



Design and Experimental Validation of a Low-Cost Laser-Assisted Linear Displacement Measuring Instrument

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ABSTRACT

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Accurate measurement of linear displacement is essential in engineering laboratories, materials testing, and instructional settings. However, many commercially available displacement measuring instruments such as Linear Variable Differential Transformers (LVDTs) and optical encoders, are costly and often require complex signal conditioning systems. This study presents the design, development, and experimental validation of a Low-Cost Laser-Assisted Linear Displacement Measuring Instrument (LALDI) intended to provide an accessible and reliable alternative. The instrument operates using a laser diode directed toward a laminated greyscale strip, where displacement is quantified through variations in light intensity detected by a light-dependent resistor (LDR). A signal conditioning circuit and microcontroller process the analog signal into measurable displacement data. The development process followed a structured design–prototype–test–evaluation framework. Experimental validation was conducted within a 0–0.42 inch (0–10.7 mm) displacement range and compared against a commercial dial indicator. Statistical analysis using paired t-test and standard deviation assessment demonstrated no significant difference between the measurements of LALDI and the reference instrument at the 0.05 level of significance. Repeatability analysis confirmed stable measurement performance across incremental testing. Cost analysis revealed that the fabricated device achieved substantial cost reduction compared with commercial displacement measuring systems while maintaining acceptable accuracy and precision. The findings indicate that LALDI provides a practical, cost-effective solution for academic laboratories and small-scale engineering applications, with potential for further refinement and scalability.

1 INTRODUCTION

Accurate linear displacement measurement has been treated as a core requirement in mechatronics, instrumentation, quality control, and precision positioning. It has been used to verify tolerance compliance, detect wear, and support feedback control in electro-mechanical systems. The need for displacement sensing has also been expanded in monitoring contexts where repeated measurements were required under field constraints and limited budgets, so cost-effectiveness and deployability were treated as design constraints rather than secondary considerations (Laflamme et al., 2023).

Linear displacement has been measured using contact and non-contact principles. Contact sensors such as linear variable differential transformers (LVDTs) have been used due to robustness and repeatability, yet signal conditioning,

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linear range behavior, and calibration demands have been treated as persistent technical issues that can influence accuracy and usable span (Rerkratn et al., 2022). Non-contact optical approaches have also been adopted, since they reduce mechanical loading and installation constraints. Optical encoders and grating-based sensors have been widely used for high-resolution positioning, but system cost, alignment sensitivity, and integration complexity have been reported as practical barriers in low-resource deployments (Shimizu et al., 2019; Zhao et al., 2025). Vision-based displacement measurement has also been explored as a lower-cost alternative in some settings, with benefits linked to reduced instrumentation cost and improved flexibility, while limitations have been associated with lighting, tracking robustness, and field uncertainty (Xu & Brownjohn, 2018).

Recent literature has shown that the technical frontier in displacement sensing has been pushed toward higher precision and multi-axis capability, but affordability and accessibility have remained uneven across laboratories and small-scale users. Reviews have reported that performance gains were often accompanied by increased dependence on specialized optics, precision mechanics, and sophisticated processing pipelines, which can raise the entry barrier for instructional laboratories and small engineering users (Shimizu et al., 2019; Zhao et al., 2025). At the same time, low-cost optical measurement lines of work have been documented in adjacent domains, which suggested that acceptable measurement utility can be achieved when sensing geometry, calibration strategy, and processing were engineered around constraints rather than around premium components (Messerer et al., 2025). This context has supported continued interest in displacement instruments that were designed for low cost while retaining stable measurement behavior.

In this study, a low-cost laser-assisted linear displacement measuring instrument was designed and developed to support practical displacement measurement needs under constrained resources. The work was positioned around an engineering objective: displacement measurement capability was to be provided through an optical principle with an implementation that can be assembled, calibrated, and maintained with commonly available parts and procedures. The study was also aligned with instrumentation priorities emphasized in current measurement roadmaps, where scalability, deployability, and economic feasibility were treated as necessary conditions for broader adoption of sensing solutions (Laflamme et al., 2023).

The study aimed to design, develop, and experimentally validate a low-cost laser-assisted linear displacement measuring instrument (LALDI) based on optical intensity modulation and to evaluate its accuracy, repeatability, and cost-effectiveness relative to a commercial dial indicator.

