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Automated defect detection in perfume bottle packaging using machine vision approach for improved quality control

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Abstract In the cosmetic industry, the quality of perfume bottle packaging was essential for both aesthetic appeal and functionality, as plastic bottles were susceptible to defects that could compromise their attractiveness and usability. Traditionally, these bottles were subjected to manual inspection, a method that was both time-consuming and frequently inaccurate. However, the bottle is manufactured with molding techniques prone to have surface defect that impact structural integrity and appearance of the bottles. Machine vision technology is one of the approaches to improve defect identification with better accuracy. This paper aims to evaluate the designated automated machine vision system to detect defects in plastic perfume bottles with greater efficiency. The system utilized a USB camera and MATLAB software to capture and analyze images of the bottles, employing a black and white detection method to identify imperfections. It integrated a laptop, Arduino UNO, LED light bar, USB camera, MG995 servomotor, and power bank to facilitate the automated sorting of defective bottles. It is determined that threshold 0.2 is the most suitable for the accuracy testing. The automated bottle defect detector manages to obtain an accuracy of more than 95% for every batch inspected. Optimizing the timing of image capture and rotation, incorporating advanced image processing algorithms, and integrating automated systems for bottle placement and removal can significantly improve performance. The overall reliability and accuracy of automatic inspection systems can be further enhanced. This innovative approach provided notable advantages, including more reliable and scalable inspections, which contributed to superior product quality, heightened customer satisfaction, and potential cost savings.

Keywords: automated inspection, defect detection, machine vision, MATLAB, quality control

1. Introduction

Spray bottles play a crucial role in various industries for dispensing liquids such as detergents, disinfectants, and perfumes. These bottles are predominantly manufactured from clear polyethylene terephthalate (PET), a material esteemed for its lightweight properties, chemical resistance, and durability (Briga-Sa et al., 2023). The production of these bottles typically involves injection or blow molding processes, which are effective for creating both robust and lightweight components (Luo et al., 2022). Despite the advantages of PET and these molding techniques, defects can emerge during production, which may impact the structural integrity and appearance of the bottles, potentially compromising their functionality and consumer appeal.

Manual inspection remains the conventional method for detecting such defects; however, it has several inherent limitations. This process is labor intensive and heavily reliant on the skill and attentiveness of operators, which increases the likelihood of errors. Consequently, quality control can be inconsistent, potentially leading to customer dissatisfaction or the rejection of entire batches. Industry standards require defect detection systems to achieve an accuracy rate exceeding 95%, meaning that the system should be able to identify no more than one defective bottle in a batch of 30 (Rahman et al., 2018).

Recent studies have highlighted the effectiveness of machine vision systems in addressing these quality control challenges. Machine vision technology has been successfully employed to detect surface defects in various products, including plastic bottles, demonstrating its ability to improve defect identification in terms of high adaptability and flexibility (Li et al., 2023; Wang et al., 2021), consistency (Azamfirei et al., 2023) and speed (Lv et al., 2020). Moreover, applications in other products, such as straw, have achieved detection rates as high as 98.8% (Chang et al., 2021). The use of high-resolution cameras and advanced image processing software, such as MATLAB, has been shown to significantly enhance defect detection accuracy (Uaron et al., 2022). These advancements suggest that machine vision systems could offer substantial improvements over traditional manual inspection methods.

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This research introduces an innovative machine vision approach specifically designed to detect defects in spray bottles, aiming to surpass conventional inspection methods. By integrating high-resolution cameras and MATLAB software, the proposed system provides more precise and efficient defect detection. This approach addresses both surface and structural defects, setting a new benchmark for quality control. Achieving a defect detection accuracy of over 95% with this system promises to increase manufacturing efficiency, reduce customer dissatisfaction, and lower batch rejection rates. This innovation is expected to lead to higher product standards and potential cost savings for manufacturers, representing a significant advancement in quality control processes for spray bottles.

