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ADVANCED SENSOR INTEGRATION FOR MEASUREMENTS THE DEFORMATIONS IN SHIPBUILDING WELDING

Andrei-Angelo MIDAN, Sorin Vasile SAVU, Adrian OLEI, Marius TEODORESCU, Andrej DAVID, Yasser DOUIMIA, Maciej KLOSAK

Abstract: *The welding process is essential in shipbuilding, having an impact on the structural integrity and performance of the ship. This study evaluates the ability of a LIDAR-type sensor system to measure distortions during welding. The paper presents research on deformation monitoring conditions using two experimental setups at distances of 350 mm and 550 mm from a deformed area. Measurements were recorded under laboratory conditions for various monitoring conditions (distance, inclination, sampling rate) with the aim of determining the optimal monitoring solution that presents satisfactory resolution and low cost. The results highlight significant variations in the strain distribution, influenced by sensor positioning and external factors. Despite challenges such as the inability to measure along the Y-axis and susceptibility to environmental interference, the sensor system demonstrated high sensitivity and accuracy in detecting deformation patterns.*
Key words: *welding, deformation measurement, shipbuilding, sensor technology, real-time monitoring.*

1. INTRODUCTION

The welding process is pivotal in shipbuilding due to its significant impact on structural integrity and overall performance of the vessel. During welding, the use of intense localized heat results in thermal expansion and contraction, leading to complex residual stresses and deformations [1]. Recent advancements in sensor technology have enabled precise measurement of distortions and stresses, thereby improving the accuracy and reliability of welding processes [2].

Various sensors have been developed to measure distortions and stresses during welding. Recent studies have demonstrated the effectiveness of strain gauges in capturing transient stress profiles during welding, particularly at typical nodes such as stiffeners, bulkheads, and longitudinal and transverse frames, where maximum stress is anticipated [3]. Thermocouples, on the other hand, are decisive for monitoring temperature changes, which are directly correlated with thermal stresses at these imperative junction points [4]. However, thermocouples require contact with the materials which cannot be applied in all cases of the nodes welding. Therefore, non-contact temperature measurements can be used in this type of welding applications. Laser displacement sensors offer non-contact measurement of distortions, providing high-resolution data on weld-induced deformations, crucial for understanding the behavior of these nodes [5].

The accuracy of measurements significantly depends on the optimal placement and distance of sensors. Research indicates that the positioning of sensors relative to the weld line influences the precision of the recorded data. For instance, strain gauges should be positioned at strategic points where maximum stress is anticipated, while thermocouples need to be placed in areas representing the thermal gradient effectively, particularly around typical nodes [6]. The optimal distance between the sensor and the weld also affects the data accuracy, with closer placements providing more detailed insights but at the risk of sensor damage due to high temperatures [7, and 8].

The integration of advanced techniques such as Digital Image Correlation (DIC) and Acoustic

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Emission (AE) sensors has further refined the measurement of welding-induced deformations and stresses. DIC uses optical methods to measure full-field displacements and strains on the surface of materials, providing comprehensive data on deformation patterns at typical shipbuilding nodes [9]. AE sensors detect stress waves emitted during the welding process, which can be correlated with crack formation and propagation at these critical junction points, offering early detection of potential failures [10].

Real-time monitoring using these advanced sensor systems facilitates immediate feedback and adjustments during the welding process [11]. Therefore, advanced data analysis techniques, including machine learning algorithms, have been employed to interpret sensor data accurately, predict potential defects, and optimize welding parameters, ensuring the structural integrity of typical nodes in shipbuilding [12, 13].

In this paper, its presented an innovative approach to measuring distortions during shipbuilding welding by integrating LIDAR sensors. The proposed system leverages advanced LIDAR technology, including the D500 Developer Kit, DTOF Laser Ranging Sensor, and 360° Omni-Directional Lidar, to provide non-contact, high-precision measurements of welding-induced deformations and stresses.

Moreover, we aim to establish a clear methodology for determining deformations, with a focus on creating a robust framework for accurate measurement. The research was conducted under controlled laboratory conditions to validate the sensor system's precision and reliability. The ultimate goal is for this developed technology to be applied in real-world shipbuilding scenarios, where accurate deformation measurement is critical for maintaining structural integrity and performance.