Objectives of the Study

1. To design and fabricate a laser-assisted linear displacement measuring instrument using grayscale-based optical intensity modulation.
2. To establish a calibration mapping between voltage output and linear displacement within the 0–0.42 inch (0–10.7 mm) operational range.
3. To experimentally compare the displacement measurements obtained from LALDI with those of a commercial dial indicator.
4. To determine whether a statistically significant difference exists between the measurements of LALDI and the reference instrument using paired t-test analysis.
5. To evaluate the repeatability and variability of the developed instrument using standard deviation and coefficient of variance analysis.
6. To analyze the total fabrication cost of the prototype and assess its cost-effectiveness compared with commercially available displacement measuring instruments.

Conceptual Framework

The conceptual framework in figure 1 illustrates how linear displacement is measured using an optical intensity-based sensing approach. The system begins with controlled linear displacement, which causes translation of the laminated grayscale strip. As the strip moves, the laser beam interacts with varying grayscale densities, producing corresponding changes in light intensity. These intensity variations are detected by the light-dependent resistor (LDR), which converts light changes into resistance variation. The voltage divider circuit transforms this resistance change into a measurable voltage signal. The microcontroller then digitizes the signal and applies a calibrated regression mapping to compute the displacement value in inches. The measured output is subsequently validated through comparison with a commercial dial indicator using statistical analysis. The framework therefore demonstrates the logical progression from physical displacement input, through optical and electronic signal processing, to validated displacement output.

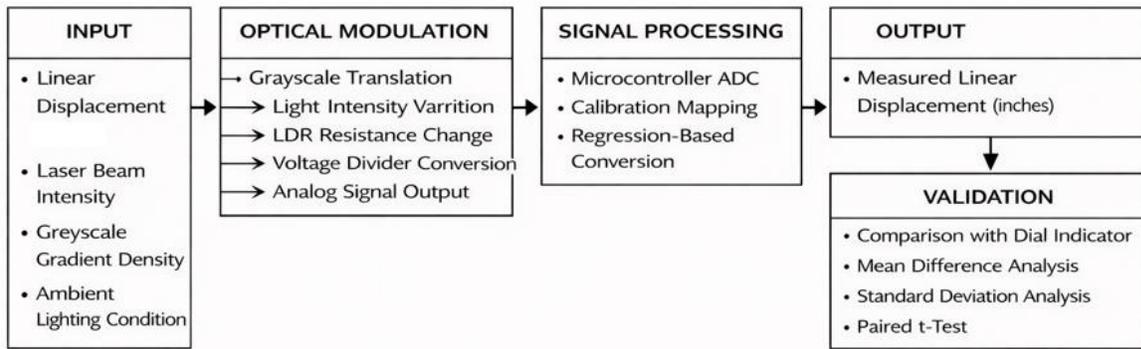


Figure 1. Flowchart of Conceptual Framework

2 LITERATURE REVIEW

Linear displacement has been treated as a core measurand in metrology, automation, and structural monitoring. Conventional contact sensors such as linear variable differential transformers (LVDTs) have been used widely because stable transduction and mature signal conditioning have been available. Their practical limitation has been linked to the narrow linear region relative to the physical stroke, so circuit and compensation techniques have been proposed to extend usable range without increasing sensor size or cost (Rerkratn et al., 2022). In parallel, noncontact optical methods have been preferred when friction, backlash, and wear needed to be avoided. Laser interferometry has been recognized as a high-accuracy option, but strict alignment and environmental sensitivity have constrained field deployment. Image-based fringe processing has been used to reduce some hardware demands while retaining fine resolution, yet computational steps and error sources have remained nontrivial in practice (Xiong et al., 2020).