2. Experimental Design

The proposed automated defect detection system, as shown in Figure 1, consists of a USB camera that is connected to a laptop and linked with MATLAB software. MATLAB software is able to capture images through image processing with the black and white thresholding method, and the values of the threshold used are 0.5, 0.4, 0.3, 0.2 and 0.1. The USB camera can be calibrated accordingly so that a clear and crisp image of the bottle can be obtained. The rechargeable light bar is placed atop the white wall with the purpose of providing adequate illumination for the USB camera to capture quality images. The electronic case holder in Figure 2 shows the Arduino UNO and power bank, which control the servomotor for the rotary mechanism.

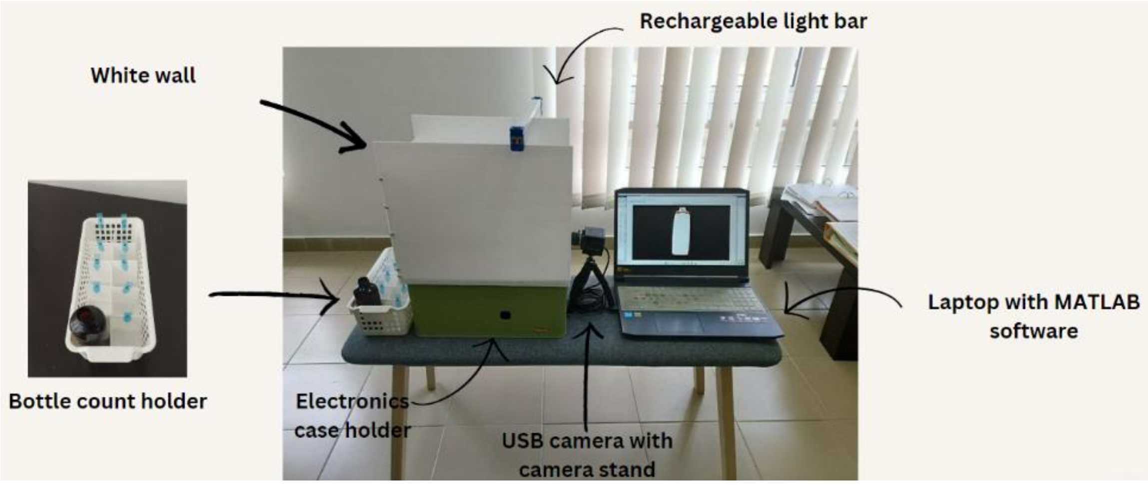


Figure 1 Experimental Setup.

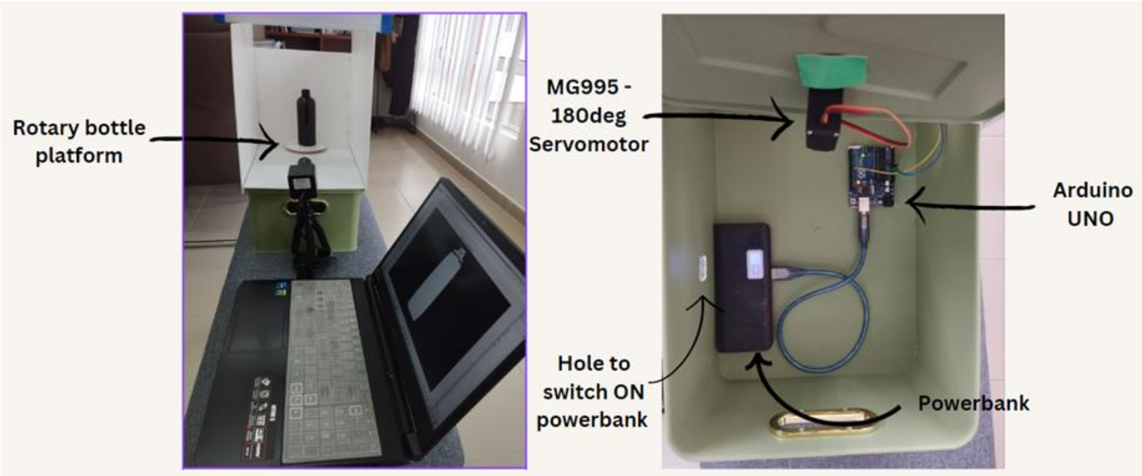


Figure 2 Rotary platform and internals of the electronic case holder.

