Eccentricity-Based Diameter Measurement: A Novel Approach for Quality Control

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Abstract: On-line diameter measurement is essential in producing round extruded products, as defects can lead to significant losses in production effort and resources. Traditional mechanical sampling inspections have been replaced by contact-free, inline measurement systems that continuously monitor diameter along the production line. While these systems effectively detect circular shapes and measure radius, they often struggle with position artifacts, leading to measurement errors. To achieve improved accuracy and precision, it is crucial to incorporate considerations of non-orthogonality into the image processing algorithm. Methods such as feature extraction and image segmentation are utilized to identify abnormalities. Additionally, integrating machine learning models enables real-time quality assessment and automated decision-making. However, the Hough Circle Transform, though effective for detecting circles, has limitations, including sensitivity to noise, computational intensity, and challenges in identifying occluded or imperfectly circular objects. This paper proposes a novel method to measure the diameter of a circle based on its eccentricity. The method involves analyzing captured images for edge detection and eccentricity measurement at various angles relative to the camera lens. Additionally, it establishes a relationship between the line-of-sight angle, the eccentricity of the perceived ellipse, and the diameter of the actual circle. The results obtained are compared with those achieved using the Hough Circular Transform (HCT), demonstrating improved accuracy with the proposed method. This study presents a practical solution for enhancing quality control in the mechanical industry, addressing current needs with an inclusive and error-resistant approach.

1 INTRODUCTION

Accurate circle detection is a critical challenge in computer vision that plays a vital role in object recognition and decision-making systems, with wide-ranging applications across various practical domains. A broad spectrum of applications such as optical character recognition used in banks, drone vision, biomedical scans recognition, vectorization of hand-drawn sketches, quality control of manufactured products and components, crowd management in surveillance video, etc (Le, Duan, et al. 2016).

With the extended scope of applications, so does the need for circle detection algorithms to improve their performance. The vast range of applications poses a greater challenge for an integrative approach. An example would be rounded objects in three dimensions like shadows and illumination from angles and intensity such as shaded and unshaded sources which can lead to under or over exposed details on digital images (Mehmood, Khan et al. 2019), with which the accuracy may suffer from detection. Controlled conditions may somehow dampen some of these effects, but they cannot prevent distortions in perception or difficulties with sorting and classification because of different object

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perspectives. These can therefore defeat the purpose of simulating an image which is as similar as possible to the actual one (Teo, Heeger, et al. 1994). The Hough Transform is a very traditional circle-detection algorithm (Ou, Deng, et al. 2022); it has, however, particularly important limitations as for tasks which are prone to perception distortions with orientations of the objects or non-orthogonal placement relative to the camera.

One of the ways through which these challenges overcome is use of the measures of ellipticity of shapes. Such might be among the best pictures that are used to represent the distorted circle in images (Singh, et al. 2020). Innovative methods have to come into place since successful production in most cases has its basis in novel approaches other than the conventional algorithms and traditional techniques (Somwang, Muangklang, et al. 2019). This study aims to address these limitations by including advanced algorithms adapted to perception-related issues, thus enhancing the reliability of circle detection in varied conditions. Another feature used in the system is the utilization of machine learning algorithms in minimizing the errors of measurement perceived for circular objects. The designed system was mainly to be used in manufacturing mechanical components. An axial joint (Cholke et al. 2024) was analyzed in simulated environments where a radius and a circumference of circular ends of the joint were measured on both sides by using the application of image processing techniques. Those results were compared with already predefined values of used parameters. The above-stated results were accurate up to the nearest expected tolerance; therefore, they were close to the expected results.

In general, this will enhance and automate the quality control process for better precision, speed, and cost efficiency. The system provided herein in a design environment that is tailored for the precise capture, processing, and classification of objects effectively addresses the key obstacles while meeting the objectives of this study. This proposed system is a feasible solution with promising applications in the mechanical manufacturing industry.

