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Research Article

Development of Low-Cost Dimensional Measurement System Using Image Processing

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ABSTRACT

Dimensional accuracy is essential in manufacturing and quality assurance processes. However, traditional measurement systems are often expensive, complex, and inaccessible to small-scale industries and academic laboratories. This research presents the development and validation of a low-cost, image-processing-based system for dimensional measurement of mechanical components. The proposed system uses two standard digital camera and open-source image processing software to measure the length, width, and thickness of sample blocks. Measurements obtained via image processing were compared with actual physical measurements to evaluate the accuracy of the system. The results revealed that the system can achieve average percentage errors of less than 4% across all measured parameters, demonstrating its potential as a cost-effective alternative for dimensional measurement.

Keywords: Image Processing, Dimensional Measurement, Low-Cost System, Machine Vision, Non-contact Measurement, Calibration, OpenCV.

INTRODUCTION

Recent advancements in industrial technologies have driven the adoption of machine-powered systems to meet critical demands for rapid production, safety, superior product quality, and efficient resource utilization [1,2]. Ensuring product quality is vital to maintaining customer confidence. Industrial image processing has emerged as a pivotal technology for monitoring attributes such as size, shape, color, and structure, enabling enhanced defect detection and error correction in manufacturing processes [3]. These systems have achieved up to a 95% reduction in errors related to dimensional control and defect detection compared to manual methods [4].

Integrating mechanical, optical, electronic, and software components, image processing systems excel in inspecting mass-produced products at high speeds with up to 99.7% accuracy in defect detection, such as identifying visible surface defects in sheet metal rolls in the automotive industry [5,6]. In metal processing, these systems demonstrate over 95% accuracy in dimensional control and defect classification, with AI-powered enhancements reducing error rates to less than 0.5%. Platforms like MATLAB/ LabVIEW have enabled precise dimensional and deformation controls in metal quality assessments [7].

Non-contact, high-precision measurement technologies, leveraging advancements in optics, electronics, and computing, provide high-speed, non-invasive measurements ideal for delicate materials. Digital image-based measurement systems achieve sub-micron resolution with less than 1%-dimensional error, fulfilling demands for automation and precision [8]. Despite challenges like lighting variations and shadows, advanced digital image processing techniques, such as grayscale conversion, Gaussian filtering, and edge detection algorithms, have minimized measurement errors to less than 3% [9].

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Our study presents a novel image-based dimensional measurement system, and achieving an average measurement error of less than 4% under varying lighting conditions (e.g., 1000 lx, 800 lx, 500 lx). Results highlight the system's reliability and its potential to significantly improve quality control processes in industrial applications [10].

1.1 Problem Statement

Measurement technologies have advanced considerably, but a number of restrictions prevent their broad use. High prices are a significant deterrent, especially for SMEs, who sometimes have limited resources and cannot afford sophisticated devices like laser scanners or CMMs. Less than 20% of SMEs worldwide [11] have access to sophisticated dimensional measurement techniques, according to studies, which makes it difficult for them to meet strict quality control requirements. Another recurring issue in this situation is accuracy. In uncontrolled conditions, the performance of manual tools is frequently impaired, and their variability ranges from ±0.2 to 0.5 mm.

In a similar vein, optical systems, despite their speed and sophistication, are susceptible to environmental factors; in low light or when measuring reflective surfaces, variations can amount to as much as ±0.05 mm [12]. These expectations cannot be met by conventional systems like CMMs, which have a throughput capability of only 30 to 50 pieces per hour [13]. This makes the need for an affordable, flexible solution that can provide high precision and dependability in a variety of industrial settings urgent.