The proposed automated bottle defect detector system uses a combination of a USB camera with image processing software (MATLAB) to inspect surface defects on multipurpose spray bottles. The USB camera captures the front and rear images of the bottle, and these two images are processed by software to check for defects. The rotary mechanism is used to rotate the bottle 180° back and forth so that the USB camera can capture images of the bottle. Each bottle will have two images (front and back), and these images will be processed in MATLAB to determine the presence of surface defects. The bottles will be placed and removed from the rotary platform after two images (front and back) are captured. The system indicates the presence of defects by using a bounding box. The system will utilize varying threshold values, and the best threshold will be chosen for accuracy testing, whereby the data recorded will be the time taken to complete inspection of one batch or 30 bottles as well as the percentage accuracy of the system. Figure 3 shows the inspection process for the multipurpose spray bottle.

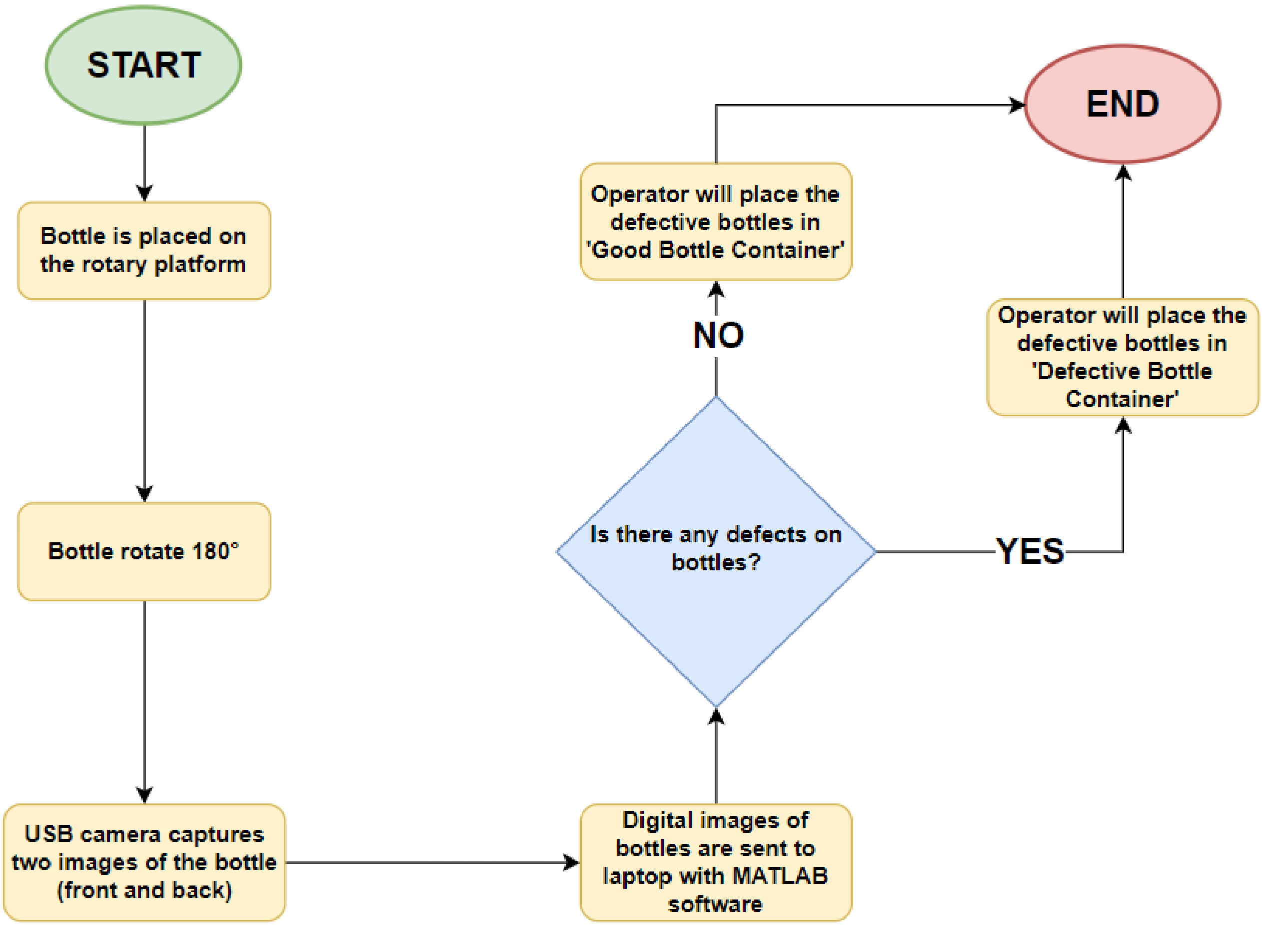


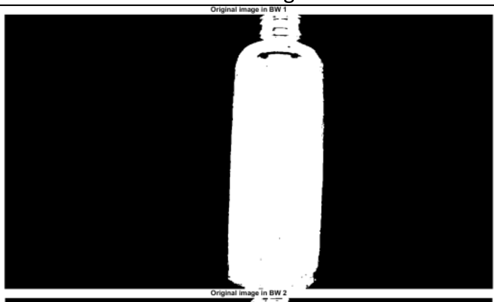
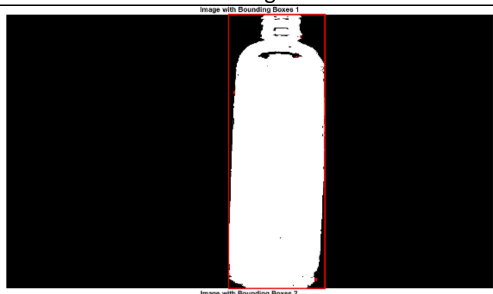
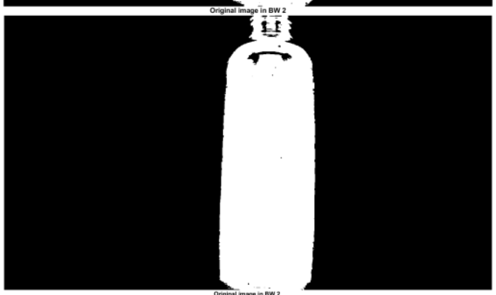
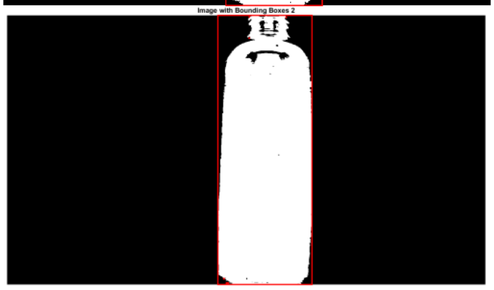
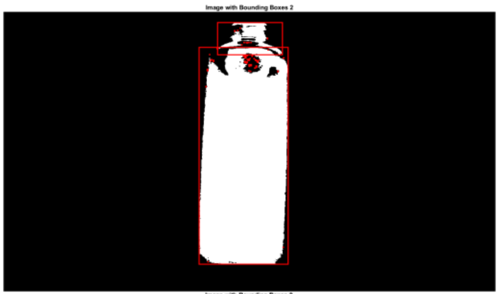
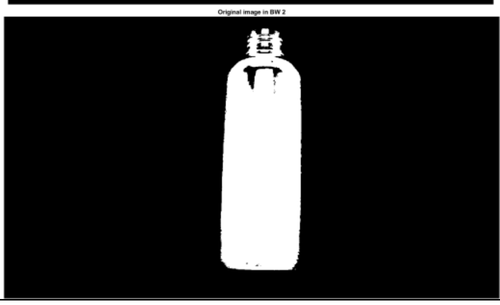
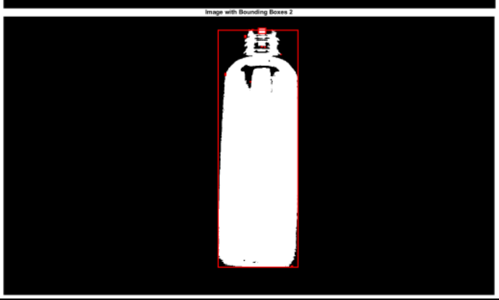
Figure 3 Inspection process flow.

