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Executive Summary of the Thesis

Study on Segmentation Techniques for Geometric Measurements in Industrial Computed Tomography

Laurea Magistrale in Automation and Control Engineering - Ingegneria dell'Automazione

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1. Introduction

X-Ray Computed Tomography(XCT) is a non-destructive measuring technique and a promising technology for metrology purposes, thanks to its ability to scan and characterize both external and internal structures of a specimen without having to destroy the test object [1]. Additionally, XCT allows the inspection of complex-shaped or assembled workpieces that may not be easily accessible for photo-optical or tactile sensors. This attribute proves particularly significant in fields like additive manufacturing, where intricate and complex geometries are frequently encountered.
The typical XCT workflow for metrology involves several distinct steps [2]:

- Physical measurement: XCT machine acquires x-ray images of the object.
- Reconstruction: employing the back-projection algorithm to generate a voxel-based representation of the part based on the XCT projection images.
- Segmentation: this step usually includes pre-processing tasks like noise reduction and applying segmentation algorithms to identify and separate the object of interest from the surrounding background or other structures within the XCT volume. Subvoxeling techniques are often utilized in a post-processing stage to refine the segmentation results, adjusting the identified points to be closer to the object's actual surface.
- Feature extraction and geometrical verification: involves identifying measuring points and their corresponding coordinates, essential for conducting measurements and analyses on the measurand.

This thesis specifically focuses on segmentation methods in XCT.

2. Objectives of the thesis

Despite significant advancements in the field, there are still challenges in segmentation analysis that need to be addressed. One major limitation is the absence of standardized procedures for segmentation and the lack of clear guidelines or benchmarks to guide researchers in choosing the most suitable method for a given application. This lack of standardization makes it difficult to objectively compare and evaluate different segmentation algorithms.

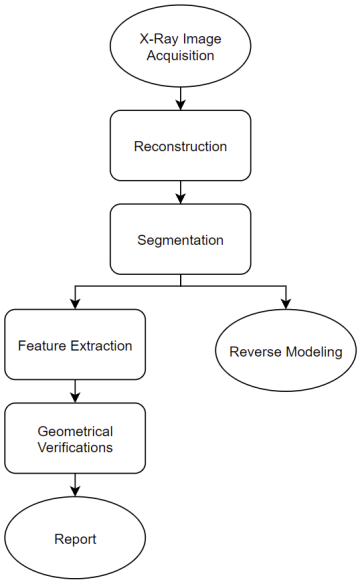

Figure 1: Workflow for metrology

Furthermore, there is a lack of comprehensive comparative studies among segmentation methods in the current literature. While individual research papers often demonstrate the effectiveness of specific algorithms or propose novel techniques, there is a need for comprehensive comparisons that assess the performance of various segmentation methods. This gap prevents researchers and potential industrial users from fully understanding the strengths and weaknesses of different approaches and limits their ability to make informed choices.
The objectives of this thesis can be summarized as follows:

- Conduct an extensive literature review to categorize the methods employed in segmentation analysis.
- Perform a comprehensive comparison of the common methods identified in the literature.
- Propose a subvoxeling technique to enhance the overall accuracy of segmentation results.

3. Literature Review

A systematic search was employed to conduct a comprehensive literature review, followed by a screening process where approximately 60 papers were identified as the most relevant papers and chosen further analysis. The primary focus was on papers related to segmentation in industrial computed tomography, with a particular emphasis on metrology.
By thoroughly examining these papers, a classification map was developed to categorize the applied methods into macro classes. The methods were divided into the following categories: threshold-based, boundary-based, region-based, neural network-based, graph-based, clustering, miscellaneous, and joint reconstruction and segmentation.
The literature review revealed the prevalent usage of certain algorithms in the field. However, it also identified the absence of comprehensive comparisons among segmentation methods as a limitation. This highlighted the significance of standardized evaluations to assist in selecting the most suitable segmentation methods.

4. Experimental setup

4.1. Specimen

The object used consists of overlapping concentric cylinders as depicted in Figure 2. The material used for the object is aluminum.

