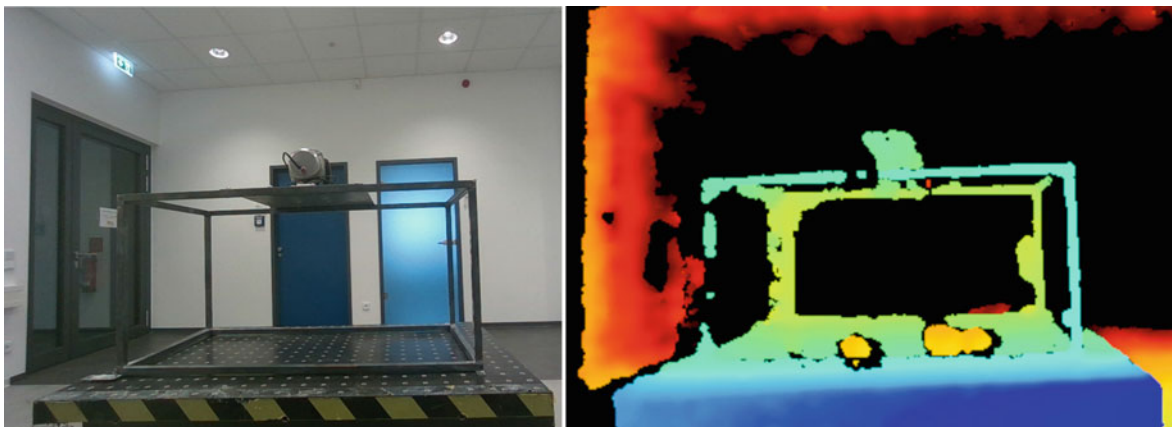


Fig. 10.2 Image taken with a stereo camera. On the left the RGB image. On the right the depth image colored with a color map. Blue means close and red far away

RecFusion is a relatively inexpensive commercial software that supports mainly Intel RealSense devices and enables real-time 3D reconstruction. Other features include high-quality texture mapping and 3D model post-processing. Overall, RecFusion offers an intuitive workflow and very satisfying 3D scan results.

10.5 Data Sources

For this work, we selected three structures that we believe represent a wide range of structures to be expected in modal analysis: a machine frame constructed of fine struts, a thin-walled vase, and a car rim (see Fig. 10.3). Particularly fine struts are not yet reliably detected by all RGBD sensors.

10.6 Data Quality Check

Since the data is coming from a sensor, a certain amount of noise should be expected. Consequently, the conditions for the triangle mesh required to perform a FEA are often not met. The data quality must be checked carefully, especially for 3D scan data.

To carry out a FEA, the triangle mesh must be closed, i.e., there must be no boundaries inside the surface. On the other hand, each edge of the triangle mesh may only belong to a maximum of two triangles, and all triangles meeting at one point must form an open or closed fan. The first condition is the watertight condition and the second is the manifold condition. See Fig. 10.4 for a visual explanation.

10.7 Data Preparation

The defects of the 3D models created during the scan can be systematically edited. In a first step, the 3D model is cleaned to remove artifacts and unwanted parts of the scan. In the cleaned scan, the manifold condition is then checked and corrected if violated. For this correction there are different strategies, e.g., deleting the points and edges, which are responsible for the violation. This step can cause holes in the triangle mesh that have to be closed to fulfill the water tightness condition. By closing the holes, however, the manifold condition can be violated again. An iterative procedure is necessary which can also



Fig. 10.3 Textured scans we use in this work. On the left a machine frame, next to it a clay vase and on the right a car rim

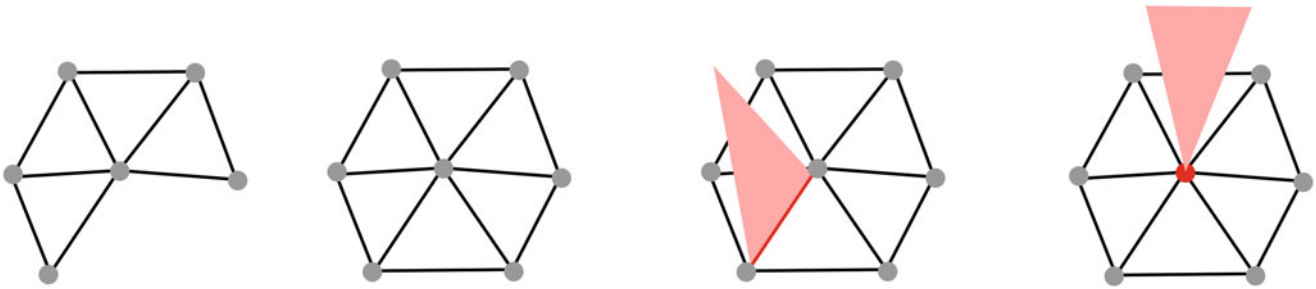


Fig. 10.4 From left to right. An open fan next to it a closed fan and next to this a fan that is not manifold by multiple edge occupation and right to it by multiple vertex occupation