The inspection system uses the black and white (B&W) testing method to detect and distinguish defects on the surfaces of bottles. The thresholds used are based on Xin et al. (2022), who used a threshold ranging from 0.5--0.1 for image processing and defect detection on workpiece surfaces. A threshold value between 0 and 1 is chosen. This value represents a fraction of the maximum intensity (255). For example, a threshold of 0.5 corresponds to an intensity value of 127.5 (0.5 * 255). Each batch contained a number of defective bottles and good bottles. The total number of bottles per batch was 30. The best threshold will then be selected for usage in the accuracy test, whereby the aim is to have an accuracy of not more than one wrongful detection or above 95% accuracy and to be faster than manual testing. A 95% accuracy means that the inspection system does not wrongfully identify bottles at least once.

To obtain images via image acquisition programmed in MATLAB, the USB camera took 20 images at intervals of 5.2 s per image. The image capture is aligned with the rotation timing of the rotary platform of 5 seconds every 180°. The delay in image capture of approximately 0.2 s allows the operator time to remove the old bottle and replace it with a new bottle for inspection. After the front and back images of a bottle are captured, it is removed from the rotary platform, and a new bottle is placed on the platform. This process is completed until all images of 10 bottles are captured, and this process is repeated twice with 20 more bottles to complete one batch or inspection of 30 bottles.

For threshold testing, the image captured by the USB camera is converted to B & W (black and white) with a threshold range (from 0.5--0.1) and, in this case, a value of 0.5. The software will draw a red rectangular box around the bottle's silhouette. If the number of red rectangular boxes is more than one per image, then the bottle is considered defective. Moreover, if the number of red rectangular boxes is only one per image, then it is a good bottle. The threshold values that are tested will be 0.5, 0.4, 0.3, 0.2 and 0.1. These ranges of values will be tested with good bottles and defective bottles to determine the most suitable threshold that will be used for accuracy testing. The bounding box (red rectangular box) determines the presence of defects. If the number of bounding boxes is one, then the image has no defects. If the image has two bounding boxes, the bottle is considered to have defects. The threshold of 0.2 is able to detect the presence of defects with the presence of two bounding boxes on the front image of the defective bottle. Hence, the threshold of 0.2 is considered for accuracy testing. Figure 4 shows preprocessed images with a threshold of 0.2.

Table 1 Preprocessing images with a threshold of 0.2.

Type of Bottle	B&W image	Bounding Box
Good bottle (front)		
Good bottle (back)		
Defective bottle (front)		
Defective bottle (back)		

3. Experimental Results

For accuracy testing, two types of data are acquired and analyzed. First, time was taken for manual inspection and automatic inspection to finish inspecting the three batches of bottles (one batch equals 30 bottles). Second, the accuracy of inspection between the two methods (manual and automatic) is important. The inspection system will utilize the best threshold.

For accuracy testing, two types of data are acquired and analyzed. First, time was taken for manual inspection and automatic inspection to finish inspecting the three batches of bottles (one batch equals 30 bottles). Second, the accuracy of inspection between the two methods (manual and automatic) is important. The inspection system will utilize the best threshold.

Three batches of bottles (30 bottles per batch) were inspected automatically, the time taken to inspect each batch, and the accuracy of the samples were collected and tabulated. The inspection system uses MATLAB's black and white method to process the image and uses bounding boxes to draw on the silhouette of the bottle and the defects. If there is more than one bounding box, a defect is present on the bottle's surface. The value of the threshold used for this test is determined during detection method testing.