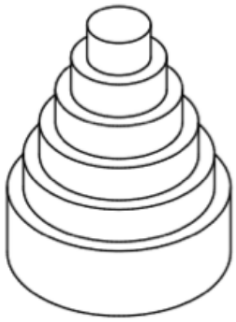

Figure 2: Aluminum specimen

Parameter Combinations		
Scan	Filter	Voltage
TI1 and TI4	No	High
TI2 and TI6	No	Low
TI3 and TI7	Yes	Low
TI5 and TI8	Yes	High

Table 1: Choice of scans' parameters combination

Table 1 provides an overview of the scan data obtained from the CT machine. In total, there were 8 scans performed, each representing a distinct combination of two parameters: voltage and filter. The high voltage setting used in

the scans was 90kV, while the lower voltage setting was 60kV. When the physical filter was employed, an aluminum filter with a thickness of 1.3mm was used.

4.2. Features

Our study aimed to measure and compare three different features of the specimens under investigation. Specifically, our focus was on evaluating two size-related features: the dimensional tolerance on the diameter (referred to as "Diameter") and the dimensional tolerance on the distance between two planes (referred to as "Height"). Additionally, we also examined a feature related to form tolerance, specifically the cylindricity of the object (referred to as "Cylindricity").

4.3. Methods

From the results of the literature review we identified some of the commonly applied methods in segmentation for industrial applications and we selected those that were most used and suitable for the application with our specimen. Specifically we chose:

- Otsu for global threshold-based methods
- Phansalkar for local threshold-based methods
- Chan-Vese for region-based methods
- Canny for edge-based methods

Apart from these standard methods, we also compared our measurements with the results obtained using VGStudioMax software.

5. Subvoxeling improvement

In this study, we implemented a subvoxeling improvement using the Taylor expansion series. This technique allowed us to accurately determine the locations of edges at a subvoxel level, specifically identifying the zero-crossings in the second derivative of the grey values in the gradient direction.
The decision to apply the subvoxeling technique to the Canny method was motivated by its direct capability to pinpoint voxels corresponding to the surface. This feature eliminated the need for an additional step to determine surface points, streamlining the segmentation process.
Additionally, given that a substantial amount of research in boundary-based methods has been conducted by a specific research group that predominantly utilized the Canny and Deriche methods, we decided to replicate their subvoxeling technique applied to the Canny method. This choice allowed us to directly compare our results with a state-of-the-art method. The subvoxeling technique we employed is extensively described in the study conducted by Yagüe-Fabra et al. (2013) [3].
In the results of the thesis, the proposed technique is referred as "CannySV" while the literature one is referred as "Canny[47]".

6. Results

The segmentation results were converted into surface voxel coordinates to evaluate the features. Plots were used to depict deviations from calibrated measurements, with the x-axis representing segmentation evaluation criteria. Each data point on the plot represents the mean of related measurements.
By analyzing the results, valuable insights into the accuracy and reliability of the segmentation methods were gained. The impact of parameters like physical filter and voltage settings was also assessed, providing information for XCT technique optimization.
All observations were validated using analysis of variance (ANOVA) to quantify dependencies on different factors.
For the diameter and cylindricity analysis, a comprehensive comparison among all methods was performed. However, due to reproducibility issues, for the height a separate analysis was conducted. This analysis involved comparing our Canny with subvoxel considering also the Canny from literature using a limited dataset.
The measurement of the diameter showed that Canny outperformed both the standard methods and the software, with a slithly improvement when both its subvoxel techniques has been applied. The ANOVA results highlighted that both the Method and the Voltage have a significant impact on the measurement, while the Filter factor seems to have a very limited impact. Additionally, none of the interactions between factors demonstrate any significant influence on the measurement.
For the cylindricity the Canny with the proposed subvoxeling technique has shown to perform much better compared to all other method, included those that inherently has subvoxeling, like Otsu and the direct measurement on the

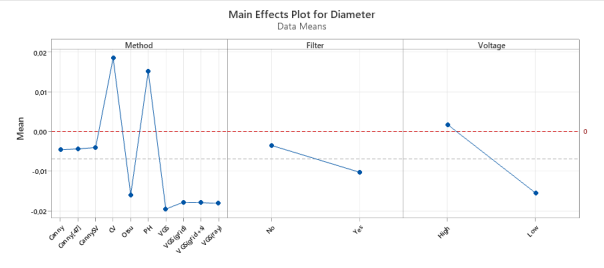

Figure 3: Main effect plot on diameter [mm]

software and also compared to Canny taken from the literature. The impact of Method, Filter and Voltage is very similar to the previous case. On the contrary, ANOVA results showed that the interactions of the second order between factors have significant influences on the measurement.

