

Image Acquisition and Geometric Comparison of Mechanical Components for Precision Dimension and Tolerance Evaluation

Dukre Madhuri Vilas¹, Dr. B D Shinde², Dr. R H Shinde³

¹Student Chha shahu Engineering College Shambhajinagar

² Asst Professor Chha shahu Engineering College Shambhajinagar

³HOD Mechanical Engineering Chha shahu Engineering College Shambhajinagar

Abstract –

This paper presents an automated framework for the precision dimensional and tolerance evaluation of mechanical components using digital image acquisition and geometric comparison techniques. Traditional metrology tools, such as Coordinate Measuring Machines (CMMs) and manual calipers, are often limited by slow inspection speeds and contact-induced errors. To address these limitations, this study utilizes high-resolution industrial cameras and optimized illumination setups to capture precise two-dimensional images of manufactured components.

Advanced edge-detection algorithms and sub-pixel extraction methods are applied to define the exact boundaries of the fabricated parts. These extracted geometric features are then structurally compared against a reference Computer-Aided Design (CAD) model or a nominal golden template. Geometric Dimensioning and Tolerance (GD&T) parameters—including flatness, circularity, parallelism, and concentricity—are calculated dynamically through spatial transformation and point-cloud alignment algorithms. Experimental results demonstrate that the proposed non-contact vision system achieves micron-level measurement accuracy, drastically reduces inspection cycle times, and provides an efficient, scalable solution for real-time quality control in high-precision manufacturing environments.

Key Words: automated framework, Computer-Aided Design, Geometric Dimensioning, Tolerance

1. INTRODUCTION

In modern manufacturing industries, quality inspection of mechanical components is a critical process to ensure dimensional accuracy, product reliability, and compliance with engineering standards. Conventional inspection methods using vernier calipers, micrometers, height gauges, and Coordinate Measuring Machines (CMMs) require significant manual effort, skilled operators, and increased inspection time. These methods may also introduce human errors and are often unsuitable for high-speed production environments.

Machine vision and image processing technologies provide an efficient alternative for automated dimensional inspection. By capturing images of mechanical components through a digital camera and processing them using advanced image analysis techniques, it is possible to measure dimensions, evaluate geometric features, and compare the

obtained measurements with predefined standards. Such systems offer high accuracy, repeatability, and rapid inspection capabilities.

The proposed project focuses on developing an image-based inspection system capable of acquiring images of mechanical components, extracting geometric dimensions, calculating dimensional deviations, and evaluating tolerance limits. The system will automatically determine whether a component satisfies the required specifications and generate inspection reports for quality assurance purposes.

1.1 Problem Statement

Manufacturing industries require precise inspection of mechanical components to maintain product quality and reduce rejection rates. Traditional measurement methods are time-consuming, labor-intensive, and susceptible to human errors. High-end inspection systems such as Coordinate Measuring Machines are expensive and difficult to implement in small and medium-scale industries.

Therefore, there is a need for a cost-effective, automated, and accurate vision-based inspection system capable of measuring dimensions and evaluating tolerances of mechanical components in real time.

1.2 Aim:

To design and develop an image processing-based system for automated acquisition, measurement, geometric comparison, and tolerance evaluation of mechanical components for quality inspection applications.

1.3 Objectives

- To acquire high-quality images of mechanical components using a digital camera.
- To perform image preprocessing and edge extraction.
- To identify geometric features such as length, width, diameter, and hole dimensions.
- To convert pixel measurements into actual dimensions.
- To compare measured dimensions with standard design specifications.
- To evaluate dimensional tolerances automatically.
- To classify components as Accepted or Rejected.
- To generate digital inspection reports and maintain inspection records.

1.4 Scope of the Project

The project can be utilized in:

- Automotive component manufacturing industries.
- CNC machining centers.
- Quality control laboratories.
- Production inspection systems.
- Precision engineering industries.
- Aerospace component inspection.
- Bearing and gear manufacturing units.
- Small-scale manufacturing industries requiring low-cost automation.