2 LITERATURE REVIEW

Quality control within the manufacturing industry has been traditionally a labor-intensive process through manual inspection to determine defects and ensure consistency. This has all changed with the advent of image processing, as this approach now makes it possible for fast, accurate, and near-real-time assessment of production lines through the detection of shapes such as the circular Hough Transform developed, as described by B. S. Singla et al., as an appropriate circle-detecting technique. However, the stretched ellipses are not included, and the transform is selective only for the circles (Singh, et al. 2020) which negates the perceived view of the circle as a result of positioning. Another intriguing approach is by Changsheng Lu et al. (Lu, Xia, et al. 2017) who utilize the arc-support line segment (LS) technique that identifies arc-like line segments through areas where a set of points reveal a gradient angle with varied changes in curve form. This method differs arc-support LS from regular line-support regions that include points with approximately aligned gradient angles and a linear distribution. Still, the main weakness of this method is that it fails to classify ellipses as circles when they do not lie orthogonally in front of the camera, which in most cases means it is rather inefficient in cases with non-uniform orientation of the object. Theoretically, this procedure can be generalized to circles, ellipses, conics in general, and curves of any number of parameters. However, the parameter space increases exponentially with every additional parameter, so the technique becomes not so efficient in terms of storage and computational time when a curve requires more than four or five parameters that introduce new memory processing challenges for real-time applications. Getting fewer parameters for better detection image enhancement is also an equally important task, as mentioned and discussed by Yousaf Mehmood et al. (Mehmood, Khan et al. 2019).

Great advancement is brought about through the integration of machine learning algorithms (Cholke et al. 2024), improving the system for real-time analysis and promoting more accurate detection, with automatic decisions in this regard, thus attaining much more efficient and reliable quality control. Fikret Ercan et al. and Tiantian Hao et al. (Ercan, Qiankun, et al. 2020), (Hao, and Xu, 2022) these early circle detection methods, especially through genetic algorithms and learning automata techniques, prove to be computationally intensive when detecting several circles in an image. Of late, with the rise in the use of deep learning algorithms, more effectiveness in object detection is marked in complex environments. Ercan et al. can get higher accuracy using fewer layers and quicker processing speed of networks in even challenging scenarios, such as under-water images with poor illumination conditions. Hao et al. proposed a circle detection model based on the combination of CNN via the method of edge feature extraction and FCOS detection network. However, the above methods are silent in the face of other challenges such as detecting ellipses as circles when objects oriented non-orthogonally with respect to the camera due to variations in depth and positioning. A more sophisticated approach could include elliptical perception into the process of detection in order to achieve a greater level of accuracy under the same scenarios.

Our proposed approach overcomes several limitations that remain in the circle detection methods of current approaches. Most of the available methods have overlooked the impact of environmental factors-illumination intensity and direction-leading to erroneous results in cases where they are applied in real-world environments. The approach developed works under controlled conditions that prevent the implementation of inaccuracies with regard to depth capture and remove variation in shadow. Further, whereas most vision algorithms dismiss the orthogonality of objects with the camera lens, our approach incorporates this, which would be characterized to be a flaw in perception due to non-alignment. Furthermore, since we realize that the circles are only seen as ellipses at any nonorthogonal view angles, we associate eccentricity with the relative orientation of the object with respect to the camera and attain more accurate classification of the ellipses that are probable to be circles with exact diameter measurement. This is a holistic solution, which is a great improvement in quality control systems, especially the mechanical industry, where measurements are always critical. The approach our circle detection method provides will improve on accuracy and reliability in general quality control processes, thus contributing to more efficiency and reduced costs of production.

3 METHODOLOGY

The proposed system's process flow, shown in Fig. 1, offers a clear, step-by-step summary of processes, showing how tasks and data move through various phases. Fig. 2 presents the hardware structure of the proposed system, offering a visual representation of the design and logical flow. This highlights the smooth integration of components to ensure efficient functionality. Additionally, Fig. 3 illustrates the system's architecture, showing the integration between components for constructive functionality.

3.1 Hardware Setup

The proposed system operates within a controlled environment.

