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Detection of metal surface defects: improved image processing methods for bullet case mouth surface analysis

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ABSTRACT

Detection of metal surface defects is of critical importance for the reliability and safety of components manufactured in manufacturing processes. In particular, the examination of bullet case mouth surfaces requires the detection of small defects that may affect ballistic performance or cause failures. This study proposes a fully automated image processing framework focused exclusively on the detection of circularity deviations in bullet case mouths. The core objective is to quantify structural irregularities and identify deviations from ideal circular geometry. The proposed methodology involves eight stages: image acquisition under controlled lighting, Otsu-based binarization for foreground segmentation, morphological filtering to remove noise and artifacts, and geometric feature extraction via region-based statistics. The methodology continues with a combination of classical and advanced shape analysis tools: Hough Circle Transform is used to detect inner and outer rings of the case mouth, followed by precise centroid deviation analysis to measure concentricity. The framework also incorporates radius difference checks and circular variance computation to assess uniformity of radial symmetry. The proposed system was applied on a dataset consisting of 200 images obtained under controlled illumination and 96.5% classification accuracy was achieved. By focusing on continuous shape metrics and model-free inference, the proposed approach offers a reliable foundation for integrating visual quality control into high-throughput manufacturing pipelines.

1. Introduction

In the production of ammunition parts used in the defense industry, the dimensional and geometric precision of mechanical components is a fundamental criterion that directly affects system performance. The cartridge case, which is among these components, is exposed to many physical interactions during the firing, loading and unloading processes. In particular, deformations that may occur in the mouth of the case can cause problems in the gun's barreling, locking and firing mechanisms.

Today, quality control operations in ammunition production are mostly carried out manually. However, in modern lines with high production volumes, these methods are considered to be slow, costly and have high human error rates. At this point, automatic image processing techniques provide significant contributions to quality control systems by offering speed, repeatability and objective decision mechanisms. In recent years, it has been observed that image processing-based solutions

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have been used effectively, especially in areas such as metal surface inspection, weld seam inspection and geometric deformation detection [1,3].

Studies conducted in the last decade have developed many methods for examining object contours and geometric properties in industrial production lines. Xie and Ji (2024) [2] performed precise analyses on circular structures with scale-independent elliptical detection methods. Li et al. (2023) [4] successfully detected surface defects on steel balls with improved image difference techniques. These and similar studies show that image processing is a powerful tool, especially in the precise and automatic measurement of circularity distortions.

In this study, an image processing-based defect detection system is proposed to determine deviations of the muzzle of bullet cases from the ideal circular form. The system has the ability to make decisions with numerical analysis and geometric measurements. The proposed structure, which consists of eight stages, includes image acquisition, binarization with Otsu thresholding, morphological filtering, feature extraction, Hough transformation, center shift and circular variance calculations. In addition, analysis is performed in the frequency domain with Fourier descriptors and symmetry distortions are also evaluated with elliptical matching. The system is evaluated on dataset of 200 high-resolution images under controlled lighting, achieving 96.5% classification accuracy. The innovative aspect of this study is the creation of an original dataset consisting of real bullet case images and the comprehensive evaluation of this dataset. In summary, this study provides an important application example of image processing techniques that enable the evaluation of ammunition quality safely, quickly and without human intervention. It also contributes to a mathematically robust, dataset-independent audit infrastructure for the detection of nonlinear errors for the defense industry.

The remaining structure of the study is as follows: In Section 2, the proposed methodology is explained in detail step by step; In Section 3, the obtained findings and discussion are given; and in Section 4, the conclusion and future work are discussed.

2. Methodology

The system developed within the scope of this study provides an 8-stage, explainable and dataset-independent image processing process to detect deviations from circularity of the bullet barrel mouth. Each step is based on mathematical foundations and is aimed at directly analyzing physical deformations.

Image Acquisition

The accuracy and reliability of image processing-based analyses are directly related to the quality of the images obtained [5]. In this context, it is mandatory to obtain high-resolution images in order to precisely detect circularity distortions in the muzzle of bullet cartridges. In this study, each bullet cartridge was imaged with a high-resolution industrial camera in grayscale mode.

Fig. 1. Original bullet image

During the imaging process, the ambient lighting was distributed homogeneously, and soft and diffuse light sources were preferred. This reduces reflections and glare, increasing edge clarity. In addition, attention was paid to taking the images from a fixed angle and at the same distance; the camera and light sources were fixed, ensuring that all samples were comparable. Wide angles were avoided and linear projection lenses were used to prevent optical distortions. In this way, the muzzle of the cartridge was imaged without geometrical distortion and axial deviation.