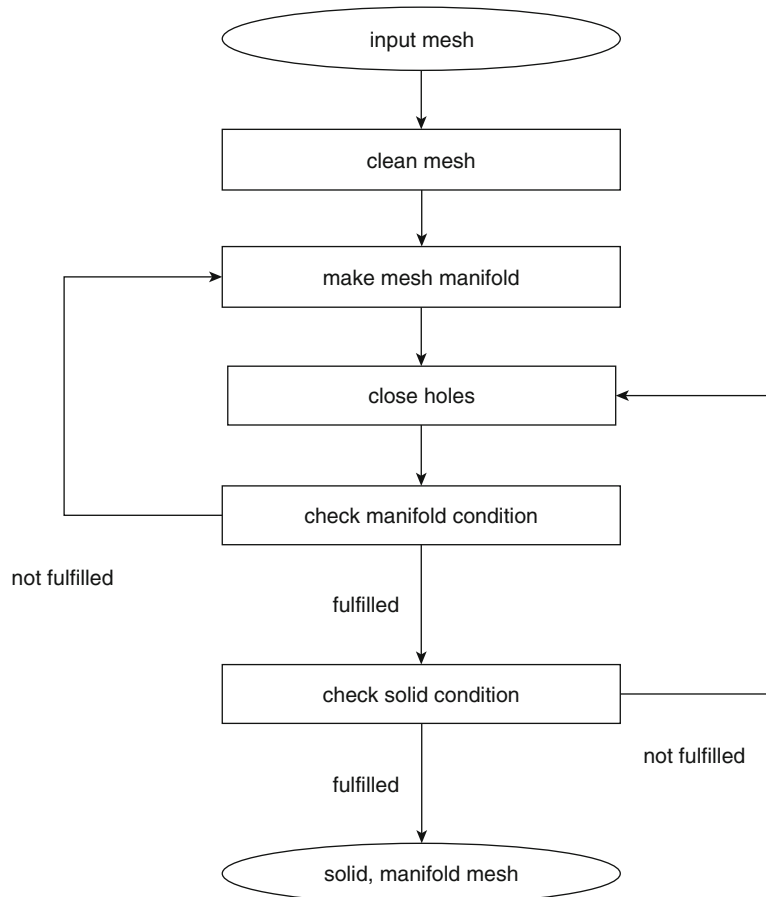


Fig. 10.5 Flow graph of the data preparation algorithm

be implemented automatically (see Fig. 10.5). A hard termination condition should be included since it is not guaranteed that both required conditions can be satisfied at the same time, which would result in an infinite loop. Our experiments show that our proposed sequence chain terminates after 1–10 iterations. If it does not terminate after a predetermined amount of iterations, it is recommended to start a new scan.

10.8 Results

We applied our algorithms to the models presented above and performed FEA on the generated geometries. To evaluate the results, we compared them with a simulation of a CAD model for the machine frame and with the results of experimental modal analysis for the car rim.

To determine the dynamic behavior of the machine frame, FEA was performed with the corresponding CAD model. This provided the identification of the modal parameters natural frequency and mode shape. It was carried out using WaveImage [3], a comprehensive structural analysis software package that offers FEA as well as measurement-based algorithms, including EMA, which will be used later in this chapter.

“General Steel” was selected as material for the simulation since the exact steel grade was not known. It was used for both the CAD model and the scan model of the machine frame. We had to consider that the machine frame is fixed to the floor. This boundary condition could easily be defined on the CAD model in WaveImage. For the scan model, this was not possible because in the geometry, the machine frame was not separated from the floor it was mounted on by our preprocessing. Besides this, our scan model generated unnecessarily many elements for the floor. This was caused by many artifacts at the bottom of the scanned floor (see Fig. 10.6). The additional mass of the floor corresponds to the mass of the machine frame and acts as a fixture for the upper part of the scanned model.

Despite the lack of boundary conditions for the scan model, we were able to find the same modes in the scan and CAD geometry. We consider a mode shape to be the same if it is found at approximately the same position in the frequency band (see Figs. 10.7 and 10.8). The maximum difference in frequency for the vibration modes shown is 10 Hz.

