

# Literature Review: Recent Advances in Laser Welding Technologies

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**Abstract:** This literature review examines recent advancements in laser welding technologies, focusing on innovative methods for monitoring and controlling critical aspects of the welding process. The review covers various approaches, including machine learning techniques combined with spectrometer measurements for beam offset detection, acoustic emission monitoring paired with deep learning models for penetration assessment, and Optical Coherence Tomography (OCT) integrated with fuzzy control systems for inline weld depth evaluation. Each study emphasizes the importance of real-time detection and adjustment capabilities to enhance welding quality and efficiency. The findings reveal that these advanced methodologies significantly improve the precision and reliability of laser welding processes across different applications, contributing to reduced defects, lower scrap rates, and heightened process efficiency. By addressing traditional limitations in monitoring and control, these innovative solutions pave the way for more reliable and automated welding practices in modern manufacturing environments.

**Index Terms**— Laser Welding, Beam Offset Detection, Machine Learning, Spectrometer Measurements, Acoustic Emission, Deep Learning, Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM), Optical Coherence Tomography (OCT), Inline Measurement, Weld Depth Evaluation, Fuzzy Control Systems, Real-Time Monitoring, Weld Quality, Process Optimization, Manufacturing Efficiency.

## I. INTRODUCTION

Welding has long been a cornerstone in the fabrication and assembly of metal components across diverse industries, ranging from automotive to aerospace. This practice is essential for creating strong, reliable connections that uphold the structural and functional integrity of products. In an era where innovation is key, the welding sector has seen a significant shift towards advanced methodologies that meet the rising expectations for precision, speed, and efficiency.

Among these advancements, fiber laser welding stands out as a game-changer. Utilizing concentrated beams of light, fiber laser technology achieves remarkably fine control over the welding process,

resulting in precision that far surpasses traditional welding methods. This shift not only minimizes heat-affected zones, which can weaken metal properties, but also enhances the ability to automate processes, thereby streamlining manufacturing operations.

Moreover, the versatility of fiber laser welding allows for the joining of a wide range of materials and thicknesses, making it an invaluable asset in modern manufacturing landscapes. As industries continually strive for improved productivity and quality, the adoption of fiber laser technology not only meets these requirements but also positions manufacturers at the forefront of their respective fields.

This paper explores the comprehensive aspects of fiber laser welding, shedding light on its operational principles, key terminologies, and the transformative impact it has on welding practices today. By delving into the mechanics and benefits of this technology, we aim to highlight its essential role in shaping the future of manufacturing, where enhanced quality and efficiency are paramount.

## II. LITERATURE SURVEY

### 1. Literature Review on Beam Offset Detection in Laser Stake Welding of Tee Joints Using Machine Learning and Spectrometer Measurements

#### Introduction

Laser beam welding (LBW) is recognized for its high productivity and relatively low heat input, making it a critical process in manufacturing, particularly for sandwich constructions. However, the efficacy of LBW is highly dependent on the precise positioning of the laser beam relative to the joint. Any deviation, known as beam offset, can result in significant defects in the welded part. Traditional seam tracking methods, which rely on visual information, are ineffective for tee joints as the joint is not visible from the top side. This necessitates the development of advanced monitoring systems capable of detecting beam offsets in real-time to mitigate defects and

reduce scrap. Recent research has explored the use of spectrometer measurements and machine learning (ML) techniques to address this challenge.

#### Spectrometer Measurements in LBW

Spectrometers are instrumental in capturing the spectral emissions from the laser-metal interaction zone. These high-dimensional data provide insights into the welding process, though their direct correlation to beam offsets is not immediately apparent. The utility of spectrometer measurements lies in their ability to offer a non-visual, real-time assessment of the welding process, making them suitable for scenarios where traditional visual monitoring is impractical.

#### Machine Learning Approaches

Machine learning offers a robust framework for analyzing complex, high-dimensional data such as those obtained from spectrometers. Various ML classifiers can be trained to recognize patterns in spectral emissions that correspond to beam offsets. The research reviewed in this document evaluated several ML techniques, including:

- Multi-Layer Perceptron Neural Network (MLPNN)
- Support Vector Machine (SVM)
- Learning Vector Quantization (LVQ)
- Logistic Regression (LR)
- Decision Tree (DT)
- Random Forest (RF)
- Feature Selection

Before applying these classifiers, feature selection is performed to improve classification accuracy. Techniques such as random forest and non-dominated sorting genetic algorithm II (NSGAI) are utilized to identify the most relevant features from the spectrometer data, thereby enhancing the performance of the ML models.

#### Results and Discussion

The reviewed study demonstrated that the integration of spectrometer measurements with ML classifiers could achieve high accuracy in detecting laser beam offsets. Specifically, an accuracy rate of 94% was reported for real-time detection of beam deviations greater than 0.9 mm from the joint center-line. This level of precision underscores the potential of ML techniques in improving the LBW process.

