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A Model-Based Visual Inspection System (MBVIS) for Critical Plastic Bottle Dimensional Measurements

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Abstract. Manufacturers have begun to adopt advanced digital methods and tools to release higher-quality products more quickly at a lower cost. Model-based technologies and Visual/Vision Inspection System (VIS) are two representative approaches and are trends to facilitate manufacturers' digitalization. With model-based technologies, manufacturers can define digital product requirements and specifications as the primary data source for engineering activities during the product lifecycle rather than relying on traditional paper-based documents. Moreover, the manufacturers can improve product defect detection efficiency and reduce labor requirements by implementing a VIS without artificial visual inspection in their inspection process. Traditionally, inspectors rely heavily on information from Two-Dimensional (2D) engineering drawings to inspect manufactured products with/without a VIS. This inspection process is out of the model-based context, hindering manufacturers from transiting paper-based to model-based processes. This paper developed a Model-Based Visual Inspection System (MBVIS) driven by Geometric Dimensioning and Tolerancing (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.

Keywords: Model-Based Definition, MBD, Model-Based Enterprise, MBE, Model-Based Inspection, MBI, Visual Inspection System, VIS, B&A Analysis.
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1 INTRODUCTION

The involvement of humans in product inspection has been a significant bottleneck that impedes the digitization and productivity of the automatic production line in manufacturing [9]. Meanwhile, the broad utilization of Two-Dimensional (2D) engineering drawings in product inspection hinders manufacturers from embracing the Model-Based Enterprise (MBE) vision. Both challenge the manufacturers to integrate new technologies (e.g., digitalization, model-based definition, machine vision) to transfer traditional paper-based inspection processes to model-based ones. Instead of manually extracting Geometric Dimensioning and Tolerancing (GD&T) information from engineering drawings to drive product 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 [5].

Furthermore, the direct inclusion of GD&T information and other information (such as notes, metadata, and material specifications) into the Computer-Aided Design (CAD) model has become feasible with the help of CAD solutions, resulting in the formation of a Model-Based Definition (MBD) dataset [17], [18]. Integrating the technologies into a Visual/Vision Inspection System (VIS) is a trend to drive the development of manufacturers' quality control processes [19], [23], [26]. Furthermore, numerous manufacturers have cited MBE as advantageous for their process improvement and product lifecycle management. An MBE integrates and manages relevant technological and commercial activities across product design, manufacturing, inspection, support, and retirement by utilizing advanced model-based technologies like MBD, Model-Based Manufacturing (MBM), and Model-Based Inspection (MBI) [5], [7], [13], [14]. However, the answer to how to utilize the GD&T information from the MBD datasets and drive the VIS to facilitate the inspection process of geometric dimensional measurements still needs further study.

To answer the question of how we can adapt a VIS to support model-based inspection, the authors proposed an image-based Model-Based Visual Inspection System (MBVIS) framework integrating MBD and VIS applications to demonstrate the process of utilizing the GD&T information from the MBD dataset and driving the VIS to measure physical targets. A plastic bottle with a high dimensional standard obtained from a plastic bottle manufacturer was chosen to evaluate the proposed system's performance in extracting GD&T information from the MBD dataset and measuring relevant critical bottle dimensions.

The remainder of the paper is organized as follows: Section 2 discusses related works on MBD and applications of MBI, Section 3 describes the proposed MBVIS framework, Section 4 evaluates the developed system by Bland and Altman (B&A) plot analysis method, and lastly, Section 5 discusses a potential user scenario to introduce the MBVIS to MBE and concludes with a summary of our contributions.

2 RELATED WORKS

The emergence of Industry 4.0 has brought about new and inventive strategies and methodologies for product data storage and processing throughout the product life cycle. As part of these strategies, MBE is employed to define product requirements and specifications using the MBD dataset as the unique data source for all engineering tasks throughout the product lifecycle, including design, manufacturing, and inspection, rather than traditional paper-based documents. MBD facilitates the utilization of annotated Three-Dimensional (3D) models as the exclusive means of communicating comprehensive product information, intending to replace or minimize the use of conventional 2D engineering drawings [11], [22], [25]. Furthermore, utilizing the MBD dataset can prevent data inaccuracies and uncertainties when moving from the original 3D models to corresponding 2D engineering drawings, significantly decreasing expenses and production time in product design and manufacturing [16].