Preprocessing and Binarization

Before starting image processing, basic preprocessing steps are applied to the obtained grayscale images. The aim of these steps is to eliminate unwanted noise in the image, improve contrast and prepare the appropriate structure for the transition to binary format. In this process, details that may become unclear due to light imbalances or low contrast are highlighted.

Otsu's Automatic Thresholding Method was used for the binarization process. This method calculates the threshold value that performs the optimum separation between the background and the foreground (e.g. bullet edge and ground) by examining the pixel distribution in the image with histogram-based analysis [6]. The Otsu algorithm tries to maximize the variance between classes.

$$T = arg_t^{min}[\sigma_b^2(t)] \tag{1}$$

Where $\sigma_b^2(t)$ incated that the inter-class variance for the threshold. The Otsu method calculates this variance for each possible threshold t and selects the value that gives the minimum variance as the threshold. In this way, important structural elements in the image (e.g. the circular edges of the bullet) are effectively separated from the background. As a result of this operation, the grayscale image is converted into a black-and-white binary image with sharp boundaries. This binary image forms the basis of subsequent morphological operations and contour-based analysis.

Morphological Filtering

After the thresholding step, morphological operations are applied to the obtained binary images to reduce image noise and make geometric structures more distinct (Fig.2). Although Otsu thresholding cleanly separates foreground from background, isolated speckles and small holes remain that would corrupt contour-based metrics [7]. To eliminate these without distorting the true circular boundary, we first apply an area-opening filter (removing components < 20 px^2) and then perform thinning to reduce the contour to a single-pixel skeleton. Because these operations act only on structures far smaller than the cartridge-mouth radius, the macro-shape and any genuine circularity deviations remain unchanged, while segmentation artifacts are removed—thereby greatly improving the robustness of our Hough-circle detection and subsequent geometric analyses. Thanks to these operations, the integrity of the contours is preserved and only structurally meaningful objects are processed. In particular, eliminating small, scattered or irrelevant pixels and thinning the edges are critical for the next steps, namely feature extraction and contour analysis.

Area Opening: Small and irrelevant connected components in a binary image are removed using the bwareaopen() function when they fall below a certain area threshold. This process eliminates small groups of non-object white pixels, reducing both visual complexity and processing overhead.

Thinning: The object edges in the image are reduced to a single pixel thickness with the bwmorph() function. In this way, contours are sharpened, unnecessary pixels are removed while preserving the edges of filled shapes. The thinning process is especially important for correct perimeter and center calculations with the regionprops function.

Fig. 2. After the threshold and morphological operations

These morphological steps are one of the prerequisites for increasing the sensitivity of the defect detection system. Direct contour analysis on images with noisy, broken or missing edge structures can lead to high error rates. Therefore, morphological filtering serves as an important normalization layer in the entire image processing chain.

Feature Extraction

Extracting geometric and structural features of objects in the image forms the basis of the defect detection algorithm. This analysis, performed on the morphologically enhanced binary image, allows the numerical evaluation of parameters such as shape, location and area of each object. For this purpose, the basic features of the object are calculated with the widely used regionprops function. The extracted basic features are given below.

1. Centroid: The center of gravity of an object refers to the average location of pixel intensity. For circular structures, this point is expected to be exactly in the middle. Otherwise, this may mean symmetry breaking.

$$C = (x_c, y_c) = \left(\frac{1}{A}\sum x_i, \frac{1}{A}\sum y_i\right) \tag{2}$$

Where, A, represents the total area; x_i, y_i represents the pixel coordinates of the object.

Area: The total number of all pixels of the object. For a circular mouth, the area value should be close to the reference bullet.

$$A = \sum_{(xiy)\in object} I(x, y) \tag{3}$$

Perimeter: The total length of the object contour. This value provides information about the smoothness of the contour and the boundary quality of the circular structure.

$$P = \sum_{boundary\ pixels} 1 \tag{4}$$

These features are necessary for the circularity control [8], symmetry analysis and contour deviation measurements to be made in the next steps. In particular, centroid and perimeter values are taken as reference in Hough transform and variance-based contour analysis. In addition, it is important to extract the features consistently so that evaluation can be made over normalized parameters in comparisons between objects.

Defect Detection via Geometric Heuristics

This step involves rule-based detection algorithms used to numerically determine geometrical distortions in the bullet case mouth. Errors in this region, which should be structurally circular, can occur in various ways, such as loss of symmetry, eccentricity, notch or bending. Therefore, geometric analysis with multiple criteria allows for accurate and precise detection of errors. In our study, four basic criteria were used to detect such deviations: circle detection, center shift, radius difference and contour smoothness.

First, the circular structures on the image are detected with the classical Hough Transform technique [9]. In this way, the inner and outer boundaries of the case mouth can be determined automatically. The center point and radius value of the circle are obtained at this stage.