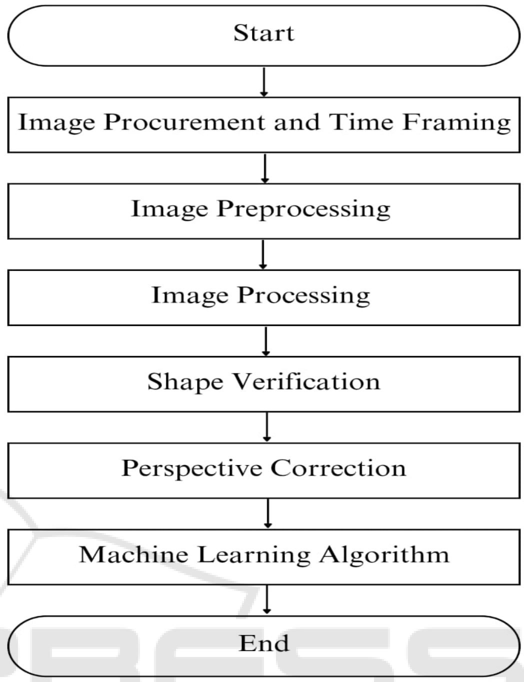

Fig. 1: Process Flow of Proposed Quality Control System

Key features of the hardware setup are as follows:

- The setup is isolated from ambient light by enclosing it in a black box, ensuring complete blockage of external illumination.
- Reference (Cholke et al. 2024) thoroughly explains the constrained setup where the internal lighting is carefully measured and maintained at an optimal level using the light intensity testing setup.
- The object of experimentation—a mechanical rod with rings on each end—is positioned orthogonally to the camera within a measured distance which, with balanced and appropriate lighting on both sides. This distance between the rod and camera is unchanged throughout the experiment.
- The camera is connected to the processing unit through a LAN cable for data communication and M12 8-pin barrel cable for power supply.

Figure 2: Hardware Setup

This entire setup ensures that physical parameters remain constant, supporting consistency and accuracy in the results.

3.2 Software Setup

The software setup seamlessly integrates with the hardware by processing images captured within the controlled environment, ensuring systematically organized, high-quality data for accurate and reliable analysis.

3.2.1 Procuring Images and Time Framing

Images of the mechanical rod are captured within the controlled environment using a high-resolution

$$x5 = \text{Median}(\{x1,x2,x3,x4,x5,x6,x7,x8,x9\}) \quad (1)$$

industrial camera with a 3-megapixel sensor. Each image is carefully tagged with relevant metadata and timestamped to facilitate detailed and accurate analysis in subsequent processing st ages. This approach ensures that all captured data is systematically organized, enabling efficient tracking and comparison across different time frames for enhanced analytical accuracy.

3.2.2 Image Preprocessing

In our project workflow, image preprocessing was the first major step where raw images were refined so that they could be of quality and consistency. Brightness and contrast were adjusted, colors normalized, and excess data filtered out. These steps produced uniform images data, which led to better accuracy in subsequent stages, such as feature extraction, object detection, and measurement, hence always leading to reliable and accurate analytical results.

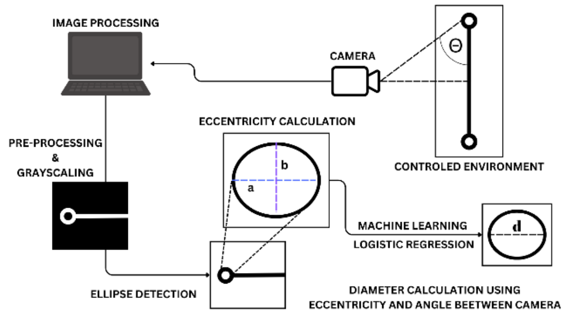

Figure 3: Architecture of Proposed Quality Control System

3.2.3 Image Processing

- After the pre-processing step, the image was first converted to grayscale, simplifying the algorithm and reducing computational requirements by transforming the image from 3-channel RGB format into a single-channel grayscale format, then blurring was done with the median filter with kernel size 3x3 to suppress noise. The Median kernel used for this system is shown in Equation 1.

$$\begin{bmatrix} x1 \; x2 \; x3 \\ x4 \; x5 \; x6 \\ x7 \; x8 \; x9 \end{bmatrix}$$

- The Hough Gradient method is then applied to identify circle center candidates and measure the distance from each side of the detected edge, using the Canny method around the center.
- This iterative action of finding the ideal distance which would suit to be the radius creates a list of “n” tuples where the circle C is represented by the parameter tuple (xcenter,ycenter,r) in which xcenter and ycenter denote the coordinates of the circle's center, and r represents its plausible radius. The distance from the image center to the center detected center is also measured and stored for calculation in subsequent steps.