The MBD's significance in the MBE approach has captured the attention of academic and industrial communities for the past twenty years [8]. The automotive and aerospace industries are the first to implement MBD technology. An example of MBD's pioneered adoption was seen in Boeing's Research and Development (R&D) of the Boeing 787 aircraft, facilitating communication between design and production partners [24]. Within the MBE framework, the engineering function generates MBD that downstream processes adopt for model-based manufacturing and inspection tasks [13]. MBD also assists manufacturers in shifting the storage and management of product information from the document center or drawing center to the model center. To achieve this transition, not only does the 3D CAD model play a fundamental role, but also Product Manufacturing Information (PMI), which typically contains the dimensions, tolerances, symbols, and texts that can be utilized to describe products [1]. The PMIs contain relevant information that can be retrieved by various departments in the company, including purchasing, production, quality assurance, assembly, and service [1]. However, retrieving data depending on departmental requirements in cross-company communications can be difficult because all product information is incorporated in MBD datasets.

Several works have been proposed in the literature to investigate the application of model-based inspection. Hedberg et al. in [13] 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. However, the authors did not explore integrating VIS and MBD in the inspection process. Liu et al. in [16] 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. However, the integrated inspection process relied on a commercial Coordinate Measuring Machine (CMM), which has a high cost and makes it unaffordable for Micro, Small, and Medium-Sized Enterprises (MSMEs), particularly in developing countries. Researchers Scheibel et al. in [20] proposed the DigiEDraw approach, which extracts and integrates dimensioning information from engineering drawings 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 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.

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 [11], [13], [16]. 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 model-based enterprises. 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. Therefore, this paper intends to develop a cost-effective MBVIS driven by GD&T information extracted from an MBD dataset.

3 METHODOLOGY

3.1 MBVIS

In this paper, the authors proposed an image-based MBVIS framework, including MBD and VIS modules, and its diagram is presented in Figure 1. The proposed framework contains four main components and is organized sequentially: Image Acquisition, Image Processing, Dimension Measurement, and Result Output.

To demonstrate how the framework works, a flowchart of the proposed MBVIS with the same color code as Figure 1, which integrates MBD and VIS modules, is described in Figure 2. Manufacturers can benefit from utilizing the MBD dataset from the ‘as-designed’ to ‘as-inspected’ within the product lifecycle through the proposed framework. Specifically, 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 annotated

3D geometric model will also be generated. Later, the inspector can refer to the MBD dataset graphic representation from the exported initial inspection report to measure the critical bottle dimensions via the proposed VIS module 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.

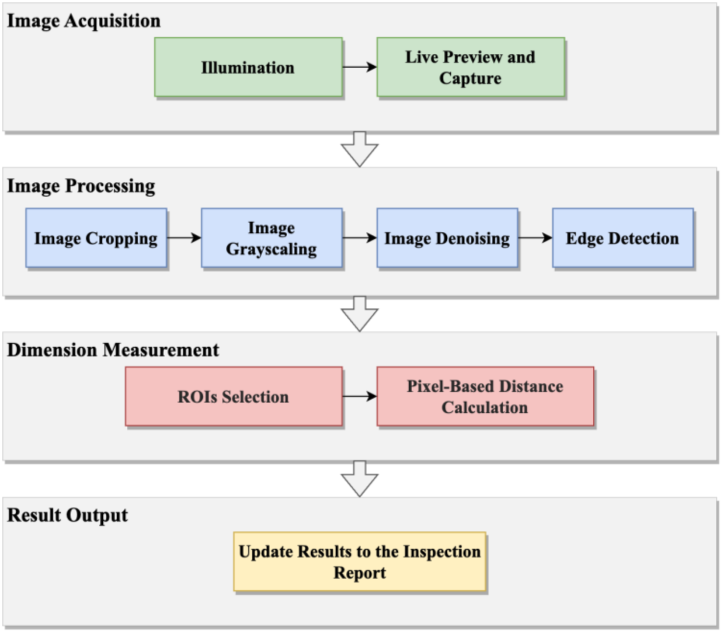


Figure 1: Proposed Image-based MBVIS Framework.