2. MATERIALS AND METHODS

2.1 Conceptual Model for Non-Contact Distorsion Measurement Using LIDAR Sensors

The primary aim of the conceptual model is to measure distortions in materials independently, without direct contact. This approach leverages the precision and versatility of LIDAR sensors, specifically the D500 Developer Kit, DTOF Laser Ranging Sensor, 360° Omni-Directional Lidar, and UART Bus [14]. This sensor is mounted on a support structure, connected to a data acquisition device, and integrated with specialized software to visualize deformations with a high degree of accuracy (0.1 mm error range).

The figure one illustrates the conceptual model for measuring distortions with the help of a LIDAR sensor. The setup includes several key components and variables that allow for precise, non-contact measurement of surface deformations.

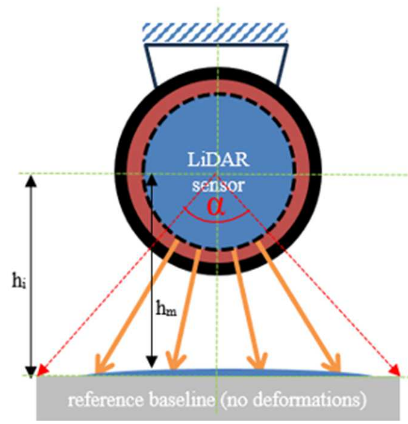

Fig. 1 Conceptual model for measuring distortions with the help of LIDAR sensor

Components and variables:

- LIDAR sensor: The central element of the setup is the LIDAR sensor, which operates by emitting laser pulses and measuring the time it takes for the reflections to return. This allows the sensor to determine distances to the surface with high precision.
- Reference baseline: This is the initial measurement taken when the surface has no deformations. It serves as the benchmark against which all subsequent measurements are compared.
- Reference height (hi): This is the height measured from the LIDAR sensor to the reference baseline (no deformations).

- Measured height (hm): This is the height measured from the LIDAR sensor to the deformed surface.
- Sensing angle (α = 0 – 360°): The LIDAR sensor operates over a full 360° field of view, allowing it to capture a comprehensive set of data points around the entire surface.
- Deformation (D): Deformation is calculated as the difference between the reference height (hi) and the measured height (hm).

Measurement process:

- Establishing the reference baseline: Initially, the LIDAR sensor is used to scan the surface and establish a reference baseline (no deformations). The reference height (hi) is measured and recorded for all angles within the 360° field of view.
- Scanning the deformed surface: After deformations occur, the LIDAR sensor scans the surface again. The measured height (hm) for each angle is recorded.
- Calculating deformations: The deformation (D) at each angle is calculated using the formula:

$$D = h_i - h_m \quad (1)$$

After extensive research into available sensor technologies, the LIDAR sensors were selected for their high precision, non-contact measurement capabilities, and adaptability to various environments.

Fig. 2 D500 Developer Kit, DTOF Laser Ranging Sensor, 360° Omni-Directional Lidar, UART Bus

The sensor is connected to a device, which records the measurements with the help of a specialized software. This software processes the data in real-time, visualizing the deformations and providing detailed analysis.

One of the significant challenges encountered during experiments is the susceptibility of the sensors to vibrations. Even minor vibrations can cause significant measurement errors, affecting the reliability of the data. To mitigate this issue, several strategies are employed:

- Vibration damping: Implementing damping materials and isolation techniques to reduce the impact of environmental vibrations.
- Calibration: Regular calibration of the sensors to ensure consistent accuracy.
- Stable mounting: Designing a robust support structure that minimizes movement and provides a stable platform for the sensors.

The conceptual model's non-contact measurement approach has broad applicability across various fields, including:

- Aerospace: Measuring distortions in aircraft components during manufacturing and maintenance to detect potential issues early.
- Civil Engineering: Assessing structural health of bridges, buildings, and other infrastructures by detecting deformations caused by load, environmental factors, or aging.