Vision-based displacement measurement has expanded rapidly because low-cost cameras and robust image processing have become accessible. Reviews of field deployment have shown that accuracy has been influenced by camera calibration, lens distortion, illumination variation, target design, and tracking strategy. These factors have been treated as interacting error mechanisms that required systematic control and compensation (Zhuang et al., 2022). A major research direction has focused on patterned targets and correlation methods that supported sub-pixel translation estimation. An “image grating” approach has been reported where a patterned plate and phase-correlation-based matching enabled micrometer-level accuracy across long travel. Error analysis and calibration routines were emphasized because optical distortion and scaling uncertainty were shown to dominate overall performance (Cheng et al., 2022). Microscopic-vision approaches have also been used to combine high resolution with large measuring range, using surface microfeatures as information carriers and relying on machine-vision algorithms for robust tracking (Wu et al., 2024). These studies supported the view that displacement could be reconstructed reliably from image features when the optical model and illumination stability were treated as design constraints.

A related stream has addressed intensity-based inference, where displacement has been mapped to changes in received light intensity rather than full-field feature tracking. This logic has been used in optical-flow and pixel-intensity approaches. It has been reported that, for small motions, pixel intensity change could be related to displacement through spatial intensity gradients, enabling displacement-related response extraction with reduced computational overhead compared with full digital image correlation pipelines (Tomac et al., 2023). Intensity modulation has also remained central in fiber-optic displacement sensing, where compact geometry, electrical isolation, and robustness in harsh environments have been emphasized. A recent review synthesized progress across intensity-, interferometric-, and grating-based fiber methods and summarized design trade-offs among range, sensitivity, and packaging complexity (Zhu et al., 2022). Extended-range and sensitivity optimization in reflective fiber configurations have continued to be reported, which reinforced that usable linear range could be engineered through geometry and differential responsivity definitions (Zubia et al., 2025).

Low-cost system design has increasingly been treated as an explicit research objective, especially for monitoring and instrumentation contexts where commercial metrology systems were cost-prohibitive. A cost-effective vision-based framework supported by standard image processing and learning-based target detection has been presented for displacement tracking, showing that consumer-grade components could support practical monitoring when target recognition and tracking were stabilized algorithmically (Messerer et al., 2025). These findings aligned with the design

logic of laser-assisted, low-cost displacement instruments, where a stable light source and a simple photosensor chain could be paired with a calibrated displacement–intensity mapping. In this context, the key technical gap has been framed around maintaining measurement linearity, repeatability, and robustness under illumination drift, surface reflectivity variation, and alignment tolerance, which were repeatedly identified as dominant error drivers across both intensity-based and vision-based displacement modalities (Zhuang et al., 2022; Zhu et al., 2022).

3 METHODOLOGY

3.1 Research Design

A design–development–experimental validation approach was adopted in this study. The work focused on the engineering development of a laser-assisted linear displacement measuring instrument (LALDI) followed by controlled laboratory evaluation against a commercial reference device. The process followed a structured development cycle that included system analysis, prototype fabrication, calibration, testing, and statistical validation. This approach is consistent with experimental instrumentation development methods where functional performance and measurement accuracy are verified through comparative analysis with established instruments (Zhu et al., 2022; Rerkratn et al., 2022).

3.1.1 System Architecture

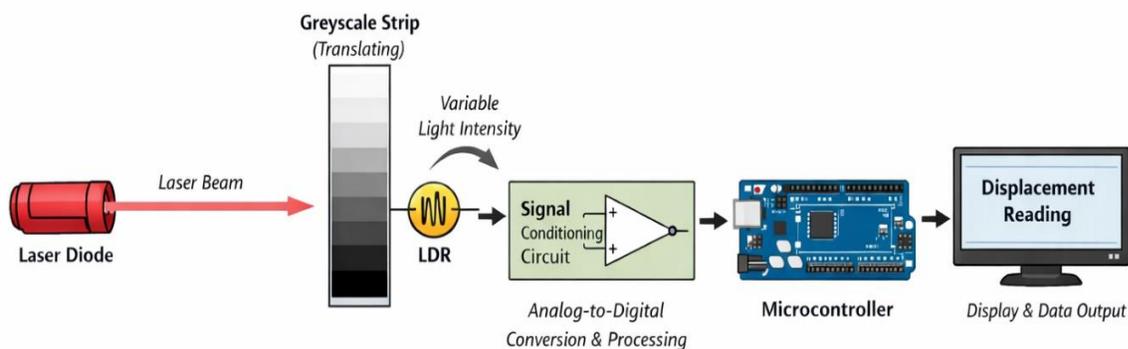


Figure 2. LALDI System Architecture

The LALDI in figure 2 was developed using an intensity-modulation optical principle. The system consisted of the following major components:

1. Laser diode as the light source
2. Laminated transparent greyscale strip as the displacement medium
3. Light-dependent resistor (LDR) configured in a voltage divider circuit
4. Signal conditioning circuit
5. Microcontroller for analog-to-digital conversion and data processing
6. Protective enclosure and mechanical mounting assembly

A laser beam was directed toward the greyscale strip. As the strip translated linearly, the intensity of reflected or transmitted light changed proportionally according to the grayscale gradient. The LDR converted variations in light intensity into corresponding resistance changes. The voltage divider configuration transformed resistance variation into a measurable voltage signal, which was then processed by the microcontroller.

This configuration aligns with optical intensity-based displacement sensing approaches where displacement is inferred from modulated light intensity rather than interferometric phase detection, thereby reducing system complexity and cost (Zhuang et al., 2022).

3.1.2 Materials and Fabrication

Figure 3 shows the LALDI prototype that was fabricated using readily available and cost-efficient components. The greyscale strip was laminated to ensure durability and stable optical response. A standard laser diode module served as the

optical source. The LDR was selected for sensitivity to visible laser wavelength. A fixed 1 k Ω resistor was used to establish the voltage divider network.

The signal conditioning circuit was assembled on a breadboard during prototyping and later transferred into a permanent configuration within a plastic enclosure. A microcontroller platform was used to digitize and interpret analog voltage values. The device was mounted on a tripod stand to minimize vibration during testing.

Component selection emphasized affordability while maintaining functional stability. The use of low-cost optical components has been reported as viable in displacement measurement systems when proper calibration and signal conditioning are implemented (Messerer et al., 2025).



Figure 3. LALDI prototype

3.1.3 Calibration Procedure

The calibration was performed prior to experimental validation. Known linear displacements were introduced incrementally from 0–0.42 inch (0–10.7 mm). For each increment, voltage output values were recorded and mapped to corresponding displacement distances. A regression-based mapping function was established to convert voltage readings into displacement values. Intensity-based systems require calibration to compensate for nonlinear sensor response and illumination variation (Zhu et al., 2022). The calibration curve was used in all subsequent measurements.

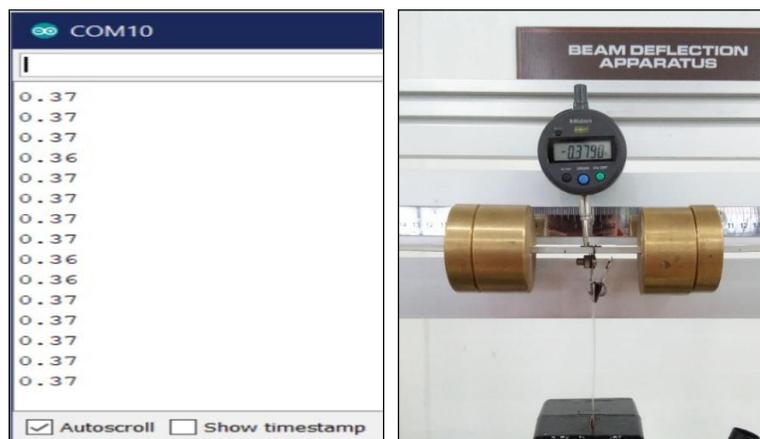


Figure 4. Calibration Procedure

3.1.4 Instrumentation Specifications

The optical source used in the system was a standard red laser diode module with a wavelength of approximately 650 nm and output power below 5 mW. The photosensor was a cadmium sulfide light-dependent resistor (LDR) with peak

spectral response in the visible light region. The microcontroller platform utilized a 10-bit analog-to-digital converter with a sampling rate of approximately 100 Hz. Calibration mapping between voltage output and displacement was established using polynomial regression. The resulting calibration curve exhibited a coefficient of determination (R^2) greater than 0.98, indicating strong correlation between sensor output and displacement.

