Comparative Analysis of 2D and 3D Visual Inspection Techniques for Precision Quality Assessment in Coffee Capsules

Pau Garrigues Carbó [1], Mauro Fabrizioli [3], Javier Pérez Soler [1], Miguel Sanchis Hernández [1], Alessandro Liani [3] and Juan-Carlos Perez-Cortes [1,2]

[1] *Instituto Tecnológico de Informática (ITI), 46022 Valencia, Spain*
[2] *Universitat Politècnica de València, 46022 Valencia, Spain*
[3] *Video Systems Srl, 33033 Codroipo, Italy*

Abstract

This paper explores the integration of Artificial Intelligence (AI) in Non-Destructive Inspection (NDI) systems, focusing on the context of the Horizon Europe project Zero Defects Zero Waste (ZDZW). The study conducts a thorough comparison between 2D and 3D computer vision techniques to evaluate their effectiveness in enhancing the quality analysis of coffee capsules. Through practical insights gained from the ZDZW project, this work aims to illuminate the strengths and trade-offs associated with each technique, providing valuable guidance for the design and implementation of AI-based solutions in NDI systems.

Keywords

Quality assessment, Non-Destructive Inspection Technology, AI quality inspection, Computer Vision

1. Introduction

In the context of Non-Destructive Inspection (NDI) systems, the integration of Artificial Intelligence (AI) has emerged as a transformative force, offering unprecedented capabilities for quality analysis [1], [2], [3]. This paper delves into the intricacies of AI application within visual NDI, with a specific focus on the context of the Horizon Europe project Zero Defects Zero Waste (ZDZW). In the pursuit of perfection, ZDZW will develop digital non-destructive inspection services (NDIS) as a set of strategic technologies to improve production efficiency, zero-defect, and sustainable manufacturing of European industries.

Within the framework of the ZDZW project, this study undertakes a meticulous examination of the integration of 2D and 3D computer vision techniques in the inspection of coffee capsules during manufacturing process. The central objective is to conduct a comprehensive comparative analysis of these techniques in enhancing precision quality assessment. Drawing on practical insights garnered from the ZDZW initiative, this work aims to illuminate the strengths and trade-offs inherent in each technique.

The significance of this research lies not only in its contribution to the specific domain of coffee capsule quality assessment but also in its broader implications for the design and implementation of AI-based solutions in NDI systems. By providing a nuanced understanding of the comparative merits of 2D and 3D visual inspection techniques, this work seeks to offer valuable guidance for researchers, engineers, and practitioners involved in the development of AI-driven solutions for Non-Destructive

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EMAIL: pgarrigues@iti.es (A. 1); m.fabrizioli@videosystems.it (A. 2); javierperez@iti.es (A. 3); msanchis@iti.es (A. 4); a.liani@videsystems.it (A. 5); jcperez@iti.es (A. 6)
ORCID: 0000-0003-3408-3249 (A. 1); 0000-0002-1256-0676 (A. 2); 0000-0002-4195-9491 (A. 3); 0000-0003-4685-0708 (A. 4); 0000-0001-9570-7727 (A. 5); 0000-0001-6506-090X (A. 6)

Inspection. As industries strive towards the ambitious goal of zero defects and zero waste [4], the insights derived from this comparative analysis are poised to play a pivotal role in shaping the future landscape of quality assurance through AI integration in NDI systems.

2. Non-Destructive Visual Inspection

The Non-Destructive Visual Inspection landscape encompasses a diverse array of methodologies and techniques, ranging from conventional human-based visual inspections to cutting-edge autonomous visual inspection processes featuring assisted AI algorithms designed to augment detection capabilities. It is important to highlight that these methodologies may extend beyond the visible spectrum wavelength, yet they are categorized under the umbrella of visual testing techniques. The discernment of defects by the human eye, with an average size detection threshold of 100μm, introduces a critical dimension to this inspection domain. However, this ability is contingent upon factors such as measurement subjectivity, interpretation, ambient conditions, and visual fatigue, among other external influences [5].