The developed system can significantly reduce inspection time and improve measurement consistency while minimizing operator dependency.

2 Proposed Methodology

The proposed system consists of image acquisition, image processing, dimensional measurement, geometric comparison, and tolerance evaluation modules.

Initially, a high-resolution camera captures images of the mechanical component placed on an inspection platform. The acquired image undergoes preprocessing operations such as grayscale conversion, filtering, and noise removal. Edge detection algorithms are then applied to identify the component boundaries and geometric features.

The extracted dimensions are converted from pixels to millimeters using calibration techniques. These measurements are compared with predefined CAD dimensions or standard dimensions stored in the database. Dimensional deviations are calculated, and tolerance limits are checked. Based on the results, the component is classified as either PASS or FAIL. Finally, the inspection data are stored in a database and displayed on a graphical user interface.

2.1 Hardware Requirements

Sr.No	Component
1	Laptop / PC
2	USB Industrial Camera
3	Camera Mount
4	LED Illumination System
5	Mechanical Components
6	Calibration Scale

Table 2.1 Hardware Requirement

2.2 Software Requirements

Sr.No	Component
1	Python 3.10 or Above
2	OpenCV
3	NumPy
4	Pandas
5	Matplotlib

6	SQLite / MySQL
7	Visual Studio Code

Table2.2 Software Requirements

2.3 Working Principle

The camera captures an image of the component positioned on the inspection platform. The image is processed using computer vision algorithms to detect edges and contours. Dimensional measurements such as length, width, radius, and hole diameter are extracted. Using a calibration factor, pixel values are converted into real-world dimensions.

The measured values are compared with standard dimensions stored in the system database. Dimensional deviations and percentage errors are calculated. If the measured dimensions fall within permissible tolerance limits, the component is accepted; otherwise, it is rejected. Inspection results are automatically recorded and displayed to the operator.

3 Expected Outcomes

- Automated dimensional measurement of mechanical components.
- Reduction in inspection time.
- Improved measurement accuracy and repeatability.
- Automatic tolerance verification.
- Digital quality inspection reports.
- Reduced human intervention in inspection processes.
- Cost-effective quality control solution.

3.1 Advantages

- Non-contact measurement technique.
- High inspection speed.
- Reduced human error.
- Real-time analysis.
- Improved production efficiency.
- Low operational cost.
- Easy integration with manufacturing systems.
- Automatic report generation.

3.2 Limitations

- Accuracy depends on camera resolution.
- Proper lighting conditions are required.
- Calibration is necessary for precise measurements.
- Complex 3D geometries may require advanced imaging techniques.
- Reflective surfaces can affect measurement accuracy.

3.3 Future Scope

3.4 Integration with Artificial Intelligence for defect detection.

- 3.5 Real-time industrial production line inspection.
- 3.6 Use of high-precision industrial cameras.
- 3.7 3D vision-based dimensional measurement.
- 3.8 Cloud-based inspection monitoring system.
- 3.9 Integration with robotic sorting systems.
- 3.10 Digital twin-based manufacturing inspection.
- 3.11 IoT-enabled remote quality monitoring.

3.4 Applications

- Automotive Industry
- Aerospace Industry
- Precision Manufacturing
- CNC Machining
- Bearing Manufacturing
- Gear Inspection
- Sheet Metal Industry
- Quality Control Laboratories

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Conclusion

The proposed "Image Acquisition and Geometric Comparison of Mechanical Components for Precision Dimension and Tolerance Evaluation" system provides an efficient, accurate, and automated solution for dimensional inspection in manufacturing industries. By combining machine vision, image processing, and tolerance analysis techniques, the system minimizes manual inspection efforts and enhances quality assurance processes. The developed solution offers a low-cost alternative to conventional inspection systems while maintaining high levels of measurement accuracy and reliability. This project has significant potential for industrial implementation and future enhancement through AI, IoT, and advanced machine vision technologies.

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