A new method for the accuracy evaluation of a manufactured piece

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Abstract. To evaluate the accuracy of a manufactured piece, it must be measured and compared with a reference model, namely the designed 3D model, based on geometrical elements. In this paper a new method for the precision evaluation of a manufactured piece is proposed, which implies the creation of the piece digital 3D model based on digital images and its transformation into a 3D mesh surface. The differences between the two models, the designed model and the new created one, are calculated using the Hausdorff distance. The aim of this research is to determine the differences between two 3D models, especially CAD models, with high precision, in a completely automated way. To obtain the results, a small piece has been photographed with a digital camera, that was calibrated using a 3D calibration object, a target consisting of a number of 42 points, 36 placed in the corners of 9 wood cubes with different heights and 6 of them placed at the middle of the distance between the cubes, on a board. This target was previously tested, the tests showing that using this calibration target instead of a 2D calibration grid, the precision of the final 3D model is improved with approximately 50%. The 3D model of the manufactured piece was created using two methods. First, based on digital images, a point cloud was automatically generated and after the filtering process, the remaining points were interpolated, obtaining the piece 3D model as a mesh surface. Second, the piece 3D model was created using also the digital images, based on its characteristic points, resulting a CAD model, that was transformed into a mesh surface. Finally, the two 3D models were compared with the designed model, using the CloudCompare software, thus resulting the imperfections of the manufactured piece. The proposed method highlights the differences between the two models using a color palette, offering at the same time a global comparison.

1. Introduction

In recent years non-metric digital cameras have known a great development, being used in a wide range of applications, such as: preservation of cultural heritage, the shoreline dynamics study, the wave movement for costal protection, soil erosion, industry, etc.

Taking into account that a manufactured piece may have imperfections, in order to determine their size, the piece must be measured and compared with a reference model, namely the designed 3D model, based on geometrical elements. This measuring process require a high precision device, either a micrometer or a CMM (Coordinate Measuring Machine), is semi-automatic and time consuming and
the comparison process is done manually. On the other hand, if we want to highlight the missing parts of the manufactured piece, we have to do it visually.

So, a new method to evaluate the accuracy of a manufactured piece and the representation completeness, in a completely automatic way, is necessary. Knowing that most of the designed 3D models are CAD models, we suggested to transform them into 3D mesh surfaces, so they can be used in the comparison process. The differences between the two models represented as mesh surfaces, the manufactured piece 3D model created based on digital images and the designed model, are now calculated using the Hausdorff distance, considering as reference model the designed model.

The camera calibration process is necessary to obtain metric information from two-dimensional (2D) images of the three-dimensional (3D) world. The purpose of camera calibration is to describe the projection model that relates both coordinate systems, and to identify intrinsic camera parameters so it can be used as a measurement device. Such parameters are usually calculated from a calibration target that contains easily and accurately detectable features in the captured image [1].

The motivation of this paper is to create a precise 3D model of a manufactured piece by close-range photogrammetry, which will be used to evaluate the accuracy of the manufactured piece and the representation completeness, in a completely automatic way.

2. Material and methods

**Equipments.** For this case study a small manufactured piece was chosen and for the images acquisition a Canon PowerShot SX120 IS digital camera (10 Mega pixel), equipped with a 5.744 mm by 4.308 mm image sensor was used. The digital image has a resolution of 2816 x 2112 pixels.

**The 3D calibration target.** Calibration using 3D calibration objects yields very efficient results, although the calibration elements must be accurate and require an elaborate configuration [1].

In the mentioned context, a target consisting of a number of 42 points, 36 of them being placed in the corners of 9 wood cubes with different heights and 6 of them on a board, was used as a 3D calibration object for the calibration model. This target was then attached to a room wall in order to make image observations. A coordinate measuring machine (CMM), produced by Aberlink, with an uncertainty within the working space of 2 µm, was used to place the target in the world coordinate system. The 42 control points coordinates were measured in the \((X, Y, Z)\) coordinate system, corresponding to the world coordinate system, with the XOY plane, the board plane and the OZ axis perpendicular to the board plane [2].

**The Hausdorff distance.** Hausdorff Distance - named after Felix Hausdorff, is the most famous metric for comparing two mesh surfaces, providing a global comparison [3].

Hausdorff symmetric distance \(d_S(S, S')\), is defined as follow [4]:

\[
ds(S, S') = \max[d(S, S'), d(S', S)]
\]

The symmetrical distance offers a more accurate measurement of the differences between two surfaces, because the one-side distance can lead to an underestimation of the distance values between the two surfaces [4].

The distance accompanied by its sign was introduced in the “CloudCompare” software for an independent evaluation of the areas that belong to the first surface and are situated inside or outside the space, relative to the second surface [5,6].

3. Results and discussions

**The Canon PowerShot SX120 IS digital camera calibration.** Having a 3D object, one image is enough to estimate the camera parameters through the calibration process, but for this experiment we used 3 images, taken from 3 different positions, the camera parameters being calculated as an average.
The control points are often circular, because they are easy to make and accurate to measure in subpixel precision from digital images.