The addition of automated visual inspection equipment, featuring optimal lighting conditions, magnification optics, higher resolution cameras, and specialized software tools for dimensional measuring and defect detection, presents a notable enhancement in visual accuracy, detectability, reliability, and inspection process speed when compared to traditional human visual inspection methods.

Over the past decade, advancements in computer vision solutions coupled with Convolutional Neural Networks (CNN) and other artificial intelligence (AI) algorithms have significantly elevated the interpretation of images [6]. This progress enables the extraction of regions of interest and the detection of previously unnoticed features across a spectrum of processes, ranging from dimensional control to defect detection. The early identification of defects during the initial stages of the production process not only improves overall quality but also results in substantial savings in both raw materials and energy consumption.

3. Multi-camera 3D inspection

A 3D multi-camera solution tailored for visual quality inspection [7] operates by concurrently capturing images from diverse perspectives, enabling the creation of a detailed 3D reconstruction of the target object. The main advantage of this approach is it can inspect the object from multiple views analysing its 3D structure as well as texture at the same time being able to 360° inspection if the object is captured in free fall. Once reconstructed, the object undergoes classification against a selection of possible known references [8], facilitating alignment with the reference model [9]. This alignment serves as the foundation for various analyses.

The **volumetric analysis** compares the reconstructed object and the reference model, obtaining the volume difference between them. With the application of a global threshold as a criterion for its overall conformity to the reference model in terms of volume. Following this, a fine-grained analysis of volumetric characteristics within previously defined regions of interest takes place. Subsequently, localized quality thresholds are applied to these pre-defined regions, facilitating an in-depth evaluation of the object's volumetric fidelity in diverse areas. The integration of both global and local thresholds enhances the effectiveness of visual quality inspection.

Figure 1: Highlighted in blue detected volumetric missing volume on a defective plastic coffee capsule.

A **surface analysis** [10] is facilitated through the training of a specialized model to learn image descriptors for each point within the 3D model though an automated training process using a reduced set of pre-validated samples [11]. For each 3D point, the cameras with the best viewing angle are evaluated and small image cropping of a predefined size are assigned, establishing a texture model with spatial reference that comprehensively captures the details of the surface at that point. The subsequent comparison between the textures acquired during the capture process and those learned by the model yields a metric quantifying the distance between the two sets of surface representations. This metric serves as a discerning tool for evaluating surface variations, providing accurate information about the fidelity of the captured surface texture with respect to the learned model.

Figure 2: Highlighted in red detected surface defect spot on a plastic coffee capsule.

In addition to this a **Geometric Dimensioning and Tolerancing** (GD&T) measurements [12], derived from the reference model, are systematically applied to the points obtained through the 3D reconstruction process [13]. This method, widely adopted in contemporary manufacturing, offers a robust and easy-to-interpret measure of quality and ensures compliance for later phases of the manufacturing process.

After all, the multi-camera solution presented here provides an engineering-perspective approach to quality inspection by integrating volumetric scrutiny, surface texture analysis, and adherence to GD&T specifications for geometrical measures. This system proves to be a valuable asset in advancing quality control processes within manufacturing industries. Through a systematic comparison of the reconstructed objects with reference models, manufacturers obtain real-time insights into potential irregularities or variations in the manufacturing process.

The integration of these analyses not only enhances the overall quality control framework but also contributes significantly to the optimization of manufacturing efficiency and resource utilization within the plastic coffee capsule production pipeline, avoiding defective units to be further processed and thus reducing the scrap and waste material.

4. 2D real-time inspection based on machine vision edge device

In many manufacturing industrial applications there is often demand of vision controls to inspect 100% of production with rates higher than 10 parts/s or more. Such controls can also be requested to be installable and operate within compact and multi-steps production lines, in order to perform intermediate checks between different stages of an existing process/assembly.