Ambient lighting conditions were controlled during testing by maintaining consistent indoor illumination and minimizing external light interference. Mechanical alignment between the laser source, grayscale strip, and sensor was fixed throughout the experimental trials to ensure consistent optical response

3.1.5 Experimental Setup

Experimental validation was conducted using a beam deflection apparatus where applied weights generated controlled displacement at the measurement point. The applied loads produced beam deflections that remained within the instrument's calibrated measurement range. Both the LALDI and the commercial dial indicator simultaneously measured the resulting displacement. This approach allowed load-controlled generation of displacement while maintaining measurement validation within the defined operational range.

3.2 Statistical Analysis

Two statistical tools were applied:

1. **Paired t-test** – Used to determine whether significant differences existed between LALDI and dial indicator measurements at the 0.05 level of significance. Comparative statistical validation is commonly used in instrumentation accuracy assessment (Rerkratn et al., 2022).
2. **Standard Deviation Analysis** – Used to assess repeatability and measurement dispersion at each displacement increment. Precision stability was evaluated by analyzing variation across repeated trials.

A cost comparison analysis was also performed to compare the total fabrication cost of the LALDI with commercially available linear displacement measuring instruments.

3.3 Scope of Measurement

The operational measurement range of the developed instrument was limited to 0–0.42 inch (0–10.7 mm). The mechanical attachment used during testing was specific to the beam deflection apparatus. The system was designed for laboratory-scale applications and not for industrial high-range metrology.

Repeatability tests were conducted using five repeated trials at each displacement increment. All trials were performed under identical conditions, including fixed alignment of the laser module, constant ambient lighting, and unchanged sensor positioning.

4 RESULTS AND DISCUSSION

Table 1 presents the average displacement readings obtained from the LALDI and the commercial dial indicator under increasing applied loads. Both instruments show a consistent increase in displacement as the applied weight increases, indicating proportional response to loading. The values recorded by LALDI closely follow those of the dial indicator at all measurement points. The differences between corresponding readings are small, and no irregular or erratic variation is observed. The data demonstrate that the developed instrument produces displacement measurements that closely approximate those of the reference device across the tested range.

The differences presented in Table 2 represent signed differences between the LALDI and dial indicator readings. These signed values were used in the paired t-test analysis to determine whether a statistically significant difference existed between the two measurement systems. Total sum of differences = 0.042

Table 1. Average Measurement Values Between LALDI and the Commercial Dial Indicator

Weight (g)	LALDI (in)	Dial Indicator (in)
0	0.00	0.00
200	0.08	0.082
500	0.10	0.116
800	0.13	0.128
1000	0.15	0.148
1200	0.18	0.175
1500	0.20	0.203
1800	0.23	0.236
2000	0.28	0.2915
2400	0.37	0.379
2700	0.42	0.4215

Table 2. Measurement Difference Between LALDI and Dial Indicator

Weight (g)	Difference (in)
0	0.0000
200	0.0020
500	0.0160
800	0.0020
1000	0.0020
1200	0.0050
1500	0.0030
1800	0.0060
2000	0.0115
2400	0.0090
2700	0.0015

Figure 5 illustrates the measurement difference between the LALDI and the commercial dial indicator across varying applied weights. The deviations remain minimal throughout the entire loading range. A peak difference is observed at 500 g, but the values decrease and stabilize at higher loads. The absence of a steadily increasing trend indicates that no systematic error or drift occurred as displacement increased. Overall, the figure confirms that the developed instrument maintained consistent and stable measurement performance within the tested range.

Table 3 presents the paired t-test analysis used to evaluate the difference between the displacement measurements obtained from the LALDI instrument and the commercial dial indicator. The analysis was conducted using 11 paired observations. The mean difference between the two instruments was 0.00382 inches, which indicates that the measurements produced by the prototype closely matched those of the reference instrument. The calculated t-value of 2.671 with a corresponding p-value of 0.024 was evaluated at a significance level of $\alpha = 0.05$. The 95% confidence interval ranged from -0.0003 to 0.0079 inches, indicating that the true difference between the two instruments remained very small. These results suggest that the LALDI device produced displacement measurements comparable to the dial indicator under the experimental conditions. All coefficients of variance indicate low variability (Table 4).

Table 4 presents the standard deviation and coefficient of variation of LALDI measurements at selected displacement levels within the 0–0.42 inch operating range. The standard deviation values are small across all displacement points, indicating minimal spread in repeated measurements. The coefficient of variance values are also low, which confirms that measurement variability remained stable relative to the mean displacement at each increment. The consistent “Low” interpretation across all tested positions demonstrates that the instrument exhibited good repeatability and stable performance within the 0–0.42 inch operating range.

