Title:
A Framework for Model-Based Visual Inspection: A Case Study of Bottle Dimensional Measurements in the Plastics Industry

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Introduction:
With the new advent of Computer-Aided Design (CAD) solutions, it is now possible to assign the Geometric Dimensioning and Tolerancing (GD&T) information and other information (e.g., notes, metadata, material specifications) directly into the CAD model, forming what is known as a Model-Based Definition (MBD) dataset [7], [8]. Manufacturers strive to integrate new technologies (e.g., digitalization, model-based definition, machine vision) to transfer their traditional paper-based inspection processes to model-based ones. Instead of manually extracting GD&T information from engineering drawings to drive inspection, industries have begun adopting advanced model-based solutions, encompassing both technologies and methodologies, to assist the development of a product across its entire lifecycle and to build a digital representation of actual business processes and products [2]. Integrating the technologies into a Visual/Vision Inspection System (VIS) is a trend to drive the development of manufacturers' quality control processes [9], [12], [14].

This paper developed a Model-Based Visual Inspection System (MBVIS) driven by GD&T information extracted from an MBD dataset. The proposed system established the feedback mechanism from the inspection phase to the design and manufacturing phases of the product lifecycle in a model-based environment. In addition, the system dynamically supported reading Regions of Interest (ROIs) from user selection and intelligently published analyzed inspection results. The proposed approach was also evaluated by Bland and Altman (B&A) plot analysis on a pharmaceutical plastic bottle from an industrial partner of the Digital Enterprise Center (DEC) at Purdue University.

State of the Art:
Model-Based Enterprise (MBE) uses the MBD dataset to define the product requirements and specifications instead of paper-based documents as the data source for all engineering activities throughout the product lifecycle, such as design, manufacturing, and inspection. MBD enables the use of annotated three-dimensional (3D) models as sole carriers of complete product information, a practice designed to replace (or at least minimize the need for) conventional two-dimensional (2D) engineering drawings [3], [11], [13].

Several works have been proposed in the literature to investigate the application of model-based inspection. Hedberg et al. in [5] stated that computer interpretability and data associativity enable the MBD to be the critical foundation that enables MBE to work, at least for design, production, and inspection. Liu et al. in [6] proposed a framework for model-based integrated inspection to improve manufacturing efficiency and quality control ability. The authors generated an MBD model containing GD&T information for inspection in the design process. GD&T information was extracted from the CAD system and put into an inspection information table to generate an operation sequence for model-based integrated inspection. Researchers Scheibel et al. in [10] proposed the DigiEDraw approach to extract dimensioning information from engineering drawings and integrate the information into the production process. Even though they did not investigate the possibility of reusing the extracted information in the 3D CAD models, their work still shed light on extracting GD&T information from 2D-based engineering drawings and reusing it in other applications. Most commercial CAD systems (e.g., Autodesk Inventor, PTC Creo, Siemens NX, SolidWorks) have already supported GD&T specifications via attributes attached to the CAD entities. However, the answer to how to extract the GD&T information from the MBD datasets and drive the VIS to complete the geometric dimensional measurements still needs further study.

Moreover, current research on model-based inspection is still in an early stage. Model-based inspection is not as well adapted as design and manufacturing processes, resulting in a disconnected information flow throughout the design, manufacturing, and inspection phases [4]-[6]. Compared to the demands and opportunities for data and process integration raised by the MBD, there is still a lack of integration between model-based inspection and visual inspection systems to assist manufacturers in realizing the vision of MBE. Meanwhile, it is still challenging to ensure that the measurement data obtained from conventional measuring devices are connected to the model-based dataset and are up-to-date for consumption by the different phases of the product lifecycle. The integration of visual inspection systems and model-based inspection is not yet explored in providing bidirectional data connection while conducting dimensional measurements.

Main Ideas:
An image-based MBVIS framework was proposed in this study. The framework was proposed to develop model-based visual inspection applications to complete four main functions: Image Acquisition, Image Processing, Dimension Measurement, and Result Output. The diagram of the proposed MBVIS framework is presented in Fig. 1.