3.2.4 Axis Identification and Foci Calculation for Ellipse Verification

For each detected center, all listed radius values are doubled and assessed as potential lengths of the major and minor axes, where the major axis is the longest and the minor axis is the shortest, with both axes perpendicular to each other, as required by the properties of an ellipse. Finally, the foci are calculated using Equation 2, where c represents the distance from the center, and a and b denote the lengths of the semi-major and semi-minor axes, respectively. The existence of these foci confirms that the detected values correspond to an ellipse.

$$c = \sqrt{(a^2 - b^2)} \tag{2}$$

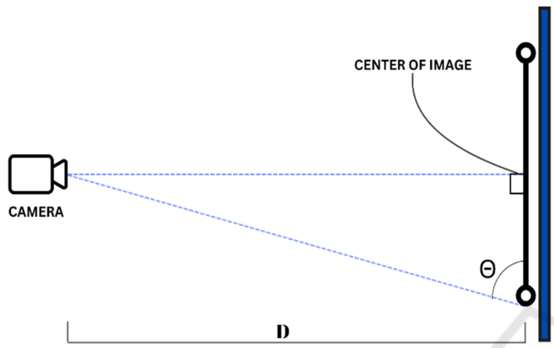

Figure 4: Camera and Line of sight angle relationship

3.2.5 Calculating Ellipticity and Camera-Angle Relationship Using Geometric Analysis

Using these verified values, the ellipticity e of the ellipse is calculated as shown in Equation 3. Next, the straight-line distance from the center of the ellipse to the camera, along with the angle Θ it forms with the image plane as shown in Fig. 4, is determined using the Pythagorean theorem. This calculation is possible because the orthogonal distance from the rod to the camera is known, and the distance from the image center to the detected center was established in the previous step. This step also establishes a relationship between the ellipse's ellipticity and its angle relative to the camera.

$$e = \sqrt{1 - \frac{b^2}{a^2}} \tag{3}$$

$$e, \cos\Theta \propto d \tag{4}$$

3.2.6 Perspective Correction Using Logistic Regression

Using these parameters, e, and Θ, the multivariable logistic regression model takes these values as inputs. This model, based on labelled data and guided by Equation 4 with d being the diameter of the circle, will determine if the center found along with the measured ellipse values correspond to a true circle with predicted diameter that happens to appear elliptical due to the perspective it is viewed from.

Figure 5: Correctly Detected circle diameter on rod using Proposed Method

Finally, the measured diameter of circles is annotated on the image accurately as shown in Fig. 5. This integrated proposed process helps to determine if the detected ellipses are true circles with precision diameter prediction.

4 RESULTS AND DISCUSSIONS

Suitable Environmental Conditions: The control of environment used in the controlled environment setup was responsible for the accuracy and consistency of the results obtained. The perfect control of environmental parameters helped assure that physical conditions were stable during the experiment, and thus, led to reliable and reproducible results. As alterations in depth perception because of light can pose a challenge in the proposed flow, controlling the ambient light with an enclosure and installation of lights with fixed illumination proved to be of immense benefit. The controlled setting thus proved instrumental in achieving consistent and accurate measurements, further validating the findings as repeatable. This setup is considerably recommended for the mechanical industry to achieve proper quality control-that is why it becomes so invaluable in its application, especially for ensuring the highest standards of mechanical manufacturing processes.

Verifying the presence of Ellipse: In order to verify the existence of an ellipse, the given problem was actually important to determine if the circle was to be well defined. The identification of axes and foci calculation are important steps in this verification process. This phase of the methodology brings a differentiating factor between the proposed method and other methods currently in use within the industry. With rigorous identification of an ellipse before finding the circle, the method strengthens the reliability and accuracy of the findings. Ability to detect slight changes in the characteristics of the ellipse allows for more accurate quality control, particularly in industries requiring precision, such as the mechanical and manufacturing industries.