MATERIALS AND METHODS

2.1 System Setup

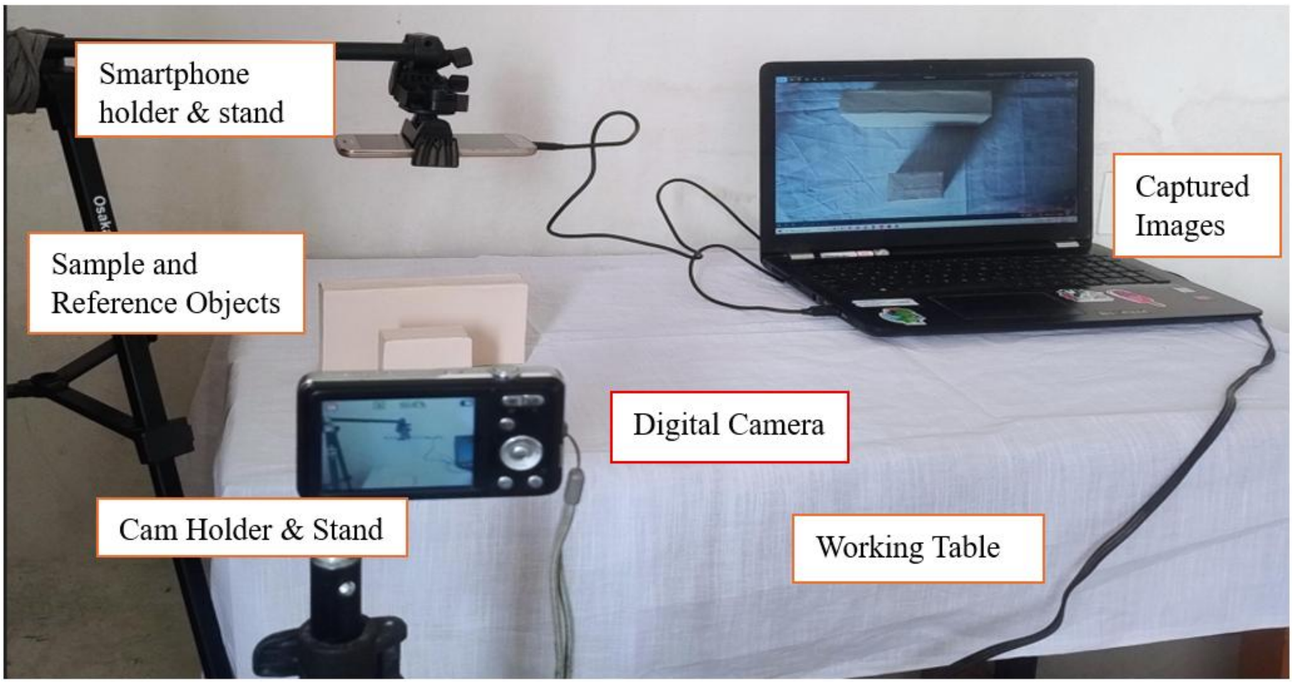

Figure 2.1

The system consists of:

- A smart phone and one high-resolution digital camera.
- A uniformly lit background and surface.
- Mild Steel blocks with known dimensions (as in Table-1)

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Table 1

Sample	Dimensions (L × W × H)
A	20 mm × 25 mm × 7 mm
B	25 mm × 25 mm × 8 mm
C	50 mm × 25 mm × 7 mm
D	75 mm × 25 mm × 8 mm

- Image processing software developed in Python using OpenCV

2.2 Calibration and Measurement Principle

To ensure accurate measurement, a reference block with known dimensions is included in each captured image. The pixel-per-millimetre ratio is calculated based on the known length of the reference block in every reading by the software developed. This ratio is then used to convert pixel measurements of the sample block into real-world units.

2.3 Image Processing Workflow

The measurement process includes the following steps:

1. **Image Acquisition**: Capture high-resolution images of the reference and sample blocks.
2. **Preprocessing**: Convert images to grayscale and apply filters to reduce noise.
3. **Edge Detection**: Apply Canny edge detection to identify object boundaries.
4. **Contour Detection**: Use OpenCV functions to detect contours of both the reference and sample blocks.
5. **Dimension Calculation**: Measure pixel dimensions of the sample and convert them using the calibrated scale.

EXPERIMENTAL PROCEDURE

Experiments were conducted in two configurations:

1. **Sample kept parallel to the reference block**
2. **Sample aligned with the reference block**

For each configuration, three dimensions (length, width, and thickness) were measured using image processing keeping width value 25mm as scaling factor in all measurement for pixel to real value conversion and compared against actual measurements.

