Layer contour characterization in additive manufacturing through image binarization

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Abstract: On-Machine Measurement adoption will be key to dimensional and geometrical improvement of additively manufactured parts. One possible approach based on OMM aims at using digital images of manufactured layers to characterize actual contour deviations with respect to their theoretical profile. This strategy would also allow for in-process corrective actions. This work describes a layer-contour characterization procedure based on binarization of digital images acquired with a flat-bed scanner. This procedure has been tested off-line to evaluate the influence of two of the parameters for image treatment, the median filter size (Sf) and the threshold value (T), on the dimensional/geometrical reliability of the contour characterization. Results showed that an appropriate selection of configuration parameters allowed to characterize the proposed test-target with excellent coverage and reasonable accuracy.

Keywords: Additive manufacturing, Contour characterization, Binarization thresholding.

1. Introduction

Additive Manufacturing (AM) encompasses a series of processes capable of creating a three-dimensional geometry from bidimensional layers that are stacked vertically. AM processes can generate complex geometries without special tooling or ad-hoc fixtures, they are versatile and relatively fast since they can reduce the lapse between design and production [1]. Nevertheless, there are also some drawbacks that difficult the industrial adoption of AM. A lower geometrical and dimensional quality, especially when they are compared with material removal processes, is among those drawbacks.

Consequently, great efforts are being conducted to obtain early characterizations of geometrical and dimensional distortion of AM parts, including on-machine metrology (OMM) [2]. Among the different technologies that could be used for in-process OMM, flat-bed (FB) scanning is obtaining promising results [3]. Nevertheless, some issues like image distortion [4-6] or image processing [7] have a great influence upon the quality of contour detection, affecting the feasibility of metrological procedures based on FB scans.

The present work analyses the feasibility of using image binarization to accurately characterize layer contours in material extrusion (MEX) AM processes. This research analyses the relevance of two processing steps: image filtering and image binarization. A test specimen was manufactured and digitized using a commercial FB scanner. The variability of a series of quality indicators with respect to variations in two parameters, the size of a noise filter and the binarization threshold, were calculated and analysed. Image processing included several additional consecutive steps, like region filling and isolation, contour tracing and discretization, local distortion adjustment (LDA), and point clustering.
2. Materials and methods

The experimental plan included the design and manufacturing of a test specimen. This part was then digitized using a Coordinate Measurement Machine (CMM) to obtain reference values that will be used for comparison. The part was also digitized using a FB scanner and the digitized image was processed to extract discrete points along the contour under different combination of test conditions. The results obtained with each test combination were compared with the reference ones to characterize the influence of variations in image processing factors upon the quality of contour reconstruction. This procedure will be described in detail in the following paragraphs, although a summary is provided in the flowchart of figure 1.

Figure 1. Experimental procedure.

2.1. Design verification and digitalization of a test specimen

An ad hoc test specimen was used to characterize the quality of contour reconstruction, since the usual benchmark artifacts (NIST-type) have multiple contours and are not fully adequate for the current state of the technique. The upper layer contour of an inverted conical frustum was selected as characterization subject (figure 2(a)). This geometry provided a sharp contour while minimizing the noisy effect of lower layers. The 8 mm distance between the target layer and the background contributes to create certain level of contrast between them. The upper circumference had a nominal size of 40 mm, and the specimen was manufactured in white polylactic acid (PLA) in a SigmaR16 BCN3D printer. A chamfered square profile was used in the external contour of the specimen in order to facilitate its positioning onto the scanner bed.

Once manufactured, a digitizing procedure was performed with a DEA Global Image 09-15-08 CMM, calibrated according to ISO 10360-2:2009 [8]. The maximum permissible error of length measurement \( E_{0,MPE} \) was (equation 1):

\[
E_{0,MPE} (\mu m) = 2.2 + 0.003 \cdot L \quad (L \text{ in mm})
\]  

A discrete-contact probing strategy was used to digitize 360 contour points (one for each 1°). The diameter and the location of the centre was then calculated by means of a least-squares fitting algorithm. Considering the relative position of digitized points, the radial deviations with respect to the theoretical radius were calculated and thereafter used as reference values. Temperature in the laboratory during verification procedures was maintained within a range of 20 ± 2 °C and metrological operations were performed using PC-DMIS metrology software.
Test specimen was then digitized in an Epson V39 FB scanner. A 2400 dpi resolution was used to obtain an 8-bit grey-scale image. Accordingly, each pixel would represent one of 256 intensity levels, ranging from 0 (pure black) to 255 (pure white). Figure 2(b) shows the raw digitized image.