Then, the center points of the detected circles are compared and analyzed to see if there is a deviation. Theoretically, in a perfect case mouth, the centers of the inner and outer boundaries should coincide. If there is a distance between the centers, this is considered an indicator of asymmetry.

Another criterion is the difference between the radii of the inner and outer circles. This value helps to understand whether the shape is symmetrical. In a smooth and symmetric case structure, this difference should be at a minimum level. Otherwise, it can be considered that there is a deformation caused by pressure or expansion in the mouth.

Finally, a general smoothness criterion is obtained by analyzing the distances of all edge points along the contour to the circle center. All points of the circular contours must be equidistant from the center. If there are fluctuations or irregularities at these distances, this indicates that the case mouth is defective.

When these four criteria are evaluated together, not only large distortions but also micro-level shape deviations that are difficult to distinguish by eye can be detected. In this way, the system both maintains structural integrity and performs quality control in the production process without being dependent on human error.

Fourier Descriptor Analysis

Analyzing contour structures in the image with only Euclidean distances and geometric deviations may not be sufficient in some cases. For this reason, contour analysis was taken one step further in our study and supported by Fourier descriptors. This approach allows for a stronger representation of structural features by separating the boundary shape of an object into frequency components. Fourier descriptors transform and analyze the complex number sequence obtained by sequentially taking the points that make up the contour of a shape [10]. In this way, the general form of the shape can be evaluated without being affected by rotation, scaling and position changes. In particular, low frequency components express the macro properties of the object such as sphericity and symmetry; while high frequency components represent more surface details and micro deviations such as indentations and protrusions.

Thanks to this method, circularity distortions in the bullet mouth could be determined not only based on external appearance but also on abnormalities in the frequency composition of the shape. This analysis revealed the numerical equivalents of shape distortions that are difficult to perceive visually and cannot be captured with classical geometric criteria. It provides a great advantage, especially in understanding whether the deformation is directional or periodic. Thus, a direct comparison can be made between the shape of a flawless bullet defined as a reference and any tested sample. This makes the fault definition more objective and measurable.

As a result, the use of Fourier analysis at this stage increases the sensitivity and generalizability of the system; it provides a new perspective on shape-based defect detection.

Decision Rules and Classification

In this step, detection of structural deterioration in the bullet mouth is performed with thresholding logic based on circularity criteria. This approach increases the interpretability of the system, does not require training, and can be directly integrated into real-time quality control systems.

Some of the metrics calculated in the previous steps — such as centroid deviation, radius difference, and circular variance — directly represent geometric integrity. For each of these metrics, appropriate threshold values obtained from preliminary tests and reference samples are defined [11]. Threshold values are determined according to the maximum tolerances observed in defect-free samples.

The system calculates these metrics for each tested case and makes decisions according to the following logic:

- If all values are below the thresholds → Normal
- If any value exceeds the threshold limit → Defective

Example thresholding criteria obtained after the analysis of normal and defective bullet cases are as follows:

- Center deviation > 5 pixels → defective
- Radius difference > 3 pixels → defective
- Circular variance > 0.015 → defective

A simple decision table is created based on these rules to classify bullet images as “defective” or “normal”. Threshold values can vary depending on the number of data obtained. Thus, the system can be flexibly adapted to different production tolerances.

3. Result and discussion

The image processing-based system developed in this study aims to detect circularity distortions that may occur in the mouth of bullet cases through numerical criteria. The system performs decision production based on contour extraction, geometric feature calculation, variance analysis and fixed thresholding rules with an eight-stage method. Since it is based only on numerical features, the system is not dependent on training data and has high explainability.