For the following experiments the camera calibration toolbox for Matlab (version 3.0) implementing the Heikkila and Silven’s method was used [7,8]. This Matlab toolbox is available at www.ee.oulu.fi/~jth/calibr/ and utilizes a new bias correction procedure for circular control points and a nonrecursive method for reversing the distortion model. The intrinsic parameters such as focal distance \( f \), optical center point \((u_0,v_0)\), correction of radial distortion \((k_1, k_2)\), correction of decentering distortion \((p_1, p_2)\) and the image scale factor \( s_u \), for the three images taken with the Canon PowerShot SX120 IS digital camera, are presented in Table 1.

| Image | \( s_u \) | \( f \) [mm] | \( u_0 \) [pixels] | \( v_0 \) [pixels] | \( k_1 \) [mm\(^{-2}\)] | \( k_2 \) [mm\(^{-4}\)] | \( p_1 \) [mm\(^{-2}\)] | \( p_2 \) [mm\(^{-4}\)] |
|-------|----------|---------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| 1     | 1.0025   | 5.9898        | 1435.7557       | 1063.5828       | 8.97139       | -3.45656       | -5.88285       | -4.01607       |
| 2     | 1.0029   | 5.9856        | 1432.6982       | 1067.9399       | 9.13208       | -3.53836       | -6.88640       | -4.42121       |
| 3     | 1.0027   | 5.9932        | 1444.6962       | 1080.9282       | 9.16506       | -3.63519       | -6.17076       | -5.17371       |
| Average | -        | 5.9895        | 1437.7167       | 1070.8170       | 9.08951       | -3.54337       | -6.31334       | -4.53700       |

The radial and decentering distortion profiles for the Canon PowerShot SX120 IS digital camera, computed for the 3 images, are presented in figure 1. To model the radial distortion \( \Delta r \) the odd-order polynomial \( \Delta r = k_1 r^3 + k_2 r^5 \) was used, where \( r \) is the radial distance. The decentering distortion \( P(r) \) was graphically represented in a manner similar to the radial distortions, using the function \( P(r) = \sqrt{p_1^2 + p_2^2 \cdot r^2} \).

![Figure 1](image1.png)

**Figure 1.** (a) Radial and (b) decentering distortion profiles for the Canon PowerShot SX120 IS digital camera, computed for 3 images.

The designed piece 3D model creation. The designed piece 3D model was created based on its dimensions using the Autodesk 3ds Max software (figure 2a) and was converted into a mesh surface by exporting the model into *.stl file format (figure 2b).
The manufactured piece 3D model creation as point cloud. To create the 3D model of the manufactured piece, the piece was placed on a 2D grid of squares and photographed all around with the 6 mm minimum focal length of the Canon PowerShot SX120 IS digital camera, 22 images being taken from 22 different camera positions distributed circularly around the object. Using the “3DF Zephyr Pro” software [9], a dense point cloud (figure 3a) and a mesh surface (figure 3b) were automatically generated. In order to scale the model, four control distances were used, representing the sides of the squares situated in the immediate vicinity of the piece, the RMS (Root Mean Square) being 0.144 mm and the scale factor 2.23. Then, using the local coordinates of six control points representing the grid intersections, the piece 3D model was brought in a local system with the XOY plane in the grid plane, the RMS being 0.193 mm. The point cloud and the mesh surface were imported into „MeshLab“ software where, through the filtering process, only the points, respectively the mesh corresponding to the piece surface were extracted.

\[ \text{Figure 2. The designed piece 3D model (a) CAD model, (b) mesh surface.} \]

\[ \text{Figure 3. The designed piece 3D model, created in the “3DF Zephyr Pro” software (a) point cloud, (b) mesh surface.} \]

**The manufactured piece 3D model creation based on its characteristic points (CAD model).** To create the 3D model of the manufactured piece based on its characteristic points, the same images as in the previous case were used.

The characteristic points of the manufactured piece and also the corners of the 2D grid, were manually marked on each image individually. By processing the data, using the bundle adjustment algorithm implemented into “PhotoModeler Scanner 2012” [10], the 3D coordinates of all referenced points were computed, their measurement precision was estimated and also the exterior orientation parameters for each camera position were calculated. Thus, were computed the 3D coordinates of a number of 127 points, of which a total of 83 points represent the 2D grid corners (figure 4a). Knowing that the 2D grid size is 10 mm, the object was scaled using a 70 mm line whose ends were clearly identified in the images, the scale factor being 8.46.
The manufactured piece 3D model (figure 4b) was created based on its characteristic points, i.e. the points defining the top and inferior bases, the top hole limit and the limits of the small holes on the sides, using the "PhotoModeler Scanner" software specific functions, as following: point-line-surface.