![Design and dimensions of the test specimen.](image)

![Gray-scale digitized image of the test specimen.](image)

**Figure 2.** (a) Design and dimensions of the test specimen. (b) Gray-scale digitized image of the test specimen.

### 2.2. Image processing

The digitized image was processed to identify a series of discrete contour points under different test conditions, and this objective requires several independent steps: filtering, binarization, region filling and isolation, contour tracing and discretization, local distortion adjustment (LDA) and point clustering. Two processing steps, filtering and binarization, were selected as test factors and, consequently, subjected to variations in their respective parameters.

#### 2.2.1. Test combinations for image filtering and binarization

According to [9–12] FB scanner digitized images are affected by salt & pepper (S&P) noise. This type of disturbance is mainly caused by dust particles deposited on the optical surfaces. The negative influence of this phenomenon can be reduced by noise filtering. In present work, the Matlab® `medfilt2` [13] function was used. The syntax of this command is provided in equation (2).

$$J = \text{medfilt2}(I, [m, n])$$

This filter provides an output image ($J$) where the value of each pixel in the input image ($I$) has been replaced by the result of applying a median filter upon the intensity values of the m-by-n pixel neighbourhood. The present work proposes a square neighbourhood ($m = n$), so that noise filtering can be parameterized with one parameter (filter size denoted as $S_f$).

The method proposed by Otsu [14] was used for image binarization. This method allows for the calculation of a threshold ($T$) for the intensity levels, so that any pixel in the image that presents an intensity value higher that $T$ will be assigned a pure white value (1 in the binary scale), whereas in the opposite situation, the pixel will take a pure black value (0 in the binary scale). Otsu calculates the optimal grey level threshold by clustering the original greyscale values in two class for each possible $T$ and minimizing the intra-class variance [14]. Once the variance has been obtained for all possible intensity levels, the optimal $T$ is calculated as the average of those levels scoring the maximum deviation value. Nevertheless, it has not been proved if such an optimal $T$ value also provides optimal results in terms of the metrological characterization of part contour and, consequently, $T$ was included as a test parameter. Accordingly, all possible combination of $S_f$ and $T$ values contained in table 1 were tested in...
the present work, and an initially processed image was obtained for each combination. Figure 2(a) contains an example of the output image after the noise filtering and the binarization steps.

Table 1. Test factors and levels.

|   |   |
|---|---|
| T | 0, 1, 2, ..., 255 |
| S_f | 1, 3, 5, ..., 55 |

2.2.2. Secondary image processing steps Scanned images can show voids inside the material that could hinder the detection of contour. Such features could be real voids or defects related to deficiencies in the deposition strategy or optical effects related to the particularities of the scanning operation. To avoid that the reliability of contour characterization could be affected by these, an image filling morphological operation is performed using the Matlab® [15] `imfill` function (equation 3)

\[ BW_2 = \text{imfill}(BW', \text{holes'}) \] (3)

being \( BW_2 \) the output image and \( BW \) the input image already binarized by Otsu.

The target layer does not only contain the top layer of the frustum geometry, since the geometry of the chamfered features that are used to align the test specimen with respect to the FB scanner are also visible. A procedure is carried out to detect the target geometry and reject the auxiliary ones (figure 2(b)).

Once the target geometry has been isolated, contour points are extracted using the Matlab® [16] `bwboundaries` function (equation 4).

\[ B = \text{bwboundaries}(BW) \] (4)

The output \( B \) is a cell array of boundary pixel locations. An example of this sequence of processing steps is provided in figure 3.

![Figure 3](image_url)

**Figure 3.** (a) An example of the image obtained after noise reduction and binarization. (b) Identification of the objective. (c) Contour tracing.

Once this discrete representation of the layer contour has been obtained, the LDA procedure described in [6] is applied. The LDA applies a transformation to point coordinates that is based on a previous characterization of image distortion using a distortion target.