The classifiers were effective across a range of offsets, with the most notable performance observed when deviations ranged from 0.5 mm to 1.3 mm. The use of feature selection algorithms significantly contributed to this high accuracy, highlighting the importance of preprocessing in ML applications.

#### Practical Implications

The successful application of ML techniques for beam offset detection in LBW offers several practical benefits:

- **Enhanced Process Efficiency:** Early detection and correction of beam offsets reduce the occurrence of defects, leading to higher quality welds and reduced scrap.
- **Cost Savings:** By minimizing defects and rework, manufacturers can achieve significant cost savings.
- **Broader Applicability:** While the focus of this study is on tee joints, the principles and techniques developed could be adapted for other welding scenarios where traditional visual tracking is not feasible.

#### Conclusion

The reviewed literature establishes a strong case for the use of spectrometer measurements combined with machine learning to detect beam offsets in laser stake welding of tee joints. The approach addresses the limitations of traditional visual seam tracking methods and demonstrates significant potential for improving welding accuracy and efficiency. Future research could explore the scalability of these techniques to other types of joints and welding processes, further extending their applicability in advanced manufacturing settings.

#### 2. Literature Review on Laser Welding Penetration Monitoring Based on Acoustic Emission and CNN-LSTM Hybrid Network

##### Introduction

Laser welding is a sophisticated manufacturing process widely employed due to its precision and efficiency. One of the critical challenges in laser welding is achieving uniform and reproducible welds, which heavily depends on the accurate monitoring of welding penetration. Penetration monitoring is particularly difficult due to the complex dynamics of the keyhole formed during the laser-metal interaction. This literature review focuses on

the feasibility of using acoustic emission (AE) measurement for penetration monitoring and the application of a hybrid Convolutional Neural Network (CNN) and Long Short-Term Memory (LSTM) network for analyzing AE data.

#### Acoustic Emission in Laser Welding

Acoustic Emission (AE) refers to the phenomenon where transient elastic waves are generated by the rapid release of energy from localized sources within a material. In the context of laser welding, AE can be used to monitor keyhole dynamics and penetration depth by analyzing the characteristics of the acoustic waves produced during the welding process. The complexity of these waves necessitates advanced methods for their analysis and interpretation.

#### High-Speed Photography and Acoustic Emission Techniques

To understand the generation mechanism of acoustic waves in laser welding, high-speed photography combined with AE techniques can be employed. This approach allows for in-situ visualization of keyhole dynamics, offering insights into how pressure fluctuations at the keyhole wall produce acoustic waves. This understanding forms the basis for developing effective monitoring systems.

#### Time-Frequency Characterization using Variational Mode Decomposition

One advanced technique proposed for characterizing the acoustic energy distribution in laser welding is Variational Mode Decomposition (VMD). VMD is an adaptive time-frequency analysis method that decomposes the AE signal into multiple subsignals, each representing different frequency components. By analyzing these subsignals, it is possible to gain a detailed understanding of the acoustic energy distribution across different welding penetrations.

#### Deep Learning for Acoustic Feature Extraction

- Convolutional Neural Network (CNN)

CNNs are powerful tools for spatial feature extraction from data. In the context of AE signals, CNNs can effectively capture patterns in the frequency domain that correlate with different welding penetration levels.

- Long Short-Term Memory (LSTM)

LSTMs are a type of recurrent neural network (RNN) particularly suited for temporal sequence prediction. They can retain information over long periods, making them ideal for analyzing time-series data such as AE signals.

- Hybrid CNN-LSTM Model

The reviewed study proposes a novel hybrid model combining CNN and LSTM networks. This model is designed to extract both spatial and temporal features from the AE signals, providing a comprehensive analysis of the data. The hybrid approach leverages the strengths of both CNNs and LSTMs, resulting in high classification performance.

#### Results and Discussion

The study demonstrated that the hybrid CNN-LSTM model could achieve remarkable accuracy in penetration monitoring. Specifically, the proposed approach achieved a test accuracy of 99.8% with a standard deviation of 0.21, indicating a high recognition rate for welding penetration. This high accuracy underscores the potential of deep learning techniques in enhancing the precision and reliability of penetration monitoring systems.

#### Practical Implications

The development of an efficient end-to-end penetration monitoring system using AE measurements and deep learning techniques represents a significant advancement in the digitization and intelligence of the laser welding process. Such systems can provide real-time feedback, ensuring uniform and high-quality welds while reducing the need for post-process inspections and rework.

#### Conclusion

This literature review highlights the innovative use of AE measurements and deep learning for penetration monitoring in laser welding. The hybrid CNN-LSTM model proposed in the reviewed study offers a powerful tool for extracting and analyzing acoustic features, achieving high accuracy in penetration detection. The findings contribute to the ongoing efforts to digitize and automate the laser welding process, paving the way for more efficient and reliable manufacturing practices.