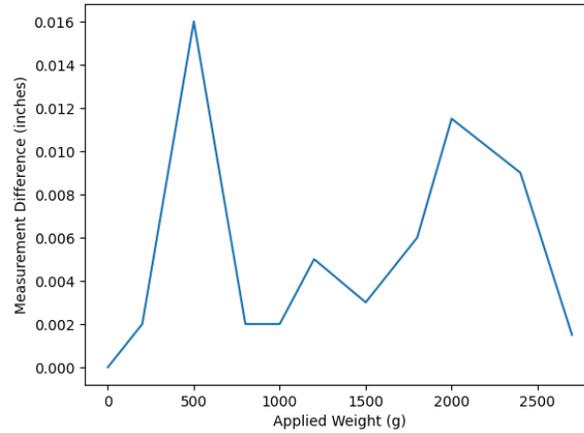


Figure 5. Measurement Difference between LALDI and Dial Indicator

Table 3. Paired t-Test Analysis of Measurement Differences Between LALDI and Dial Indicator

Statistical Parameter	Value
Number of Paired Observations (n)	11
Mean of Paired Differences (in)	0.00382
Standard Deviation of Paired Differences (in)	0.00474
Standard Error of the Mean Difference (in)	0.00143
Degrees of Freedom	10
Calculated t-value	2.671
Significance Level (α)	0.05
p-value	0.024
95% Confidence Interval for Mean Difference (in)	-0.0003 to 0.0079
Statistical Decision	No significant difference

Table 4. Repeatability Statistics for LALDI Measurements (n = 5 trials per displacement increment)

Displacement (in)	Standard Deviation	Coefficient of Variance	Interpretation
0.00 in	0.00083666	0.836660027	Low
0.10 in	0.028627609	0.028928465	Low
0.20 in	0.024365755	0.012200568	Low
0.30 in	0.001545154	0.000515008	Low
0.40 in	0.001300000	0.000324992	Low

Table 5 presents the detailed cost breakdown of the components used in fabricating the LALDI prototype. The total material cost amounted to Php 1,539, which includes the microcontroller, optical components, enclosure materials, and supporting accessories. The largest cost contributors were the Arduino Uno R3 and the PVC enclosure, while passive electronic components such as resistors and wires accounted for minimal expense. The table demonstrates that the device was constructed using affordable and readily available components, supporting the objective of developing a cost-effective alternative to commercial linear displacement measuring instruments. The prototype was fabricated at a total cost of Php 1,539 using readily available components. This demonstrates that practical displacement measurement instrumentation can be developed using low-cost materials suitable for laboratory and instructional applications.

Table 5. Total Cost of the Device

Description	Qty	Unit Price	Total Price (Php)
Arduino Uno R3	1	530	530
Breadboard	1	95	95
Greyscale Strip	4	25	100
Light Dependent Resistor	2	10	20
1k-ohm resistor	2	2	4
Breadboard Male Wires	10	4	40
PVC Switch Box (Enclosure)	2	250	500
Tripod	1	150	150
Spray Paint (Black)	1	100	100

Table 6. Cost Analysis

Instrument	Typical Cost
Dial Indicator	Php 3,000–10,000
LVDT Sensor System	Php 20,000–80,000
Optical Encoder System	Php 10,000–50,000
LALDI Prototype	Php 1,539

The results demonstrated that the Laser-Assisted Linear Displacement Instrument (LALDI) achieved measurement performance comparable to the commercial dial indicator within the tested range. The close agreement observed in Table 1 indicated that the optical intensity modulation mechanism effectively translated grayscale variation into proportional displacement values. The measurement differences summarized in Table 2 remained small and did not exhibit a progressive increase as applied load increased, which suggests that systematic drift or cumulative scaling error was not introduced during operation. This behavior supports the stability of the voltage divider configuration and the consistency of the laser-LDR interaction across displacement increments.