The set of points identified by the `bwboundaries` function is variable and, accordingly, there is not a bi-univocal relationship between the contour points identified with image processing and the reference contour points measured with the CMM. To overcome this difficulty, each digitized point is assigned to the corresponding angular sector in a point clustering procedure. First, a least square algorithm is applied to determine the best-fit circumference, which also provides the coordinates of its geometrical centre. Then, the contour is divided into 360 angular sectors and contour points in each sector are identified and
labelled. The average radial distance for all the points within the same angular sector is then calculated and this value \( \overline{P_iC} \) is used for comparison purposes. This procedure is represented in figure 4.

![Figure 4](image_url)

**Figure 4.** Representation of the information within one sector before and after the clustering procedure.

### 2.2.3. Quality indicators and optimization criterion.

The quality of the contour reconstruction has been addressed by means of three quality indicators (QI): the coverage factor \( (C_f) \), the average of radial deviations \( (\overline{D}) \) and the standard deviation of radial deviations \( (\sigma_D) \).

Firstly, if one or several angular sectors did not contain any valid point, it results in an incomplete characterization of layer contour. Hence, the completeness of contour characterization can be characterized by means of a \( C_f \), defined as the percentage of sectors where at least one valid point has been assigned with respect to the total number of sectors. This QI reflects the percentage of contour reconstruction, so that the higher its value the better the contour reconstruction.

Secondly, the difference between the radial distance calculated from the digital image \( \overline{P_iC} \) and the reference radial distance calculated with the CMM \( \overline{P_iC}^* \) is computed for each angular sector, and the resultant value \( D_i \) is used to assess the quality of contour reconstruction (equation 5).

\[
D_i = |\overline{P_iC} - \overline{P_iC}^*|
\] (5)

Based on the results of \( D_i \) for the 360 angular sectors considered in this work, two additional QI were determined. The average of radial deviations \( \overline{D} \) reflects the overall similarity between FB scan-based characterization and CMM characterization, and low values of this QI would mean that both methods achieve similar result. The standard deviation of radial deviations \( \sigma_D \) represented the variability of \( D_i \) along the contour, and low values of this parameter would mean that the individual results provided by both methods are similar with independence of the angular sector considered.

An optimization criterion was also defined to provide a comprehensive optimal solution that gives preference to precision against completeness. Under this “accuracy priority” criterium, results of \( \sigma_D \) and \( \overline{D} \) indicators are assigned to 0.1 µm ranges and the algorithm seeks for a combination that scores both within the minimum range. If no combination simultaneously fulfils both conditions, 0.2 µm ranges are used and the procedure continues until at least one combination matches both conditions.

### 3. Results and discussion

Analysis of results showed that all tested combinations of \( S_f \) and \( T \) achieved full (100%) coverage. This means that, with independence of the size of the noise filter and the threshold used for binarization, the procedure is always capable of identifying the test objective and detect contour points in every angular sector. Nevertheless, this result does not indicate that the reconstruction was reliable at all, as it can be observed in figure 5. The representation of \( \sigma_D \) and \( \overline{D} \) results for all combinations of \( S_f \) and \( T \) shows that appropriate results (under a metrological point of view) are only achieved for a narrow range of \( T \) values. This means that, despite providing complete coverage, most of the tested combinations are useless for
geometrical characterization of the manufactured contour. Considering only those combinations of factors with $D$ under 10 $\mu$m, recommended $T$ values should be comprised between 183 and 194, and a similar result can be observed regarding $\sigma_D$. Additionally, although $S_f$ showed clearly lower influence upon quality results, it is preferable to select lower values for this parameter. The behaviour of $\sigma_D$ was quite similar, with the only difference of $T$ having a higher impact on the reduction of quality for a given $S_f$ value.