Final calculation: The relationship found then forms the core of the proposed algorithm, which significantly generalizes what has been previously known. It led to the understanding of how the eccentricity of an observed ellipse is connected with the angle at which the center of this ellipse makes with the camera lens. As the experiment results show, with further movement of the circular part of the rod away from the center, it started behaving like an ellipse, which has its eccentricity close to the value one. The eccentricity will be zero for a circle that is exactly at the center. This relationship thus offers deeper insight to the geometrical behavior of the object and forms a solid ground for further refinement of the quality control process. Thus, this proposed method brings clarity and precision in the identification of even minor deviations in the object for maintaining high-quality standards in production environments.

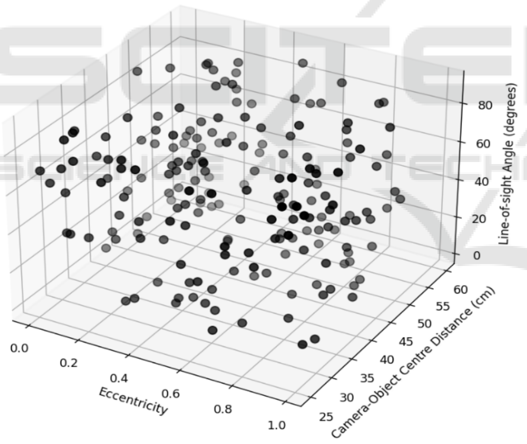

Figure 6: Plot of Multivariable Logistic Regression Model

Machine Learning Outcome: The observations made and structured into a dataset provided foundational results that confirmed the relationship discussed in Equation 1. This dataset served as the basis for further analysis, offering valuable insights that are crucial for improving the accuracy of the quality control system. The plot of Logistic Regression in fig. 6 shows 200 sample data points correctly tagged for building the model. It shows how the multiple variables are co-related. The derived relationship is crucial and base for measuring diameter for further test objects. Machine learning algorithms applied to this data enhanced the system's predictive capabilities, making it more adaptive and efficient. As the system processes more data, it improves its ability to identify patterns and anomalies, thereby achieving higher precision in quality control. Additionally, it aids in detecting edge cases, ensuring that after a certain extent perceived ellipse is correctly identified as a true ellipse and not mistakenly classified as a circle. This approach not only validates the underlying theory but also demonstrates the power of integrating advanced data analytics in industrial applications. The positive results validate the potential of machine learning to optimize processes, contributing to reduced defects and greater consistency in production lines.

5 SYSTEM COMPARISION

A comparison was done against the Standard Hough Circular Transform, and it was presented showing the ability of the proposed system to easily outperform the simple implementation of this standard method and overcome challenges and drawbacks associated with the standard method.

5.1 Handling Skewed Perception

Skewed perception refers to the distortion or misrepresentation of an object or feature in the image due to various camera angle, lens distortion, or object orientation. Since this rod placement is distorted, the HCT fails to correct perspective. Instead, with the proposed method, all these problems are handled by extra processing steps to correct the skewed perception. It takes into consideration the orientation of the object, and the angle of the camera to apply the geometric transformations or corrections for realignment of the object with the image. The method proposed here adjusts the distorted view of the rod by compensating for angular misalignment and works well to ensure accurate detection and representation of circular features. More importantly, this allows more reliable analysis even with an imperfectly placed object, making the system more robust and accurate compared to the traditional HCT approach.

5.2 Managing False Positives and False Negatives

The standard approach suffers from high false positives and false negatives for detection of the actual circles as "not circles" and vice versa. This misclassification would arise from any inadequacy in handling variations in object appearance, orientation, and lighting conditions, which directly affect the accuracy of such traditional techniques. The proposed method corrects some of the problems of the standard method, by checking for eccentricity along with center and radius determination. This way, it correctly identifies even true circles, especially those having an eccentricity of zero; these are usually classified as false positives by the standard Hough Circular Transform (HCT) method. In addition, by making a rigid determination of several parameters before creating classifications, the proposed method reduces the occurrence of false positives. As shown in Fig. 7 the proposed method correctly outlines the detected edge as it is perceived as an ellipse rather, the HCT method sticks to marking a circle missing the actual edge and inaccurately providing the diameter value further. It leads to this holistic assessment to be duly optimized thresholds in detecting circular objects from non-circular ones in this system.