For the car rim, experimental modal analysis was performed with WaveImage to determine its dynamic behavior. This provided the modal parameters (natural frequency, mode shape, and damping) from known system excitation and measured system response (Fig. 10.9).

In the experimental setup, the car rim was elastically supported and aligned. A broadband impulse excitation of the system was applied at the outer, lower edge of the rim using an automatic impulse hammer. The resulting system response



Fig. 10.6 From left to right. (1) bottom of machine frame with artifacts. (2) reconstruction result. (3) scanned model of vase. 4: reconstruction result of vase. Even the inside was reconstructed well, but the mass distribution in the reconstruction result is no longer symmetrical

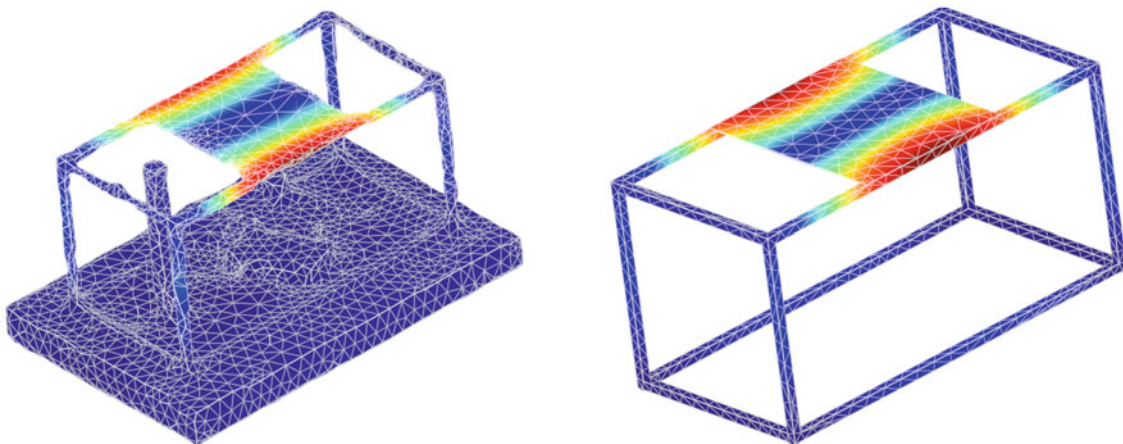


Fig. 10.7 Corresponding mode shapes on machine frame. Left: scan model with mode shape at 89.6 Hz. Right: CAD model with mode shape at 94.0 Hz

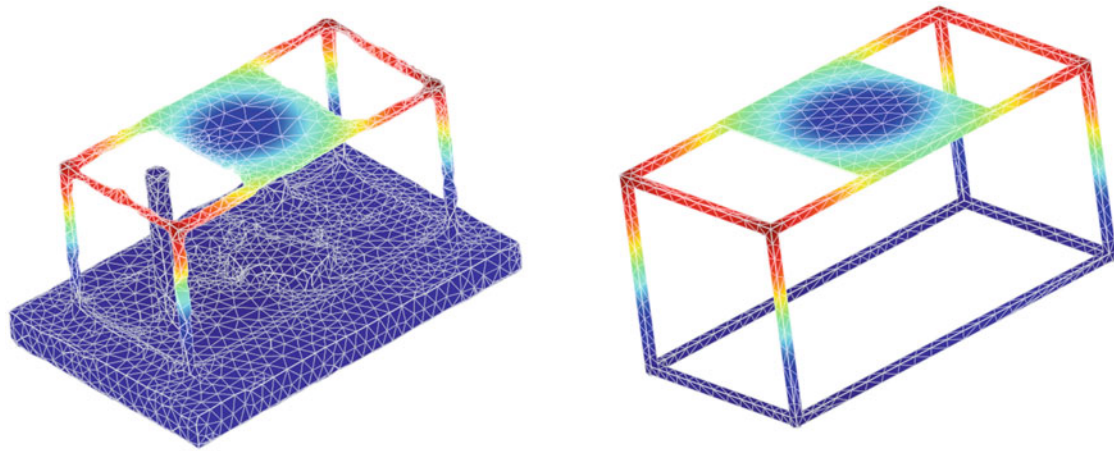


Fig. 10.8 Corresponding mode shapes on machine frame. Left: scan model with mode shape at 65.0 Hz. Right: CAD model with mode shape at 54.0 Hz