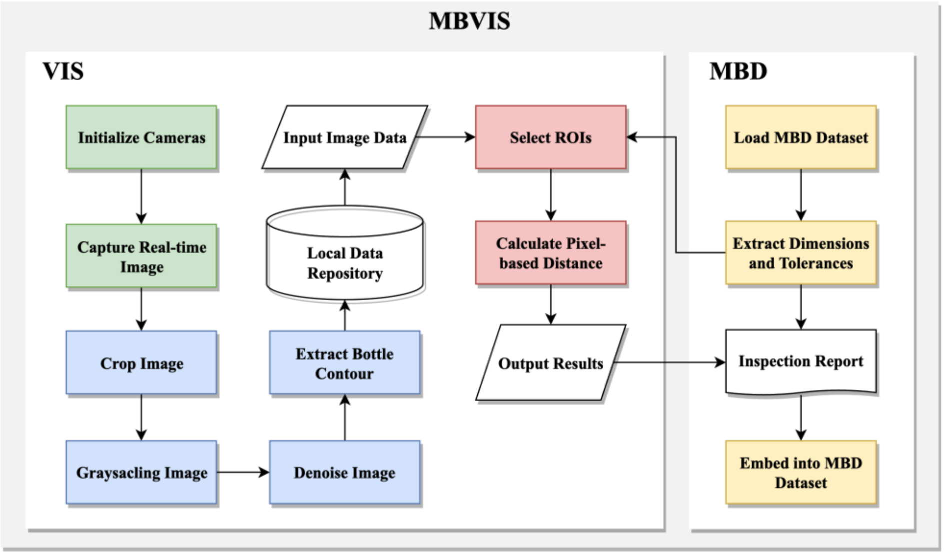


Figure 2: MBVIS Flowchart.

To validate the concept of MBVIS, the authors created an MBD dataset to digitally represent the plastic bottles from the partner company, which contained a 3D CAD model and GD&T information (Figure 3). 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 (Figure 3), 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 measurement results were analyzed by B&A analysis in section 4.

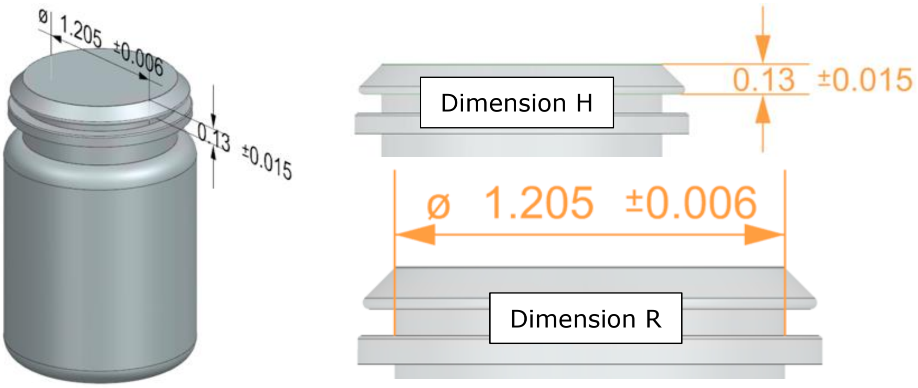


Figure 3: Left: A trimetric view of the plastic bottle MBD dataset with R and H dimensions. Top-right: Dimensions H (the distance of the bottle's highest point to the tangent of the bottle thread). Bottom-right: Dimension R (the outside diameter of the neck on a bottle cap).