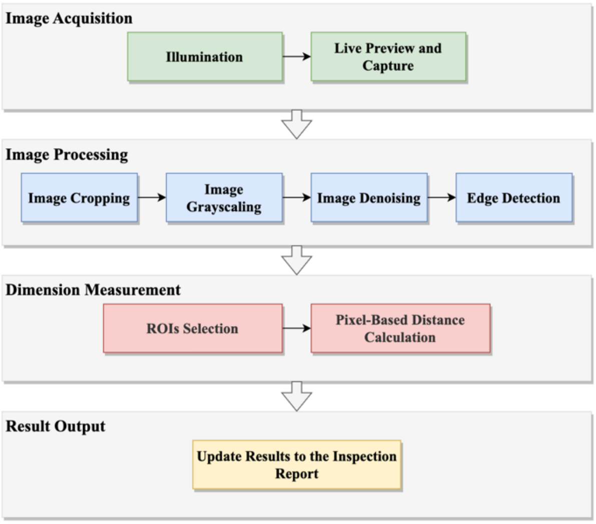

Fig. 1: Proposed Image-based MBVIS Framework.

To demonstrate how the framework works, a flowchart of the proposed MBVIS with the same color code as Fig. 1, which integrates MBD and VIS modules, is described in Fig. 2. Through the proposed framework, manufacturers can benefit from utilizing the MBD dataset from the 'as-designed' to 'as-inspected' within the product lifecycle. In the inspection phase of the product lifecycle, an inspector first loads the predefined MBD dataset and extracts relevant GD&T information from the MBD module. An initial inspection report with various views of the 3D geometric model will also be generated. Later, the inspector can refer to the MBD dataset representation from the exported initial inspection report to operate the proposed VIS module to measure critical dimensions in the inspection phase. All the real-time measurement results are stored in the inspection report and embedded into the MBD dataset for product design phase or next-phase consumption within the model-based enterprise framework.

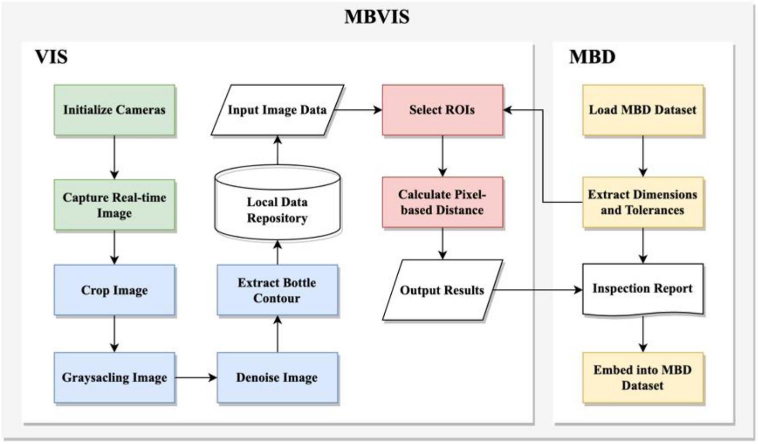

Fig. 2: MBVIS Flowchart.

The MBD module of the proposed system relied on software named MBDVidia (version: 3.2201.28). MBDVidia can read various mainstream 3D model formats and data exchange forms with Product Manufacturing Information (PMI) information, which was used in the study to extract GD&T information from the MBD dataset. Fig. 3 describes the GD&T information extraction flowchart. The process starts with loading the MBD dataset in a supported data exchange format. MBDVidia automatically reads and displays all PMI information from the MBD dataset. Then users can manually delete the undesired GD&T information that does not need to be inspected in the visual inspection system. Lastly, all remaining GD&T information is exported to an inspection report in the data structure (e.g., XLSX, XLS, XML), easily readable by humans and computers.

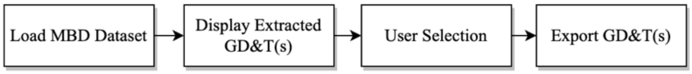

Fig. 3: GD&T Extraction Flowchart.

The VIS module was implemented using Python 3.7.0 programming language with open-source libraries (e.g., NumPy, openpyxl, OpenCV, Pandas, and PIL). According to conducting a series of image processing operations, including cropping, grayscaling, denoising, and edge detection, the target images are ready for the inspector to select target regions to measure via the proposed VIS module. Once the inspector obtains the inspection report from the MBD module and completes the visual inspection of the target, the results can be updated and stored in the inspection report.

Evaluation:

In this study, the authors created an MBD dataset of a plastic bottle from the partner company, which contained a 3D CAD model and GD&T information (Fig. 4). In addition, the authors focused mainly on quantifying the level of agreement between the proposed MBVIS and a commercial VIS from the partner company on the same type of plastic bottle in measuring two critical bottle dimensions of R and H (Fig. 4), hence determining whether the agreement is sufficient for the two systems to be used interchangeably. Furthermore, the authors collected measurement data on R and H dimensions (unit:

inches) from the proposed MBVIS and the commercial VIS from the partner company. The Bland and Altman (B&A) plot analysis [1] was chosen to evaluate the interchangeability between the two systems.