The conceptual model for non-contact distorsions measurement using LIDAR sensors represents a significant advancement in precision measurement technology.

2.2 Optimized portable sensor support system

The support structure used for sensor mounting during measurements is constructed from wood, offering a straightforward yet effective solution. This design is advantageous for its portability and ease of use, allowing for easy relocation and setup as needed in different testing environments. The simplicity of the wooden construction ensures that it remains lightweight and easy to handle, making it a practical choice for various measurement scenarios in shipbuilding.

One of the key features of this wooden support is its adjustable height mechanism. The support can be moved vertically, enabling precise positioning of the sensor at various heights. This flexibility is helpful for optimizing sensor placement relative to the weld line and other key points on the ship structure.

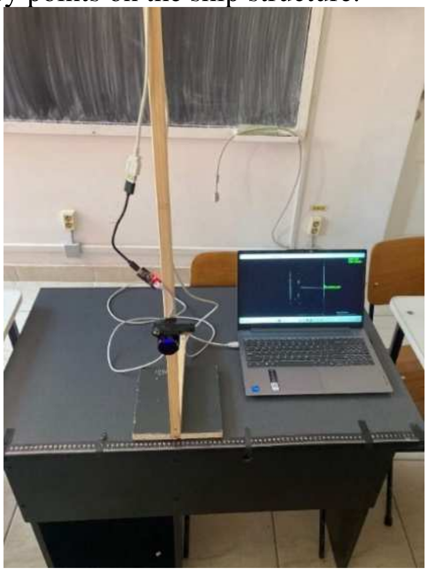

Fig. 3 Setup for real-time monitoring of deformations using a portable sensor support system

The support's construction also allows for easy customization and modification. Additional attachments or mounts can be added to accommodate different types of sensors or measurement devices.

2.3 Calibration procedures for sensor setup

The calibration of the sensor setup is a fundamental step to ensure accurate measurements of distortions and stresses. The reference zone, as seen in the figure three, serves as the initial point for calibration, commonly referred to as the zero point. Once this reference zone is selected, the calibration process involves several steps to align the sensor's readings accurately with the physical environment.

Firstly, the sensor is placed on the adjustable wooden support, allowing for precise positioning in relation to the test specimen:

- The support's height is adjusted to ensure the sensor is at the correct level for accurate data acquisition.
- The reference ruler fixed on the workbench provides a fixed scale to aid in the precise alignment of the sensor.

Next, the sensor is connected to the data acquisition system to establish a baseline:

- Initial readings are taken to ensure accurate data.
- The sensor is checked for correct positioning.
- Any potential obstructions are removed to avoid interference.

The software interface, as shown in figure four, plays an important role in the calibration process:

- The software displays the sensor's readings in real-time, allowing the operator to make necessary adjustments.
- The calibration process is iterative, involving fine adjustments to ensure that the sensor's digital readings match the physical measurements accurately.

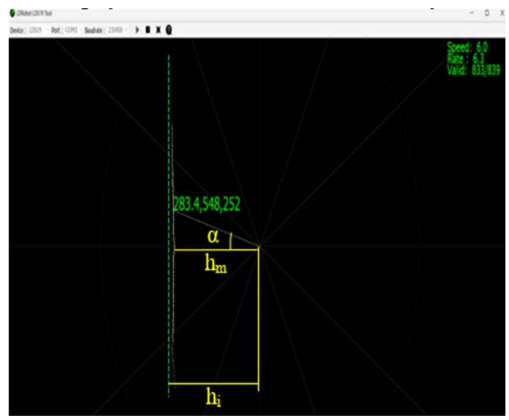

Fig. 4 D500 Lidar Kit software interface

During calibration, it is essential to ensure that the sensor's output remains stable. This involves checking the speed, rate, and validity of the sensor readings, as displayed in the software interface.

Additionally, environmental factors such as vibrations, changes in airflow and lighting conditions are considered during calibration, as they can affect the sensor's performance. The calibration is repeated multiple times to verify the accuracy and consistency of the readings.