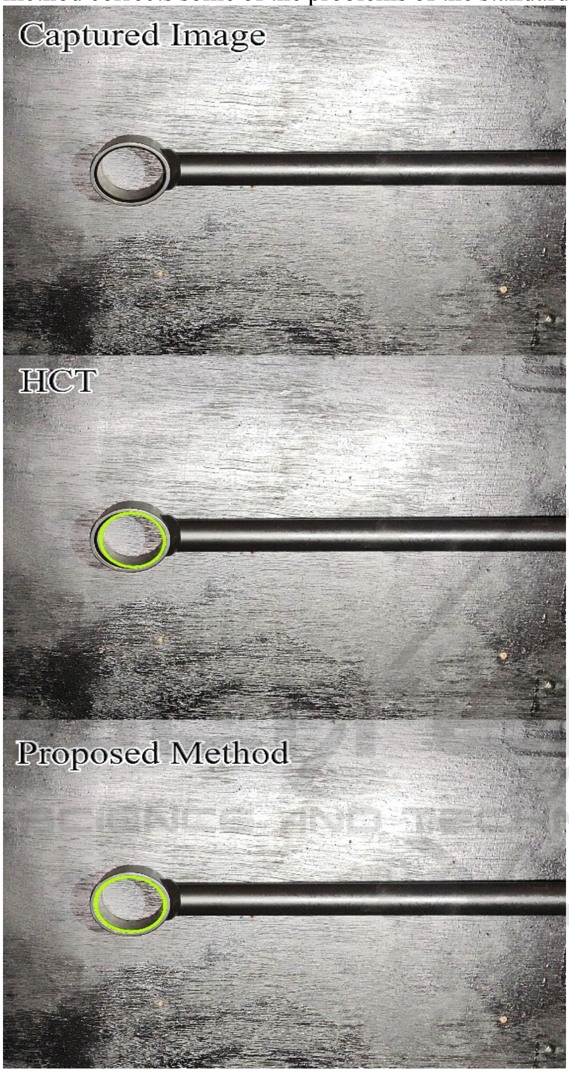

Figure 7: Detection Comparison of HCT and Proposed Method

Table 1: System Comparison with Error Percentage.

x	Actual Diameter	Detected Diameter	Error Percentage
HCT	3.4 cm	3.15 cm	7.35%
Proposed Method	3.4 cm	3.36 cm	1.17%

5.3 Accuracy, Precision and Adaptability

The proposed method demonstrates significant improvements in accuracy, precision, and adaptability over the standard Hough Circular Transform (HCT). By incorporating additional parameters such as eccentricity, alongside center and radius, the proposed system accurately identifies circles with an eccentricity of zero, which are often misclassified by the HCT. As presented in Table I, if a sample circle of actual diameter 3.4 cm is to be detected, then it is observed that the proposed method is more precise as compared to HCT, with the percentage error being 1.17% and, for the HCT method, 7.35%. Increased precision reduces misclassifications due to false positives and false negatives, thus improving the reliability of the classification.

The proposed method also has the adaptability shown in its optimized thresholds and then dealt with variations in the said lighting, orientation, and positioning. Unlike the standard method, which is sensitive to changes in environmental conditions, the proposed approach remains adaptive and consistent with different setups involved. This adaptability not only ensures accuracy and precision in controlled conditions but also makes the method versatile for broader applications within the mechanical industry and quality control environments.

6 CONCLUSIONS

The study concluded with a detailed approach to automatic quality inspection in mechanical manufacturing, with added improvement in circle detection accuracy irrespective of orientation and levels of lighting. Combining geometric analysis, eccentricity checks, and machine learning capabilities into the system made it strong against those traditional methods that the Hough Circular Transform approaches tend to falter with perspective distortions. The results confirm that this method improves precision, reduces false detections, and adapts effectively to real-world production environments. With this in mind, the comprehensive, error-resistant approach presented here seems particularly promising for the optimization of quality control processes toward higher efficiency and reliability in manufacturing.

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