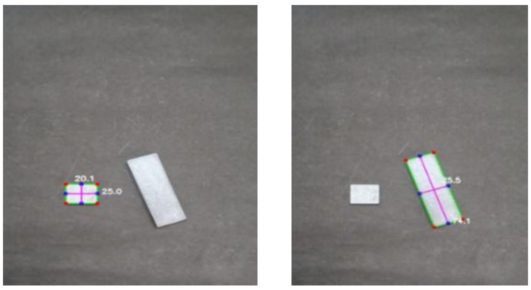

Figure 3.1 Image for measurement of length and width of sample D kept aligned with sample A as reference block. The output value is as given by developed algorithm.

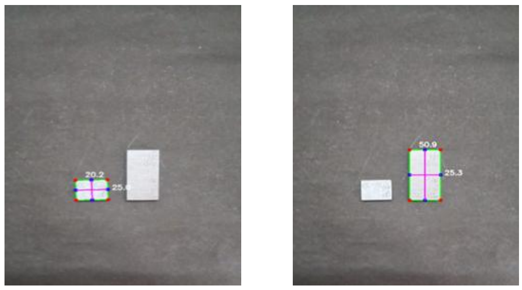

Figure 3.2 Image for measurement of length and width of sample C kept parallel with sample A as reference block. The output value is as given by developed algorithm.

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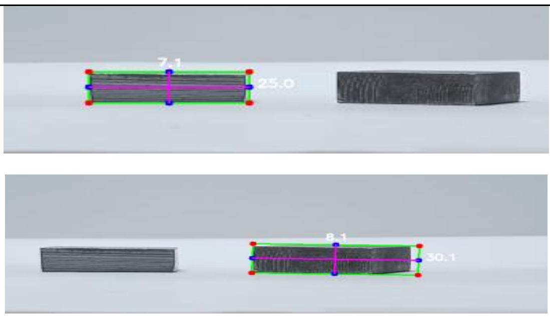

Figure 3.3 Images showing the reference block A-B for height measurement when sample A is reference and B is kept in aligned condition.

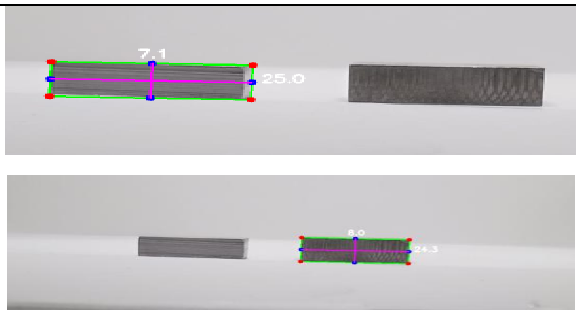

Figure 3.4 Images showing the reference block A-B for height measurement when sample A is reference and B is kept in parallel condition.

RESULTS AND DISCUSSION

4.1 Accuracy Evaluation

The accuracy of the system was assessed by calculating the percentage error for each measurement:

DATA TABLE OF DIMENSION FOR SAMPLE KEPT PARALLEL TO REFERENCE BLOCK

Reference Block	Sample Block	Length			Width			Thickness		
		Image processing	Actual	Error (%)	Image processing	Actual	Error (%)	Image processing	Actual	Error (%)
A	B	**25.0**	25.0	0.00	**24.7**	25.0	1.20	**8.0**	8.0	0.00
A	C	**50.9**	50.0	1.80	**25.3**	25.0	1.20	**7.2**	7.0	2.86
A	D	**73.9**	75.0	1.47	**25.2**	25.0	0.80	**8.2**	8.0	2.50
B	A	**19.7**	20.0	1.50	**24.4**	25.0	2.40	**7.2**	7.0	2.86
B	C	**50.3**	50.0	0.60	**24.8**	25.0	0.80	**6.9**	7.0	1.43
B	D	**72.6**	75.0	3.20	**24.8**	25.0	0.80	**7.9**	8.0	1.25
C	A	**19.8**	20.0	1.00	**24.7**	25.0	1.20	**7.1**	7.0	1.43
C	B	**24.9**	25.0	0.04	**24.7**	25.0	1.20	**8.1**	8.0	1.25
C	D	**74.3**	75.0	0.93	**25.4**	25.0	1.60	**8.0**	8.0	0.00
D	A	**19.5**	20.0	2.50	**24.7**	25.0	1.20	**6.7**	7.0	4.28
D	B	**24.6**	25.0	1.60	**24.7**	25.0	1.20	**7.6**	8.0	5.00
D	C	**48.9**	50.0	2.20	**24.5**	25.0	2.00	**7.1**	7.0	1.43
		Average % Error		**1.40**	**Average % Error**		**1.30**	**Average % Error**		**2.02**