The paired t-test analysis further strengthened this observation. The computed t-value (2.671) was lower than the critical value (2.764) at the 0.01 level of significance, indicating that no statistically significant difference existed between the prototype and the reference instrument. From an engineering perspective, this result confirms that the displacement estimation derived from optical intensity variation can approximate the mechanical reference readings within acceptable experimental margins. The mean difference of 0.00382 inches represents a very small fraction of the total displacement range, which supports the practical usability of the device for laboratory-scale applications.

Repeatability analysis also confirmed consistent measurement behavior. The low standard deviation and coefficient of variation values across all tested displacement levels demonstrated minimal dispersion among repeated trials. This indicates that the grayscale strip provided uniform optical response and that signal conditioning and analog-to-digital conversion remained stable during testing. The absence of high variability suggests that the primary source of minor deviation was likely experimental alignment tolerance rather than inherent sensor instability.

The cost analysis provided additional technical significance. With a total fabrication cost of Php 1,539, the device was constructed at a fraction of the price of commercially available displacement measuring systems. The simplified architecture eliminated expensive interferometric optics, precision encoders, and external data acquisition modules. This confirms that a carefully calibrated intensity-based optical approach can deliver acceptable accuracy while maintaining affordability.

Despite these positive findings, certain limitations must be acknowledged. The operational range was restricted to 0–0.42 in within the experimental validation conducted in this study, and the attachment mechanism was specific to the beam deflection apparatus used in testing. Long-term environmental stability and industrial robustness were not evaluated. Nevertheless, within the defined laboratory scope, the developed instrument demonstrated reliable performance, statistical equivalence to a reference device, stable repeatability, and strong cost advantage.

CONCLUSIONS

The study successfully designed and developed a Low-Cost Laser-Assisted Linear Displacement Instrument (LALDI) using an optical intensity modulation principle. The prototype demonstrated proportional displacement response across the 0–0.42 inch operating range and produced measurements closely aligned with those of a commercial dial indicator. Statistical analysis confirmed that no significant difference existed between the two instruments at the 0.01 level of significance, indicating comparable measurement performance.

Repeatability testing showed low standard deviation and low coefficient of variance values across all displacement increments, confirming stable and consistent measurement behavior. The calibration process effectively established a reliable voltage-to-displacement mapping, and no systematic drift was observed throughout the experimental trials.

The total fabrication cost of Php 1,539 demonstrated that the instrument can be constructed using affordable and readily available components while maintaining acceptable accuracy and precision.

Overall, the developed device provides a practical and cost-effective alternative for laboratory-based linear displacement measurement and instructional applications within the defined operational range.

RECOMMENDATIONS

Further improvement of the LALDI is recommended to enhance performance and broaden application capability. The replacement of the light-dependent resistor with a photodiode or phototransistor is suggested to improve response linearity and sensitivity. Extending the displacement measurement range beyond the current 0–0.42-inch range through refinement of the grayscale strip design and optical alignment is also recommended.

Future development should include the integration of a digital data logging system or computer interface for real-time monitoring and data storage. The fabrication of a more robust and compact enclosure suitable for industrial environments is likewise advised.

Additional testing under varying environmental conditions, including changes in ambient lighting and temperature, is recommended to evaluate long-term stability and operational reliability. Commercial pilot testing in laboratory or small-scale engineering settings may further validate the practical applicability of the device.

DECLARATIONS

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Credit Authorship Contribution Statement

David Mark M. Mueller contributed to conceptualization, system design, prototype development, data collection, statistical analysis, software programming, and writing of the original draft. **Remy G. Tamson** contributed to methodology validation, technical supervision, system evaluation, review, and manuscript editing.

Ethical Statement

The authors confirm that this research was conducted in full compliance with the ethical standards set by the International Journal of Engineering Innovation and Dissemination (IJEID). All participants provided informed consent prior to their involvement, and approval was obtained from the relevant educational authorities. The study adhered to principles of transparency, confidentiality, and academic integrity, with all data reported honestly and all sources properly cited. The study involved laboratory-based instrumentation testing and did not involve human or animal subjects. Therefore, formal ethical approval was not required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The authors declare that the data supporting the findings of this study will be made available upon reasonable request.

AI Usage Disclosure

Artificial intelligence tools were used only for language refinement and formatting assistance. All scientific analysis, experimental design, and interpretation were conducted by the authors.

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