2.4 Experimental program

For this study, two experimental cases were analyzed to evaluate the distortion and stress measurement capabilities of the sensor system. The simulator was fixed approximately 350 mm from the deformed zone, with a roulette-looking piece of deformed paper attached to the reference zone. Measurements were taken before and after adding the piece of paper, with two sets of data recorded for each condition.

Case one – sensor at approximately 350 mm

The sensor was fixed approximately 350 mm from the deformed zone, with a roulette-looking piece of deformed paper attached to the reference zone. Measurements were taken before and after adding the piece of paper, with two sets of data recorded for each condition.

The first set of measurements, taken before adding the deformed paper, showed the following values from table one.

Table 1

Measurements for the experiment where the sensor is set at approximately 350 mm

α [°]	h_m [mm]	h_i [mm]
306	366	372
295	352	354
288	317	321
272	311	316
266	325	338
259	335	337
247	344	352
238	356	356
231	368	374
217	379	388

The first set of measurements provided baseline data, highlighting the sensor's ability to detect deformations distributions. The values varied significantly across different angles, indicating deformation profiles. For instance, the measurements at 306° ranged from 366 to 372, while at 295°, they varied from 352 to 354.

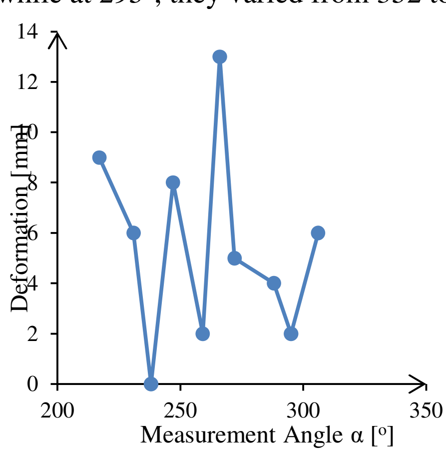

Fig. 5 Distorsions measured for the first case using baseline reference

The circular arc of the surface was identified between 311° and 204°. This range was critical in determining the deformation patterns induced by the addition of the deformed paper.

The equation (2) describes the relationship between deformation (D) and distortions (d) from the figure five.

$$D = -0{,}004\alpha^3 + 1{,}7\alpha^2 - 311{,}7\alpha + 20258 \quad (2)$$

Where:

- D is the distance measured by the sensor.
- α is the observed distorsion.

Case two – sensor at approximately 550 mm

In the second experimental case, the sensor was positioned approximately 550 mm from the deformed zone, with a roulette-looking piece of deformed paper attached to the reference zone. Measurements were conducted before and after introducing the deformed paper, recording data for each condition to analyze the impact on deformation and stress profiles.

The measurements for this setup are as presented in the table two.

Table 2

Measurements for the experiment where the sensor is set at 550 mm

α [°]	h_m [mm]	h_i [mm]
306	570	577
295	562	564
288	557	557
272	551	552
266	554	555
259	557	566
247	566	576
238	575	582
231	583	593
217	589	600

The initial measurements were taken to establish baseline data before introducing the deformed paper. The values exhibited significant variation across different angles, indicating deformation profiles. For instance, at 306°, the measurements ranged from 570 to 577, while at 295°, they ranged from 562 to 564. These variations highlighted localized stress concentrations and deformation zones, essential for understanding the structural integrity before additional deformation was introduced.

The circular arc of the surface was identified between 303° and 222°, major for determining the deformation patterns by the addition of the deformed paper.

The equation (3) describes the relationship between distance (D) and distortions (d) from the figure six.

$$y = -0{,}1\alpha^3 - 2\alpha^2 + 9{,}5\alpha + 14{,}1 \qquad (3)$$

Where:

- D is the distance measured by the sensor.
- α is the observed distorsion.