DATA TABLE OF DIMENSION FOR SAMPLE KEPT ALIGNED TO REFERENCE BLOCK

Reference Block	Sample Block	Length			Width			Thickness		
		Image processing	Actual	Error (%)	Image processing	Actual	Error (%)	Image processing	Actual	Error (%)
A	B	**25.0**	25.0	0.00	**25.0**	25.0	0.00	**8.1**	8.0	1.25
A	C	**50.5**	50.0	1.00	**25.1**	25.0	0.40	**7.1**	7.0	1.43

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Reference Block	Sample Block	Length			Width			Thickness		
		Image processing	Actual	Error (%)	Image processing	Actual	Error (%)	Image processing	Actual	Error (%)
A	D	**74.1**	75.0	1.20	**25.5**	25.0	2.00	**8.4**	8.0	5.00
B	A	**20.0**	20.0	0.00	**25.1**	25.0	0.40	**7.1**	7.0	1.43
B	C	**49.6**	50.0	0.80	**24.8**	25.0	0.80	**7.3**	7.0	4.28
B	D	**73.2**	75.0	2.40	**24.9**	25.0	0.40	**8.4**	8.0	5.00
C	A	**20.3**	20.0	1.50	**25.3**	25.0	1.20	**7.4**	7.0	5.71
C	B	**25.2**	25.0	0.80	**25.2**	25.0	0.80	**8.1**	8.0	1.25
C	D	**73.6**	75.0	1.87	**25.0**	25.0	0.00	**8.3**	8.0	3.75
D	A	**19.6**	20.0	2.00	**24.8**	25.0	0.80	**7.2**	7.0	2.86
D	B	**24.5**	25.0	2.00	**24.5**	25.0	2.00	**7.7**	8.0	3.75
D	C	**48.6**	50.0	2.80	**24.6**	25.0	1.60	**6.9**	7.0	1.43
		Average % Error		**1.36**	**Average % Error**		**0.87**	**Average % Error**		**3.09**

This study analyzed dimensional measurements of metallic blocks using a dual-camera setup—one mounted above (smartphone) for length and width estimation, and another placed perpendicularly for height (thickness) measurement. The image processing results were compared with actual physical measurements obtained using a Vernier caliper.

Two configurations were tested:

- Parallel placement: The sample was placed next to a known reference block.
- Aligned placement: The sample was placed in direct alignment with the reference block.

The following figure presents a comparison of average percentage errors across both configurations:

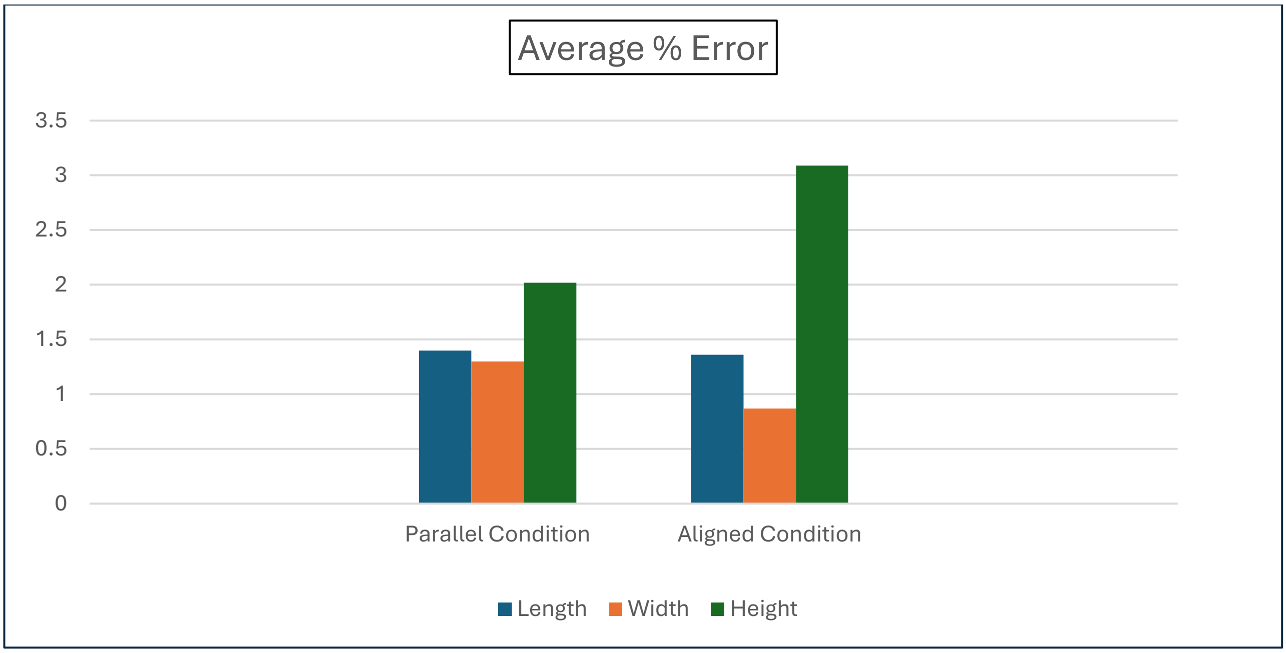

Figure 4.1: Average Dimensional Error by Configuration

Summary of Results

Parameter	Avg. Error (Parallel)	Avg. Error (Aligned)
Length	1.40%	1.36%
Width	1.30%	0.87%
Thickness (Height)	2.02%	3.09%

4.2 Discussion

- Length and Width Estimation: Both configurations achieved less than 1.5% error in measuring length and width. The top-view camera effectively captured edges and bounding boxes using standard edge-detection techniques. Aligned placement yielded better width accuracy, likely due to clearer edge contrast with the reference block.
- Height Estimation: Thickness (height) measurement errors were higher, averaging 2.02% for parallel and 3.09% for aligned configurations. This discrepancy arises due to:
  - Perspective distortion in side images.
  - Non-uniform lighting, which affected edge clarity.
  - Smaller size of thickness dimension (typically 7–8 mm), making it more sensitive to pixel-level errors.
- Camera Calibration: Calibration was performed using a known standard block, but slight angular misalignment between the top and side cameras may have contributed to cumulative errors, especially in aligned configurations.
- Repeatability: Results showed good consistency across multiple measurements. However, certain samples (e.g., D–B and C–A in the aligned group) displayed higher thickness errors (up to 5.7%), indicating potential shadowing or detection failures.
- Cost Efficiency: The entire setup was implemented using low-cost webcams and open-source tools (OpenCV), affirming the system's affordability compared to industrial metrology instruments.

The proposed dual-camera image processing approach is a promising low-cost alternative for dimensional measurement of simple block-type objects. While performance is reliable for length and width dimensions, enhancements in height accuracy require improved calibration methods and lighting setups. Future development can integrate AI-based segmentation and stereo calibration for more robust results.

CONCLUSION

This study successfully demonstrates the development and validation of a low-cost image processing system for basic dimensional measurement tasks. The findings and implications of the work can be summarized as follows:

1. Measurement Accuracy

The proposed system achieved an average measurement error of less than 4%, indicating sufficient accuracy for general-purpose applications where ultra-high precision is not critical. This level of performance validates the system's reliability for non-critical dimensional assessment tasks.

2. Cost-Effective and Accessible Design

The system leverages open-source image processing libraries and standard hardware components, significantly reducing development and deployment costs. Its affordability enhances its accessibility for educational institutions, research laboratories, and small-to-medium enterprises (SMEs).

3. Scalability and Customization

The modular architecture of the system ensures ease of scalability and adaptability to various use cases. It can be readily customized to accommodate different object sizes, lighting conditions, and measurement requirements, making it a versatile solution.

4. Opportunities for Future Development

This work provides a foundation for further technological advancements, including:

- Incorporation of 3D imaging techniques to enable volumetric and surface analysis.
- Development of automated shape recognition for enhanced measurement automation.
- Integration with robotic systems to facilitate in-line inspection and real-time feedback in industrial automation environments.

5. Practical Implications

The system presents a viable alternative to expensive metrology tools in scenarios where moderate precision suffices. Its combination of low cost, reasonable accuracy, and scalability makes it a promising solution for a wide range of practical applications.

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