For this case study, all the image coordinates errors were less than 5 pixels tolerance suggested by "PhotoModeler Scanner". The overall residual of the project was 0.847 pixels, less than the recommended of 5 pixels. The total error for determining the world coordinates, range between 0.018 mm and 0.186 mm. The angles between the projection rays range between $140.0765 \div 890.9712$, the recommended angle being of 900, with an average of 830.2070.

Comparing the buildings under study by the proposed method. To determine the accuracy of the manufactured piece by the proposed method, the 3D models created as a point cloud and the CAD model, must be compared with a reference model considered for this case study the designed 3D model. In order to compare the 3D models, they must be brought in coincidence. For this case study the models were aligned using 3 common points.

![Figure 4. The manufactured piece 3D model, created in the "PhotoModeler Scanner" software, (a) the resulted elements of the bundle adjustment, scaling and rotation processes and (b) detail.](image)

After comparing the manufactured piece 3D model, created as a point cloud, with the designed 3D model of the piece, the following differences were obtained: maximum positive of $0.58 \text{ mm}$, maximum negative of $-1.42 \text{ mm}$, mean difference of $0.23 \text{ mm}$ and the standard deviation of $0.32 \text{ mm}$, as can be seen in figure 5. Analyzing the color palette we can easily obtain the value for the Hausdorff distance, for example some points situated on the top of the 3D model are colored in blue tone, corresponding to a value of about $-1.40 \text{ mm}$ on the scale. On the other hand, the points around the upper hole are colored in yellow and orange, corresponding to values between 0 and 0.33 mm and the rest of the top points are colored in green, corresponding to a value of around $-0.73 \text{ mm}$, so we can say that there is a small dent on the top of the manufactured piece. For the side of the piece, the differences are in range of $-0.30 \text{ mm} \div 0$ and $0 \div 0.30 \text{ mm}$. 
Figure 5. (a) The differences between the manufactured piece 3D model, created as a point cloud and the reference model, (b) the differences distribution histogram.

We can compare the manufactured piece 3D model, created based on its characteristic points and represented as a mesh with the designed 3D model, represented also as a mesh, but the Hausdorff distances are calculated only in the vertices of triangles (figure 6a). In order to obtain a better accuracy, a sampling of each triangle surface is necessary. Thus, for each triangle which belongs to the mesh surface, 100 sample points were generated and after computing the distances between each point and the designed 3D model mesh (figure 6b) [11,12], the following differences were obtained: maximum positive of 0.19 mm, maximum negative of -0.37 mm, mean difference of 0.09 mm and the standard deviation of 0.09 mm.

Analyzing the color palette we can easily say that the differences for the side of the 3D model are around -0.37 mm (blue color) for a small upper part, between -0.16 mm and -0.02 mm (green color) for the most of the side and between -0.02 mm and +0.19 mm (yellow to red) for a small bottom part. The same differences can also be observed for the top of the 3D model.

If we want to highlight the missing parts of the manufactured piece, we assume that our 3D model doesn’t have the side holes. Second, we create sample points for each triangle of the mesh surface and we calculate the Hausdorff distance for each point. From figure 6c we can see that the points located in the right of the holes are colored in red, blue and yellow, showing the maximum differences between the two models, while the rest of the points are colored in green, the differences being close to 0. We can conclude that from our 3D model the holes are missing.

Figure 6. The differences between the piece 3D model, created based on its characteristic points and the reference model (a) mesh 3D model, (b) sample points of each triangle of the mesh, (c) sample points of the mesh without the holes on the side.

4. Conclusions
Before any camera system is used for photogrammetric projects, the intrinsic parameters of the camera: focal length (f), optical center point (u₀,v₀), correction of radial distortion (k₁, k₂), correction of tangential distortion (p₁, p₂) and the medium image scale factor s₀, as well as the extrinsic parameters (rᵢⱼ, X₀, Y₀, Z₀) should be determined in the calibration process.

The accuracy in 3D reconstruction of an object is directly proportional to the accuracy of determining the scale factor, so it is recommended to use a 2D grid to be photographed simultaneously with the object.

When creating a 3D model as a point cloud by using the Structure from Motion algorithm, the result is obtained with high accuracy, in a completely automated way and in a very short time. By comparing it with the design 3D model, by the proposed method, the imperfections are measured and highlighted using a color palette. For a correct estimation of the imperfections size, we have to take into account the RMS of the 3D model.
When creating the 3D model as point-line-surface (CAD model), we lose much of the representation fidelity, i.e. small holes, big scratches, etc. and when comparing it with the design 3D model, we obtain only dimensional differences.

The proposed method for 3D models comparison, offers a comprehensive assessment of the differences between two 3D models by using a color palette, the user being able to quickly and accurately identify the errors of the 3D model that was compared with a reference model considered with no errors. It also illustrates the missing elements of the 3D model that was evaluated by generating sample points for each triangle surfaces which are components of the mesh surface, or by changing the reference model with the compared model.

The disadvantage in using this method for 3D models comparison is that we can compare only the exterior of the manufactured piece, because the images are taken only for the exterior of the piece.

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