High-speed acquisition and processing vision edge unit developed by Video Systems, integrated with space-saving 2D cameras, can cope with both requirements. In particular regarding the inspection rates, the low-power edge architecture is designed to allow the execution [14] of complex machine vision algorithms with a processing capacity of up to 20-25 parts/s. The process is currently based on a high-performance DSP system with SIMD parallel computation capability, suitable for computation of matrix data such as images.

On the software side, algorithms are designed to extract features of interest from the images (contours, blobs, ...) thanks to advanced machine vision techniques: the features are finally used to assess quality conformity, typically based on free-of-defect conditions or within-tolerance dimensional controls. AI models can also be trained using the web-based suite of AI tools available in the application framework, including SOTA techniques for supervised object detection and classification: trained models are finally deployed in the edge unit, while guaranteeing the high processing capacity.

Moving back to the inspection of coffee capsule during manufacturing process, it is reported the case of a specific patented design of a capsule body, where a real-time visual control is installed within the assembly line used for the final coffee capsule production, to monitor the punching of the silicone disc at the center of the capsule bottom by means of a steel needle. The position of the punched hole is required to be within a certain defined distance from the center of the silicone septum, for correct coffee flow extraction from the hole during the dispensing phase.

The acquisition and processing speed is capable to cope with the maximum production rate of 800 parts/minute for the line, and the final result of captured image analysis is the correct identification of both the septum circumference and the punched hole, so to estimate its distance from the septum center based on previous dimensional calibration on reference samples.

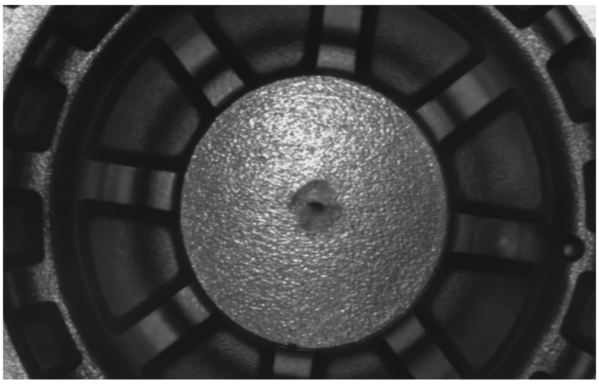

Figure 3: Two images of different punched capsules in normal conditions; in the second the results of the analysis are superimposed (septum circumference in yellow, hole in green)

Absence of the hole (typically due to broken needle) or out-of-tolerance measurement for its position can be used to alert the operator of defective conditions in production. Also, a continuous drift of the hole-center distance in time can be used for preventive actions like the anticipated maintenance of needle substitution, so improving the operator work and the system productivity.

5. Conclusions

In this study, we conducted a comprehensive analysis of 2D and 3D visual inspection techniques within the Horizon Europe project Zero Defects Zero Waste (ZDZW), focusing on coffee capsule quality assessment. Our findings highlight distinct advantages in both approaches.

The multi-camera 3D inspection system offered a holistic quality assessment by integrating volumetric scrutiny, surface texture analysis, and adherence to Geometric Dimensioning and Tolerancing (GD&T) specifications. This system enabled real-time defect detection, empowering manufacturers to adjust processes promptly and optimize efficiency while minimizing waste.

Conversely, the 2D real-time inspection based on machine vision edge devices demonstrated rapid acquisition and processing capabilities, particularly suitable for high-speed inspections in manufacturing lines.

As we explore the complexities of 2D and 3D visual inspection techniques for coffee capsule quality assessment, it becomes clear that the integration of these methods is essential. Combining 2D and 3D approaches will not only improve the efficiency of quality assessment but also lead to a more complete understanding of product quality. Looking ahead, prioritizing the development of interoperable frameworks and standards will drive the advancement of non-destructive inspection systems, aligning with the overall goal of achieving zero defects and zero waste in manufacturing.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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