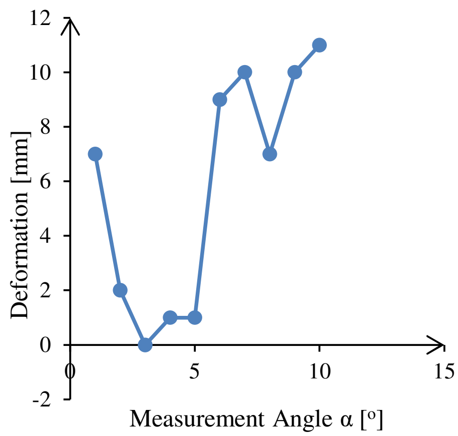

Fig. 6 Distorsions measured for the second case using baseline reference

3. RESULTS AND DISCUSSIONS

Comparing the results from the two cases reveals key differences and similarities in the sensor's performance and the deformation patterns observed:

Measurement range and accuracy: The sensor positioned at 550 mm provided higher measurement ranges (e.g., 570-577 at 306º) compared to the 350 mm setup (e.g., 366-372 at 306º). This indicates that the sensor can capture more extensive deformation profiles at a greater distance, potentially due to a broader field of view or reduced interference from immediate surroundings.

Variation in deformation profiles: Both cases exhibited significant variations in measurements across different angles, highlighting localized stress concentrations. However, the degree of variation was more pronounced in the 550 mm setup, suggesting that the increased distance allowed for capturing more detailed stress distribution data.

Circular arc of deformation: The identified circular arcs of the surface were slightly different between the two cases (311-204º for 350 mm vs. 303-222º for 550 mm). This difference indicates that the deformation pattern's extent can vary based on the sensor's positioning, with the 550 mm setup covering a broader range.

Impact of deformed paper: The introduction of the deformed paper significantly altered the stress distribution in both setups. The sensor system's ability to detect these changes demonstrates its sensitivity and accuracy in monitoring deformations. The changes were more substantial in the 550 mm case, suggesting that the sensor's increased distance enhances its capability to detect and analyze structural changes.

The comparative analysis between the two cases confirms the sensor system's efficacy in measuring distorsions and stresses during welding processes in shipbuilding. The increased distance in the 550 mm setup provided higher measurement ranges and more detailed deformation profiles, highlighting the importance of optimal sensor positioning.

Moreover, the results from the two experimental cases provide valuable insights into the deformation and stress measurement capabilities of the sensor system in shipbuilding. However, several challenges and limitations must be addressed to ensure accurate and reliable measurements.

One of the primary difficulties encountered is the sensor's inability to measure deformations along the Y-axis.

- This limitation restricts the sensor's capability to provide a complete three-dimensional analysis of the deformation patterns.
- In shipbuilding, where structural integrity is influenced by multi-axial stresses and deformations, the absence of Y-axis data can lead to incomplete assessments.
- The lack of Y-axis measurements can result in potential oversight of vital stress concentrations.

Additionally, the sensor's measurements are highly susceptible to small movements or vibrations:

- The experimental setup requires a stable and controlled environment to minimize these disturbances.
- Any minor displacement or vibration can significantly affect the accuracy of the recorded data, leading to potential errors in the deformation and stress analysis.
- This sensitivity necessitates meticulous attention to the sensor mounting and environmental conditions during data collection.

External factors also play a significant role in influencing the measurements [15]:

- Variations in ambient temperature, airflow, and lighting conditions can introduce noise and affect sensor performance.
- Changes in temperature can cause thermal expansion or contraction of the sensor components, leading to drift in the recorded values.
- Fluctuations in airflow can introduce vibrations or alter the thermal gradient around the sensor, further complicating the measurements.

Moreover, the placement and distance of the sensor from the deformed zone are needed for obtaining accurate data:

- As seen in the comparative analysis, the 550 mm setup provided higher measurement ranges and more detailed deformation profiles compared to the 350 mm setup.
- However, the increased distance also introduces the risk of environmental interferences and reduced resolution in capturing fine details.
- Balancing the sensor distance to optimize measurement accuracy while minimizing external influences remains a challenging task.

The iterative calibration process is essential for aligning the sensor's readings accurately with the physical environment.

4. CONCLUSION

The study confirms the effectiveness of the sensor system in accurately measuring distorsions and stresses during welding processes in shipbuilding. The comparative analysis between the two cases, with sensors positioned at 350 mm and 550 mm from the deformed zone, revealed several critical insights. The sensor placed at 550 mm demonstrated a broader measurement range and more detailed deformation profiles compared to the 350 mm setup, indicating that increasing the sensor distance can enhance the detection of stress distributions and deformation patterns. However, this benefit must be balanced against potential resolution loss and increased susceptibility to environmental noise.