3.2 MBD Module

The MBD module of the proposed system relied on a piece of software named MBDVidia (version: 3.2201.28). MBDVidia can read various mainstream 3D model formats and data exchange forms with PMI information used in the study to extract GD&T information from the MBD dataset. Figure 4 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. The exported report serves as a visual reference for inspectors to manually select relevant Regions of Interest (ROIs) of the dimensions R and H from the captured bottle images (Section 3.3) to complete the measurements. A user interface of the MBDVidia is presented in Figure 5. In this study, the "Radial Dimension (1)" and "Linear Dimension (2)" (as shown in Figure 5) representing dimensions R and H were exported for the inspector to conduct the corresponding measurements for the plastic bottles via the VIS module.

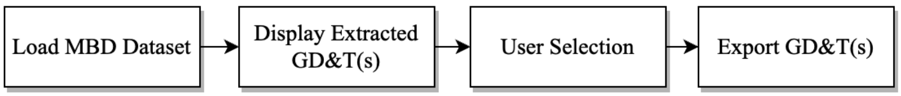


Figure 4: GD&T Extraction Flowchart.

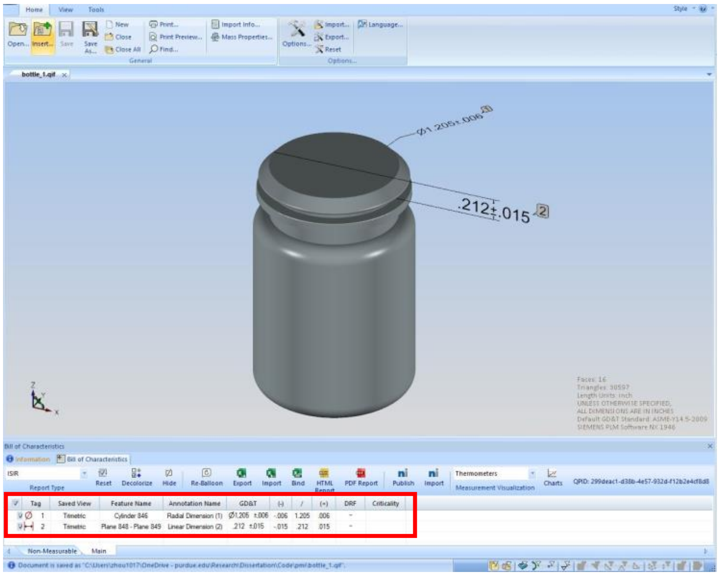


Figure 5: MBDVidia User Interface.

3.3 VIS Module

The VIS module contains four main functions to conduct dimensional measurements: Image Acquisition, Image Processing, Dimension Measurement, and Result Output. The module was implemented using Python 3.7.0 with open-source libraries (e.g., NumPy, openpyxl, OpenCV, Pandas, and PIL).

In Image Acquisition, a high-quality bottle image can be captured via the developed VIS module through the proper settings of the system's illumination. Figure 6 is an example of the raw image of the target plastic bottle. Later, in Image Processing and Dimension Measurement, according to conducting a series of standard image processing operations, including cropping, grayscaling, denoising, and edge detection, the target images are ready for the inspector to select ROIs to measure. Figure 7 shows a final proceeded bottle image before the user ROIs selection. The bottle edges are extracted and ready for the inspector to draw bounding boxes to convert pixel-based distances to actual measurements. The flowchart of the ROIs selection is shown in Figure 8. Lastly, in Result Output, once the inspector obtains the inspection report from the MBD module and completes the visual inspection of the target bottle, the results can be updated and stored in the inspection report for further consumption.

Figure 6: A Captured Image of a Bottle.

Figure 7: A Proceeded Image of the Bottle.