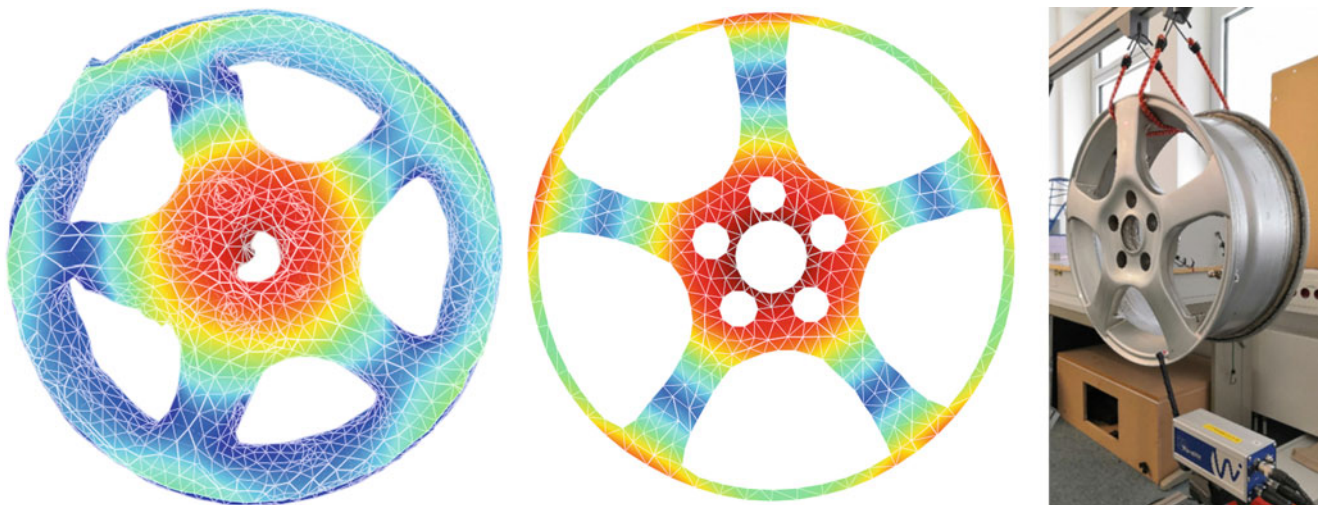


Fig. 10.9 Mode shapes on the car rim. Left: mode shape at 1569.5 Hz after reconstruction and FEA simulation. Center: mode shape at 1215.0 Hz calculated with EMA based on LSV measurements. Right: measurement setup with impulse hammer WaveHIT

was recorded via a laser scanning vibrometer (LSV) [4]. This is a noncontact measurement method, which, thanks to its scanner unit, also provides an automated scan of the structural surface over any number of measurement points. In this series of measurements, more than 400 measuring points were selected to achieve a high local resolution and to ensure a high quality of the result. The measurement setup is shown in Fig. 10.9.

Since the exact material composition of the car rim was not known, “General Aluminum” was chosen for the FEA. The boundary conditions were set as free since the car rim was elastically supported for the EMA. The deviations between measured and simulated modes of vibration were larger than in the previous example. This was to be expected, since the results of different calculation methods, namely, FEA and EMA, were compared. It was due on one hand to the not precisely known material parameters in the simulation and on the other hand to the absence of boreholes in the car rim in the scan model. The elastic mounting can also influence the measurement and must be taken into account when evaluating the results.

10.9 Conclusions and Outlook

We successfully demonstrated a workflow for the automatic construction of a triangle mesh with subsequent mode shape calculation by means of a FEA simulation. Employing it requires little skills and knowledge with CAD programs by the user. Together with stereo cameras available on the market, we have designed a cost-effective system that greatly simplifies the creation of geometries for modal analysis. With this system, even users with little experience in geometry modeling are able to create 3D scans that can be used for FEA simulation.

Our system benefits from the rapid development in the field of stereo cameras, which provides depth images of better and better quality. It is also possible to use other measurement systems such as laser scanners as long as they provide either a point cloud or a triangle mesh. In the case of a point cloud however, a triangulation is necessary as an initial step of our algorithm since concepts like the edge and the closeness of a surface are difficult to implement on point clouds.

A necessary improvement of our system is the separation of the structure under investigation from the environment. To achieve this, semantic segmentation could be used. This is a current branch of research in the field of computer vision that aims to use images and depth information captured from stereo cameras to map semantic information onto the created 3D model. It could support the user cleaning up the recorded 3D models.

Acknowledgments I would like to thank all the people that made this work possible, in particular Maik Gollnick for giving important insights and feedback on modal analysis topics touched in this work, Jan Heimann for providing results and insights on LVS measurements, and Jacob Krause for the intense proofreading and correction hints.

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