The average inspection time per batch and accuracy of automatic inspection by the inspection system are calculated via Equation (1) and Equation (2], respectively. Equation (3) calculates the average accuracy per batch for automatic inspection. Table 2 shows the time taken for both manual and automatic inspection to inspect 30 bottles or one batch, whereby the time is in minutes. Figure 4 shows the comparison between the times taken for manual inspection and automatic inspection.

$$Average\ time\ taken = \frac{(Batch\ 1\ time + Batch\ 2\ time + Batch\ 3\ time)}{Total\ number\ of\ batches} \quad \text{Equation (1)}$$

$$Batch\ number = \frac{(Total\ number\ of\ bottles - number\ of\ wrongful\ detection)}{Total\ number\ of\ bottles} \quad \text{Equation (2)}$$

$$Average\ accuracy = \frac{(Batch\ 1\ accuracy\ (\%) + Batch\ 2\ accuracy\ (\%) + Batch\ 3\ accuracy\ (\%)}{3} \quad \text{Equation (3)}$$

Table 2 Manual inspection vs automatic inspection time in minutes.

Batch number	Time taken in minutes for manual inspection (min)	Time taken in minutes for automatic inspection (min)
Batch 1	6.75	7.83
Batch 2	7.08	8.12
Batch 3	6.97	8.33

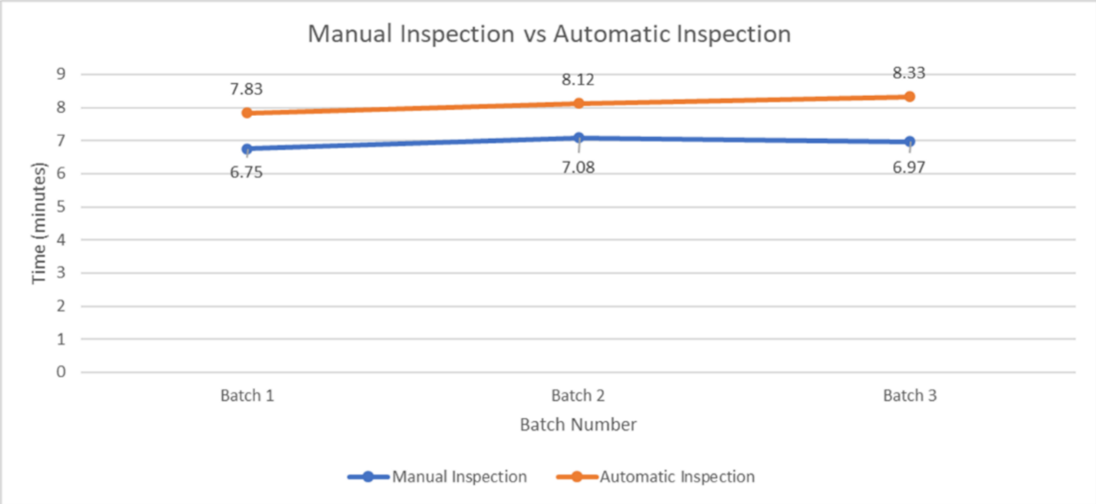


Figure 4 Manual inspection time vs automatic inspection time.

Compared with manual inspection methods, automatic inspection systems, although frequently used for consistency and efficiency, may occasionally necessitate a longer period to complete a batch. Specifically, these automated systems may take approximately one minute longer per batch. For the first batch, manual inspection managed to complete the inspection in 6.75 minutes, whereas automatic inspection took 7.83 minutes. Similarly, for batch 2, automatic inspection took 8.12 minutes, whereas manual inspection took only 7.08 minutes. Finally, the automatic inspection took 8.33 minutes to inspect batch 3, whereas the manual inspection method took only 6.97 minutes.

This extended duration can be attributed to several factors intrinsic to automation, such as the need for comprehensive data processing, calibration, and the implementation of intricate algorithms to analyze and detect anomalies with high precision. Furthermore, automated systems may experience reduced throughput because of the time required for machinery to transport items through inspection stations or to accommodate variations in item size and type. Despite this increased inspection time, automation can still offer considerable advantages in terms of accuracy and reduced human error, thereby proving to be a valuable asset in various industrial contexts.