![Figure 5](image)

**Figure 5.** (a) Distribution of $\overline{D}$ results. (b) Distribution of $\sigma_D$ results.

Considering the minimization of the intra-class variance used by Otsu, the optimal value for $T$ was 192. On the other hand, the proposed “accuracy priority” criterion provides an optimal value of 183 for this parameter. Although the values are quite similar, the likeliness between image characterization and CMM characterization was found to be very sensitive to the selected threshold values (table 2).

| Table 2. Optimal combinations of factors under both considered criteria |
|---------------------------------|---------------------------------|---------|
| $T$    | $S_f$   | $\overline{D}$ [$\mu$m] $\sigma_D$ [$\mu$m] $C_f$ [%] | $T$    | $S_f$   | $\overline{D}$ [$\mu$m] $\sigma_D$ [$\mu$m] $C_f$ [%] |
| 192    | 15      | 8.82    | 8.50    | 100    | 183    | 7       | 5.93    | 5.87    | 100    |

The blue line (figure 6(a)) represents the variation of $\overline{D}$ as a function of $S_f$ for the Otsu optimal $T$ (192), whereas the red line in the same figure corresponds to the optimal calculated with the accuracy priority criterion (183). It can be observed that the results for Otsu are less dependent on $S_f$ than the results for the “accuracy priority”. “Accuracy priority” achieves the best result in terms of the metrological characterization of the layer contour, since $\overline{D}$ is 48.7% higher for Otsu (table 2). Similarly, $\sigma_D$ is a 44.8% higher for the Otsu optimal than the best result (5.87 $\mu$m) achieved with the “accuracy priority” optimal.

![Figure 6](image)

**Figure 6.** (a) Distribution of $\overline{D}$ as a function of $S_f$ for “accuracy priority” optimal $T$ (183) (red line) and Otsu optimal $T$ (192) (blue line). (b) Distribution of $\sigma_D$ as a function of $S_f$ for “accuracy priority” optimal $T$ (orange line) and Otsu optimal $T$ (blue line).
These results showed that, although the selection of optimal T with Otsu minimizes the intra-class variance, this criterion does not necessarily provide the best results in metrological terms. In fact, a certain range of T values close to the accuracy priority optimal did also provide better results for the QI than the Otsu optimal. This finding also points out that image processing methods have been designed to achieve objectives that are different than those required for an accurate characterization of geometries and contours.

The idea that the optimal processing configuration in terms of contour tracing should be also optimal in terms of geometrical reliability was proved to be wrong. This conclusion should lead to carefully analyse the influence of processing methods and configuration upon the reliability of results and avoid common places that are assumed to be true. And additional finding is that, although T has a higher influence upon QI, Sf cannot be neglected as a source of error. Figure 6 shows how for a given value of T, the optimal results corresponded to a particular value of Sf and, consequently, the best results were obtained for a singular combination of processing parameters. Figure 7 illustrates the differences in contour reconstruction for the CMM reference digitizing, the Otsu optimal and the “accuracy priority” optimal.

![Figure 7. Polar graph of the radial deviations $D_i$ calculated with the reference method (CMM) and the processing of FB scans with the Otsu optimal (Otsu) and the “accuracy priority” optimal (Generic AP).](image)

It can be observed how Otsu optimal implies a clear deviation between $P_i C$ and $P_i C^*$ in certain sectors (300° to 330°) and misses abrupt variations in contour shape (180°). On the other hand, these deviations are less pronounced in the case of the “accuracy priority” optimum.

4. Conclusions

Image binarization has proved to be a valid option for layer contour characterization of AM parts. Within the limits of this research, binarization achieved full coverage of contour with independence of the tested combination of filter size and threshold.

Nevertheless, it has also been proved that an adequate election of T and Sf is key to achieve the best possible results in terms of accuracy. Only a narrow range of T values would provide results relatively close to those achieved with a CMM, whereas out of that range the quality of contour reconstruction severely drops. The experimentation has also shown that the optimal T value calculated by Otsu does not achieve the best metrological results. Instead, optimal results demand a careful selection of image
processing configuration, since the quality indicators considered in this work are very sensitive to variations in $T$. The proposed “accuracy priority” criterion achieves quality results that are similar to those achieved by an CMM, which is a promising result. Nevertheless, although results pointed out that an adequate processing of images captured with a flatbed scanner could achieve a reliable characterization of contour geometry, they also reflect the difficulties of such procedure in terms of robustness. Variations on illumination and contrast could affect the quality of these results, so additional research must be conducted before flatbed scanning could be used for On Machine Measurement.

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