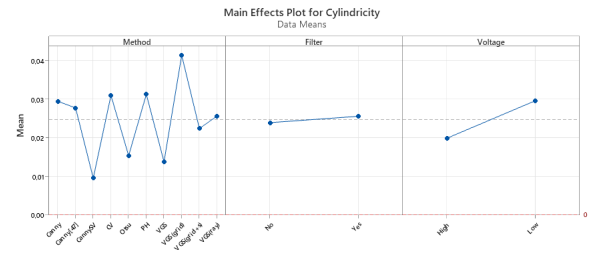

Figure 4: Main effect plot on cylindricity [mm]

Finally, for the height, the VGStudio software performed best while the standard methods were very similar to each others. The proposed subvoxeling technique instead hasn't performed very good and actually decreased the accuracy of the Canny method since it was heavily underestimating. The ANOVA indicated that the step measured has a significant influence on the measurement while the Methods becomes relevant when its interaction with the step is considered.

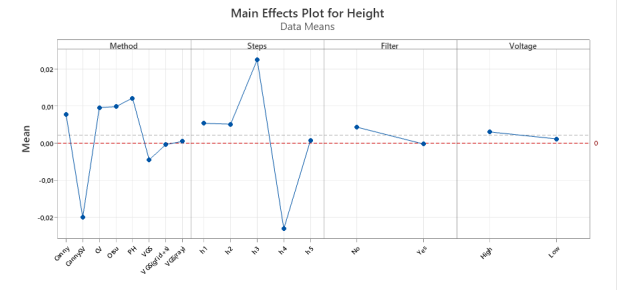

Figure 5: Main effect plot on height [mm]

Additionally, when analyzing a limited dataset of four tomographic images, the literature method showed similar results to our Canny subvoxeling technique, but both methods underestimated the measurement compared to the original Canny method. This issue is likely attributed to the noise present in the flat surfaces, which are nearly parallel to the X-rays. This noise might poses challenges in accurately identifying certain points for height measurements.

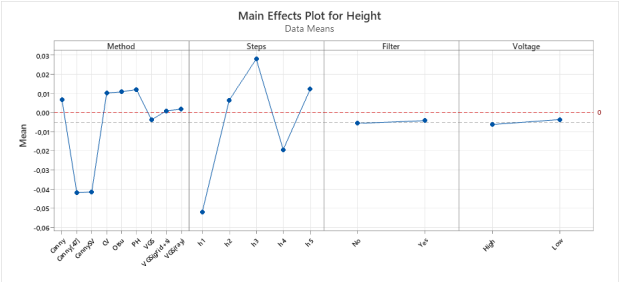

Figure 6: Main effect plot on height with Canny from literature [mm]

7. Conclusion and Future Work

In this thesis, the problem of segmentation analysis in industrial computed tomography was addressed. The lack of standardized procedures and comprehensive comparative studies in the field motivated the objectives of this research, which included conducting a literature review, performing a comparative analysis of segmentation methods, and proposing a subvoxeling technique.

The literature review provided a comprehensive overview of the segmentation methods used in industrial CT, categorizing them into macro classes and highlighting the dominant techniques. The comparative analysis focused on four commonly used methods and evaluated their performance based on various parameters of interest.

The proposed subvoxeling technique aims to improve the accuracy of segmentation results by considering finer details at the subvoxel level. The performance of the proposed technique has been evaluated and compared to the methods identified and to a commercial software.

Future work could include further refinement and optimization of the subvoxeling technique, to investigate the causes behind the poor performances on the dimensional tolerance on the distance between two planes. Furthermore, exploring the excellent performance observed in

the form tolerance measurements could involve testing various other form tolerances. Additionally, the proposed technique could be applied to different datasets and compared with alternative subvoxeling methods to assess its generalizability and effectiveness across different applications.

References

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