Another experimental design for validating the accuracy of the proposed inspection system is to compare manual inspection accuracy and automatic inspection accuracy via Equation (4) and Equation (5). Table 3 and Figure 5 show the inspection accuracy results via manual and automatic methods.

$$\text{Batch number} = \frac{(\text{Total number of bottles} - \text{number of wrongful detection})}{\text{Total number of bottles}} \quad \text{Equation (4)}$$

$$\text{Average time taken} = \frac{(Batch\ 1\ time + Batch\ 2\ time + Batch\ 3\ time)}{Total\ number\ of\ batches} \quad \text{Equation (5)}$$

Table 3 Comparison between manual inspection accuracy and automatic inspection accuracy.

Batch no.	Accuracy of manual inspection (%)	Accuracy of automatic inspection (%)
Batch 1	90	96.67
Batch 2	96.67	96.67
Batch 3	93.33	100
Average accuracy	93.33	97.78

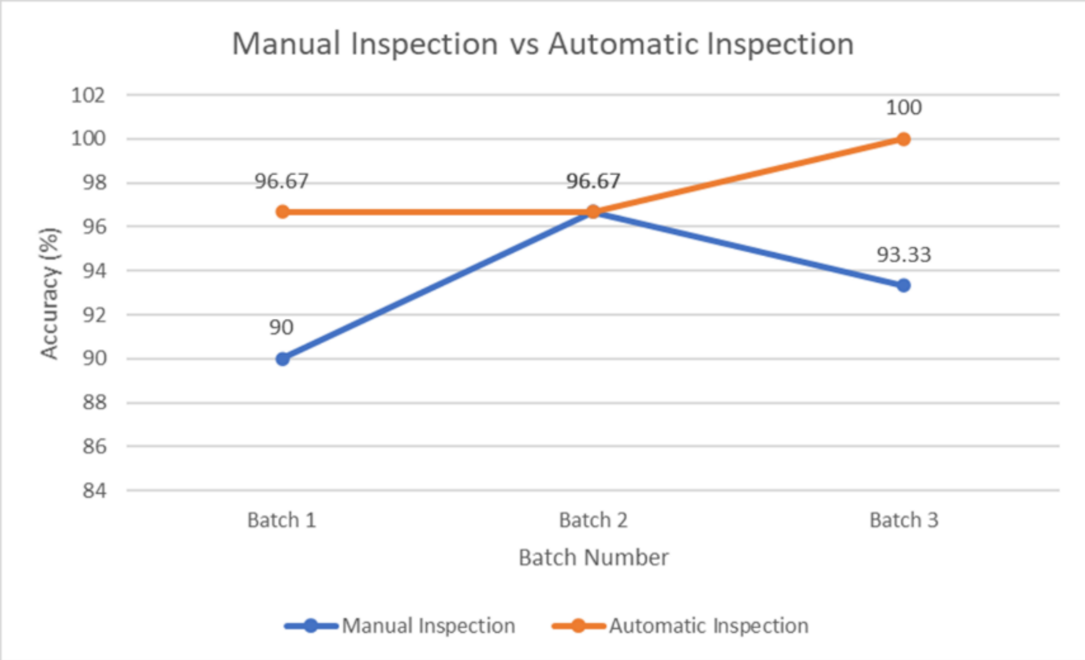


Figure 5 Manual inspection accuracy and automatic inspection accuracy.

Figure 5 shows that automatic inspection has higher accuracy than manual inspection does. For Batch 1, automatic inspection achieved an accuracy of 96.67%, whereas manual inspection achieved 90% accuracy. For Batch 2, both inspection methods achieved the same accuracy, which was 96.67%. Finally, the automatic inspection managed to achieve 100% accuracy for Batch 3, whereas manual inspection obtained only 93.33% accuracy. In comparison, the accuracy of automatic inspection is 4.45% higher than that of manual inspection.