Both setups effectively detected changes induced by the deformed paper, underscoring the sensor system's high sensitivity and accuracy. The ability to discern even minor structural changes is vital for early detection of potential issues and ensuring the integrity of ship components. A significant limitation, however, is the sensor’s inability to measure deformations along the Y-axis. This restricts the capability to provide a complete three-dimensional analysis of deformation patterns, potentially leading to incomplete assessments of structural integrity.

Overall, the sensor system demonstrated significant potential in accurately measuring distortions and stresses during welding processes in shipbuilding. The findings highlight the importance of optimal sensor placement and controlled experimental conditions to ensure accurate and reliable measurements. Future work should aim to develop multi-axial sensor systems that capture three-dimensional deformation patterns, while improving environmental stability to reduce external interference.

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Integrare avansată a senzorilor pentru măsurătorile deformațiilor în sudarea construcțiilor navale

Procesul de sudare este esențial în construcția de nave, având un impact asupra integrității structurale și a performanței navei. Acest studiu evaluează capacitatea unui sistem senzorial de tip LIDAR de a măsura deformațiile în timpul sudării. Lucrarea prezintă cercetări privind condițiile de monitorizare a deformațiilor folosind două configurații experimentale la distanțe de 350 mm și 550 mm față de o zonă deformată. Măsurătorile au fost înregistrate în condiții de laborator pentru condiții variate de monitorizare (distanță, înclinație, viteză de eșantionare) cu scopul de a determina soluția optima de monitorizare care să prezinte o rezoluție satisfăcătoare și un cost redus. Rezultatele evidențiază variații semnificative în distribuția deformațiilor, influențate de poziționarea senzorului și de factori externi. În ciuda provocărilor, cum ar fi incapacitatea de a măsura de-a lungul axei Y și susceptibilitatea la interferențe de mediu, sistemul sensorial a demonstrat sensibilitate și precizie ridicate în detectarea modelelor de deformare.
Cuvinte cheie: sudură, măsurarea deformării, construcții navale, tehnologie cu senzori, monitorizare în timp real.

Andrei-Angelo MIDAN, PhD student, University of Craiova, midan.andrei.c3i@student.ucv.ro, +40 755 851 887, 1 Călugăreni Street, Drobeta Turnu Severin, Mehedinți, România.

Sorin Vasile SAVU, Prof Habil., PhD., **corresponding author**, University of Craiova, sorin.savu@yahoo.com, +40 722 691 192, 1 Călugăreni Street, Drobeta Turnu Severin, Mehedinți, România.

Adrian Bebe OLEI, Assoc Prof, PhD, University of Craiova, bebe.olei@edu.ucv.ro, +40 728 864 010, Călugăreni Street 1, Drobeta Turnu Severin, Mehedinți, România.

Marius TEODORESCU, Pharma Plus, t_g_marius@yahoo. com, Phone: +40 742134 525, Calea Bucuresti, Craiova, Romania

Andrej DAVID, Associate Professor, PhD, Lecturer, University of Zilina, andrej.david@uniza.sk, +421 41 513 3551, Univerzitna 8215/1, 010 26 Zilina, Slovakia.

Yasser DOUIMIA, Engineer, PhD student, Universiapolis / École Polytechnique d'Agadir, Mechanical Engineering, yasser.douimia@e-polytechnique.ma, +212 5 28 23 34 34, E-POLYTECHNIQUE - CAMPUS UNIVERSIAPOLIS, Bab Al Madina, Qr Tilila, B.P. 8143, Agadir, Morocco.

Maciej KLOSAK, Assoc Prof, PhD, Eng., Universiapolis / École Polytechnique d'Agadir, Mechanical Engineering, maciej.klosak@e-polytechnique.ma, +212 5 28 23 34 34, E-POLYTECHNIQUE - CAMPUS UNIVERSIAPOLIS, Bab Al Madina, Qr Tilila, B.P. 8143, Agadir, Morocco.