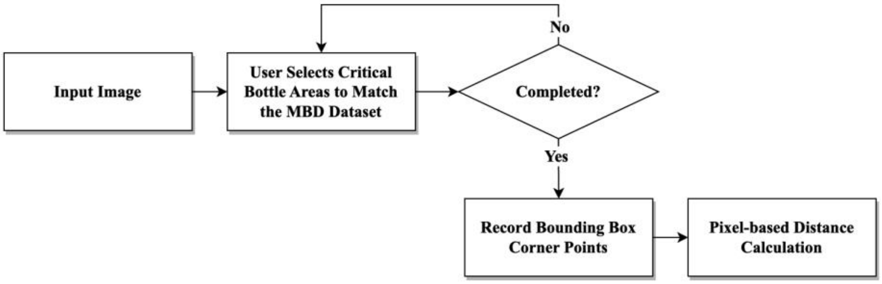
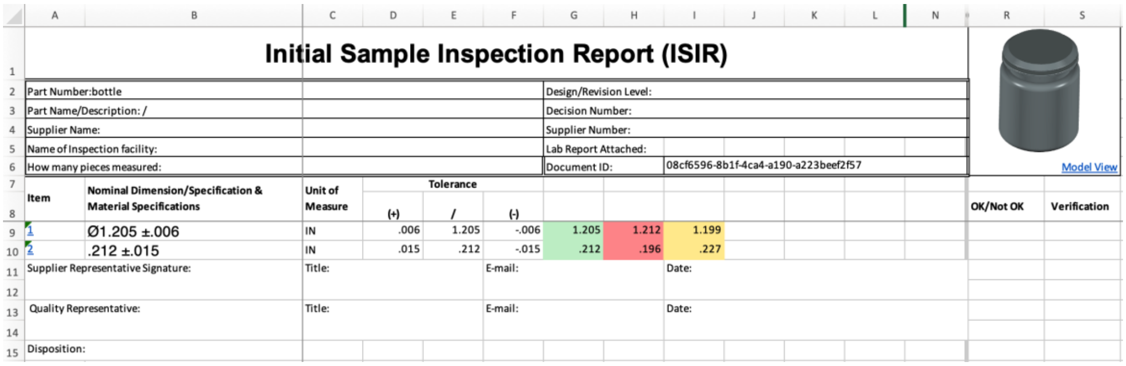


Figure 8: Bottle ROIs Selection Flowchart.

A sample inspection report of the bottles exported from MBDVidia is presented in Figure 7. The measurement results of dimensions R and H from the MBVIS were exported to the inspection report in the XLSX format. According to the practice of filling measurement results in the inspection report, measurement results of dimensions R and H were appended to cells G9 and G10; H9 and H10; I9 and I10; and so on (Figure 9). A Python script was developed to automatically complete the measurement result filling to the inspection report file without human intervention. A color code is available to review the measurement results quickly: green denotes "pass," red indicates "fail," and yellow denotes "precisely meeting the upper or lower limits."



Initial Sample Inspection Report (ISIR)

Item	Nominal Dimension/Specification & Material Specifications	Unit of Measure	Tolerance (+)	/	(-)	G	H	I	OK/Not OK	Verification
1	Ø1.205 ±.006	IN	.006	1.205	-.006	1.205	1.212	1.199		
2	.212 ±.015	IN	.015	.212	-.015	.212	.196	.227		

Part Number:bottle; Part Name/Description: /; Supplier Name:; Name of Inspection facility:; How many pieces measured:; Design/Revision Level:; Decision Number:; Supplier Number:; Lab Report Attached:; Document ID: 08cf6596-8b1f-4ca4-a190-a223beef2f57; Model View; Supplier Representative Signature:; Title:; E-mail:; Date:; Quality Representative:; Title:; E-mail:; Date:; Disposition:

Figure 9: Sample Inspection Report of the Bottle.

To provide different levels of inspection data traceability, the sample report template (as shown in Figure 9) can be customized to meet various manufacturers' needs. In this paper, the authors used only one inspection report file to record all collected critical bottle dimensional measurement data measured by the proposed MBVIS. Moreover, to integrate the MBD and VIS, the inspection report obtained from the proposed MBVIS can be easily attached to the MBD dataset for consumption by the different phases of the product lifecycle. The inspection report can be manually or automatically linked to the MBD dataset as a reference and stored in any product data management or product lifecycle management systems to support model-based inspection data traceability.