4. Discussion

Compared with manual inspection methods, automatic inspection systems generally demonstrate superior accuracy because of their ability to consistently apply precise, predefined criteria and algorithms across all examined items. These systems utilize advanced technologies, including high-resolution sensors, imaging systems, and sophisticated software, to identify and measure minute deviations or defects that may be overlooked by the human eye. The reliance on data-driven analysis enables automated systems to reduce subjective variability and human error, ensuring that each item is assessed under uniform conditions. Moreover, the capacity to process large volumes of data rapidly and without fatigue enhances the reliability of defect detection, leading to more consistent and accurate outcomes. Consequently, while manual inspection may suffer from inconsistencies due to human factors, automatic inspection offers a more dependable and precise methodology, particularly in contexts involving high volumes or complex inspection tasks.

In terms of accuracy for automatic inspection with respect to one bottle per inspection time, result shows automatic inspection lead to slower 2 seconds in average for one bottle. In other words, higher quantity of bottle lead to more time to complete inspection per batch. Lv et al. (2020) stated that human inspection is inefficient and oftentimes inaccurate with manual inspection was referring to the quality of inspection not for the completion time. In industry, production time is crucial but to sustain the quality is to be argued. For this study, the setting for machine vision inspection has to be improved for time optimization.

In terms of accuracy for automatic inspection with respect to zero wrongly defect detection, quality of inspection is nearly 98 percent in average compared to manual inspection which is 90 percent in average. Defect detection with algorithm design gain better accuracy than manual inspection based on Song et al. (2022). Researcher also relate the better defect detection, the faster the inspection time completion (Lv et al., 2020) which are not allign with the result of this paper.

Several potential limitations are associated with the current system. First, the delay between rotation and image capture may affect image stability, potentially leading to motion blur or misalignment. Ensuring that the bottles are securely positioned and that the rotary platform functions smoothly is essential to minimize these issues. Additionally, capturing images from both the front and back of each bottle might result in redundant data if defects are not expected to vary between these views. Evaluating the value of additional images versus the time and resource costs is important. Furthermore, the time required for image capture could impact the overall efficiency of the inspection process, making it necessary to balance thoroughness with operational efficiency (Kazim et al, 2022).

To improve the system's effectiveness, several enhancements could be considered. Optimizing the timing of image capture and rotation could improve efficiency without compromising image quality. The incorporation of advanced image processing algorithms to account for minor bottle movements or rotations could increase defect detection accuracy. Additionally, the integration of automated systems for bottle placement and removal could streamline the process, reduce human intervention and minimize potential sources of error (Kazim et al., 2022). In conclusion, while the system demonstrates a methodical approach to bottle inspection, careful attention to timing, stability, and efficiency is crucial to achieving reliable and accurate results in practical applications.

5. Conclusions

In conclusion, the program developed in the MATLAB software is able to detect defects present on the bottle by drawing two bounding boxes in the image as indicators of defects being identified successfully. Although automatic inspection systems may necessitate slightly more time per batch than manual methods do, their advantages in terms of accuracy and consistency are considerable. The additional time required for data processing, calibration, and implementation of complex algorithms is counterbalanced by the significant reduction in human error and the ability to detect minute defects that might be overlooked by manual inspection. This renders automated systems particularly valuable in industrial contexts where precision and reliability are of utmost importance. The experimental comparison between manual and automatic inspection methods further highlights the superior accuracy of automated systems, as evidenced by the higher average accuracy rates achieved in the study. To increase the efficacy of these systems, it is essential to address potential limitations such as image stability and the efficiency of the inspection process. Optimizing the timing of image capture and rotation, incorporating advanced image processing algorithms, and integrating automated systems for bottle placement and removal can significantly improve performance. By concentrating on these areas, the overall reliability and accuracy of automatic inspection systems can be further enhanced, making them indispensable tools for quality assurance in various industries.

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Ethical considerations

This research has no ethical testing.

Conflict of Interest

We declare that there is no conflict of interest in this study.

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