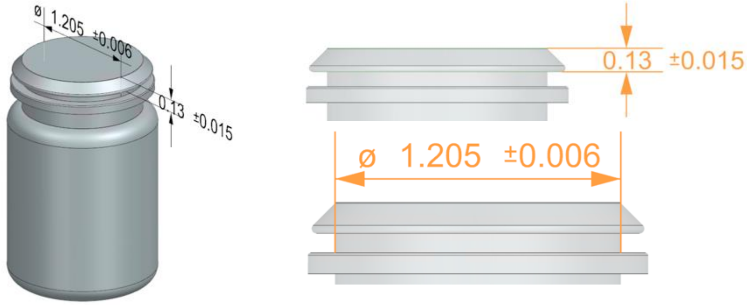

Fig. 4: Left: A trimetric view of the plastic bottle MBD dataset with R and H dimensions. Top-right: Dimensions H (the distance of the bottle's highest point to the tangent of the bottle thread). Bottom-right: Dimensions R (the outside diameter of the neck on a bottle cap).

An inspector and the authors collected 284 bottles' valid R and H measurements using a commercial VIS and the proposed MBVIS, respectively. In the B&A plots (Fig. 5), the limits of agreement are shown as dotted red lines with 95% confidence intervals (light purple areas), biases (as solid blue lines) with 95% confidence intervals (light green areas), and the maximum allowed differences between two systems (as solid green lines). A summary table of the B&A plots is presented in Tab. 1.

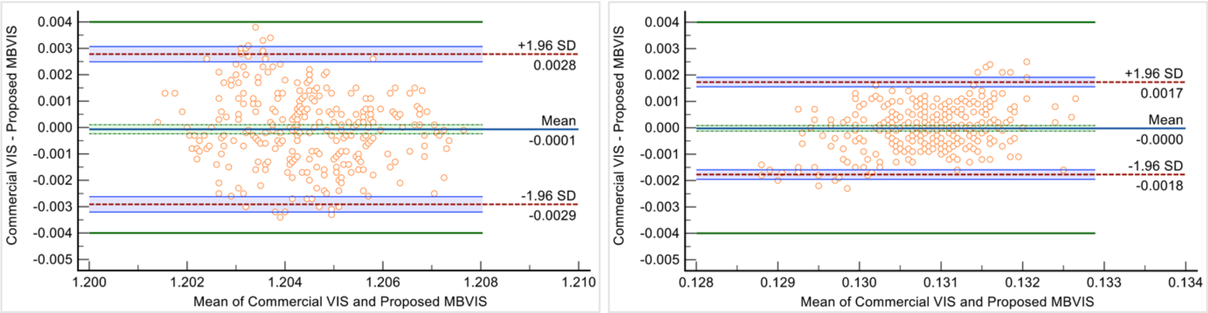

Fig. 5: Left: B&A plots for limits of agreement Analysis (N = 284) of R measurements. Right: B&A plots for limits of agreement Analysis (N = 284) of H measurements.

	R Measurements	*H Measurements*
Sample Size	284	284
Arithmetic Mean	-0.0001	-0.0000
95% Confidence Interval	-0.0002 to 0.0001	-0.0001 to 0.0001
P (*H0: Mean = 0)*	0.4429	0.6907
Lower Limit	-0.0029	-0.0018
95% Confidence Interval	-0.0032 to -0.0026	-0.0020 to -0.0016
Upper Limit	0.0028	0.0017
95% Confidence Interval	0.0025 to 0.0031	0.0016 to 0.0019

Tab. 1: B&A Plot Summary (R and H Measurements).

The limits of agreement of the commercial VIS and proposed MBVIS in R and H measurements were significantly less than the maximum allowed differences, showing a high agreement level between the two visual inspection systems. Therefore, the limits of agreement are small enough to be confident that the proposed MBVIS can be used in place of the commercial VIS for practical purposes.

Conclusions:

In this study, the authors investigated the integration of model-based definition and visual inspection in critical bottle dimensional measurement in the plastics industry. A novel MBVIS framework containing MBD and VIS modules was developed and evaluated by the B&A analysis. The measurement results proved that the proposed MBVIS could be used in place of the commercial VIS from the partner company in measuring R and H dimensions. Furthermore, according to the integration of MBD and VIS applications, the proposed MBVIS could perform high-precision dimensional measurements and provide complete model-based inspection data traceability.

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