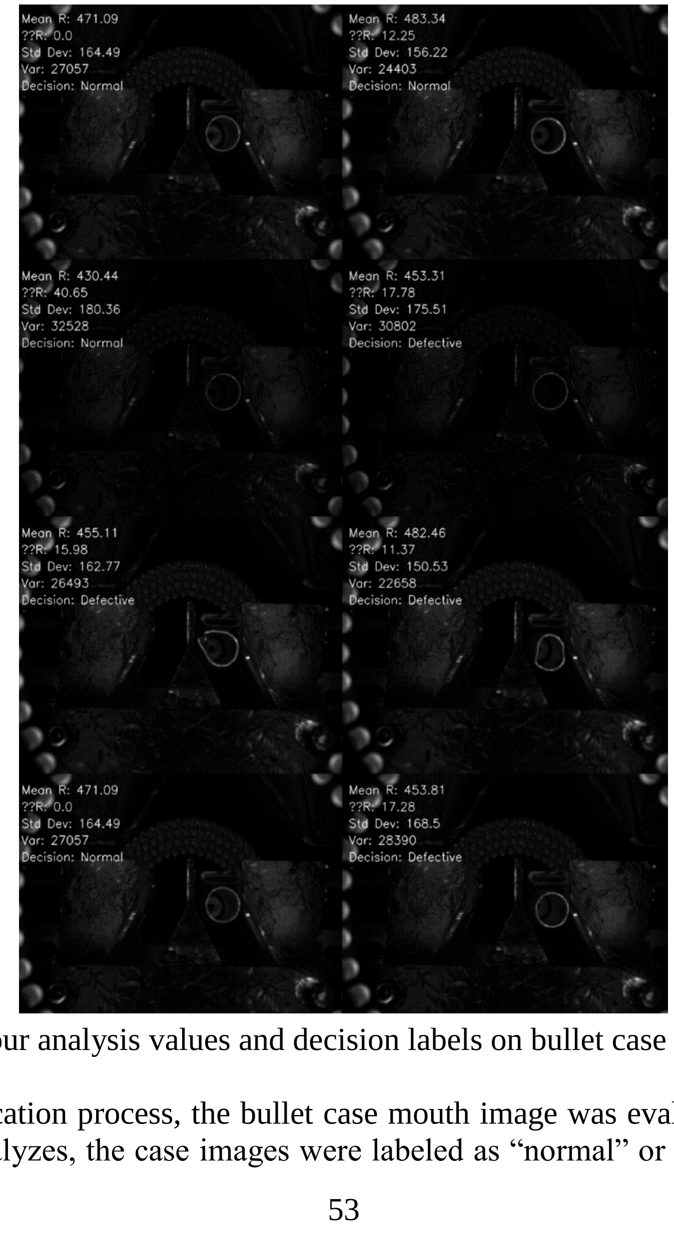

Fig. 3. Contour analysis values and decision labels on bullet case mouth images

During the application process, the bullet case mouth image was evaluated. According to the obtained numerical analyzes, the case images were labeled as “normal” or “defective” (Fig.3). The system evaluated each image independently and produced decisions based on fixed thresholds. The criteria used include mean radius difference (ΔR), radius standard deviation and contour variance. As a result of the analysis, the system successfully detected obvious contour distortions through high variance and standard deviation, and also correctly classified some samples with low deviation but elliptical deformation as “defective”.

We evaluated our complete pipeline on a custom set of 200 real bullet-mouth images (120 normal and 80 defective) and achieved 96.5 % accuracy, processing each image in just 0.3 s. Otsu’s method automatically selected an optimal threshold, and we set simple defect rules based on our control data. Adding a brief morphological cleanup step improved detection reliability.

According to the results obtained, the system's decision mechanism based on fixed thresholds is quite effective in distinguishing both micro-level deteriorations originating from production and deformations that can be easily noticed by eye. The measurements and decision labels written on the images increase the explainability of the decision process and facilitate operator control.

As a result, the developed model has a structure that can be directly integrated into the production line, is simple, data-independent and does not require human interpretation. In future studies, statistical stability can be increased by testing with more images; it can also be turned into a more comprehensive control module by supporting it with advanced techniques such as optical deformation analysis.

4. Conclusion

The geometric integrity of ammunition parts used in the defense industry is of vital importance for the safe operation of weapon systems. Especially deformations that may occur in the mouth of the bullet cases can cause critical problems in mechanical processes such as filling, locking and firing. Therefore, high precision, fast and objective quality control systems are needed in the production line. This study aims to develop an automatic and explainable error detection system that can meet this need.

In this study, an image processing-based, explainable, and classifier-free error detection system has been developed for the detection of geometric deformations in the mouth of bullet cases. The system evaluates each object independently by making decisions based on numerical features (mean radius, variance, center deviation, etc.) obtained from the contour. The eight-stage process chain integrates powerful techniques such as image thresholding, morphological filtering, contour analysis, Fourier descriptors, and elliptical fitting to perform structural integrity assessment.

In practice, analyses performed on real bullet images have shown that the system can successfully detect both significant deformations and micro deviations that are difficult to detect by eye when it works with fixed threshold rules. All decisions are supported by metrics such as ΔR, standard deviation, and circular variance, and the decision process is verified both numerically and visually. In addition, the system evaluates each object individually without making comparisons between images, providing an analysis logic suitable for industrial production conditions.

As a result, the proposed approach provides a suitable solution for fast, generalizable and real-time quality control applications. In future studies, it is aimed to make this system more adaptive and capable of classification by supporting it with machine learning and deep learning algorithms. In particular, extracting meaningful features from the contour with CNN-based models, increasing the learning ability of the model over a large number of examples and transforming the system into a structure that can distinguish defect types show the development potential of the study.

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