4 EVALUATION

Consistency in dimension measurements of plastic bottles is crucial for manufacturers to validate the "as-designed" and "as-inspected" in the pharmaceutical industry. Any inaccurate measurement results can lead to an unnecessary adjustment of the process and even significant economic losses for the companies. The proposed system is expected to have an equivalent measurement performance as the commercial one in measuring bottle R and H dimensions. This section evaluates the agreement between the proposed MBVIS and a commercial visual inspection system by performing a measurement system comparison study.

To address the gap of interchangeability between two measurement methods, Bland and Altman proposed a way of assessing agreement between measurement systems by examining the mean difference (or bias) and establishing limits of agreement (LOA) over thirty years ago [4]. Over the years, the B&A analysis has become the most appropriate way of determining the limits of agreement between measurements [6].

The B&A analysis evaluates the difference between measurements taken on the same subject to characterize the agreement between two measurement systems [21]. The B&A analysis enables the estimation of an agreement interval and the evaluation of a bias between mean differences, with 95% of the data points falling within ± 1.96 (or roughly two) standard deviations of the mean difference [15]. It also determines the bias between the two methods as a measure of accuracy [2]-[4]. The bias represents the systematic error in measurements, while the precision represents the random error (standard deviation, confidence limits), as noted by [10]. This paper used the B&A plot analysis to evaluate the interchangeability between the two systems.

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 (Figure 10), 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 Table 1.

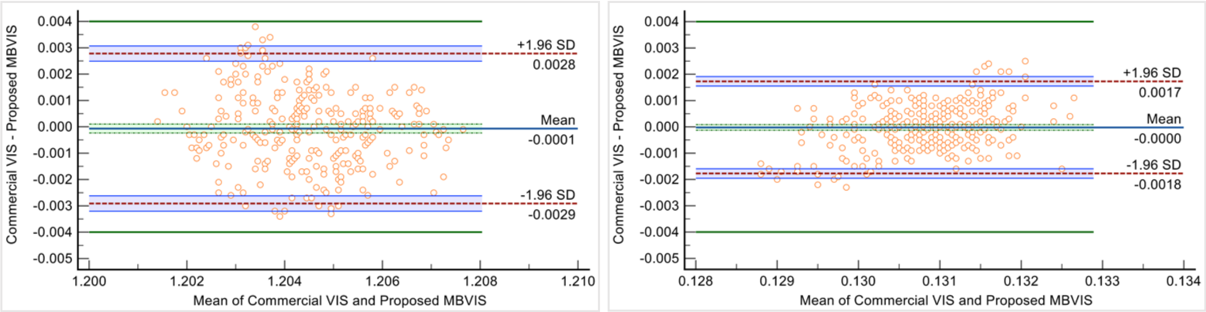


Figure 10: Left: B&A plots for limits of agreement Analysis (N = 284) of R measurements. Right: B&A plots for limits of agreement Analysis (N = 284) of H measurements.

	R Measurements	H Measurements
Sample Size	284	284

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

Table 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.

5 DISCUSSION AND CONCLUSION

Through the proposed MBVIS framework, the MBD dataset could be extended its application from the 'as-designed' to 'as-inspected' within the product lifecycle and model-based enterprise framework. Figure 11 demonstrates a potential user scenario by introducing the MBVIS to MBE. In the product design phase, product designers can focus on the 3D geometric model design, and no need to generate and maintain the 2D engineering drawings for further communication. In the process design phase, process designers can directly add PMIs to the 3D model to annotate geometric dimensions, manufacturing tolerances, and other information to construct the MBD dataset. Moreover, the detailed process planning can be designed and embedded into the MBD dataset for following manufacturing consumption. The MBD dataset can guide product manufacturing using the MBD approach without the help of traditional 2D engineering drawings. In the production phase, the shop floor technicians and inspectors can manufacture and inspect the product by the MBD dataset, respectively. Specifically, the inspectors can refer to the MBD dataset representation to operate a visual inspection system to measure critical dimensions in the inspection phase. All the real-time measurement results can be stored in the inspection report and embedded into the MBD dataset for previous-stage or next-stage consumptions within the model-based enterprise framework.

Figure 11: Introducing the Proposed MBVIS to MBE.

In this paper, 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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