#### 3.Literature Review on Inline Weld Depth Evaluation and Control Using OCT Keyhole Depth Measurement and Fuzzy Control

## Introduction

In industrial joining processes, particularly deep penetration laser beam welding, achieving high-quality welds is crucial yet challenging. The quality of welds cannot solely rely on post-process testing but must be ensured during the process itself. Consequently, control systems that operate in real-time are essential for fully automated production. This literature review examines the application of Optical Coherence Tomography (OCT) for inline weld depth measurement and the use of fuzzy control systems to maintain consistent weld quality.

## Optical Coherence Tomography (OCT) in Weld Depth Measurement

OCT is a novel, direct measurement technique capable of acquiring geometric quantities such as weld penetration depth. By providing real-time data, OCT offers significant potential for controlling the welding process effectively. This capability is vital for industrial applications where maintaining precise weld depths is critical for product integrity and performance.

## Inline Weld Depth Control Systems

Inline control systems are designed to monitor and adjust the welding process dynamically, ensuring that the weld depth adheres to specified targets. These systems utilize data from OCT to make real-time adjustments, thereby improving the efficiency and quality of the welding process. The reviewed study presents an inline weld depth control system that automatically manages the deep penetration welding process based on the target weld depth.

## Fuzzy Control for Welding Processes

Fuzzy control systems are effective in dealing with uncertainties and variations in the welding process. By incorporating fuzzy logic, these systems can handle the inherent variability in welding conditions, such as material inconsistencies and external disturbances. This adaptability makes fuzzy control a robust solution for maintaining weld quality in automated production environments.

## Experimental Validation and Performance

The performance of the proposed inline weld depth control system was validated through experiments on various aluminum alloys and at different penetration depths. The system demonstrated its capability to

maintain consistent weld depths and respond to unforeseen external disturbances. This adaptability is crucial for industrial applications where conditions can change dynamically.

## Intelligent Algorithms and Future Developments

The study highlights the potential for further advancements in laser welding technology through the integration of intelligent algorithms and innovative measurement technologies. By following the example of laser beam cutting, where processing systems have been enhanced with intelligent control capabilities, the welding process could evolve towards more intuitive and autonomous operation.

## Key Findings

- **OCT-Based Measurement:** The use of OCT for inline weld depth measurement allows for precise and real-time control of the welding process.
- **Fuzzy Control System:** The implementation of fuzzy control systems enables the handling of process variability and external disturbances, ensuring high-quality welds.
- **Experimental Validation:** The control system was successfully tested on different aluminum alloys, demonstrating its versatility and effectiveness.
- **Future Potential:** The integration of intelligent algorithms and advanced measurement techniques can further enhance the automation and efficiency of laser welding processes.

## Conclusion

This literature review underscores the importance of inline weld depth control systems in achieving high-quality welds in laser beam welding processes. The combination of OCT for precise measurement and fuzzy control for adaptive process management represents a significant advancement in welding technology. The successful implementation and validation of these systems in various industrial scenarios highlight their potential for broader adoption and further innovation.

## 4.Literature Review on Weld Tracking System Based on Laser Vision

### Introduction

Automatic welding systems have long faced challenges related to real-time performance, applicability, and welding precision. Addressing

these issues is critical for advancing automated welding technology. This literature review examines the development and effectiveness of a seam tracking system based on laser vision, designed to enhance real-time weld monitoring and improve precision in automated welding processes.

### Laser Vision in Weld Tracking

Laser vision technology is pivotal for real-time weld tracking systems. It involves using a laser vision sensor to capture images of the weld seam, which are then processed to identify key features and track the welding process accurately. The integration of laser vision into welding systems aims to provide high precision and applicability across various welding scenarios.

### System Design and Components

The proposed seam tracking system employs several advanced techniques to enhance performance:

- **Laser Vision Sensor:** Captures real-time images of the weld seam, providing the raw data necessary for further processing.
- **Image Processing Techniques:** Utilizes a median filter to eliminate noise such as arc and splash, ensuring that the captured images are clear and usable.
- **Image Threshold Segmentation:** An improved image threshold segmentation algorithm is used to determine the optimal threshold, converting the image into a binary format where the laser stripe and background are separated.
- **Feature Point Identification:** Combines the improved upper and lower average method, least square method, and Hough transform to accurately identify weld feature points. These techniques help in overcoming issues related to system jitter and unrecognized global optimal solutions.

### Methodology

The methodology focuses on enhancing image processing and feature detection to improve real-time tracking:

- **Median Filter:** Applied to reduce noise, ensuring that the image data is clean and reliable.
- **Image Threshold Segmentation:** An improved algorithm to find the optimal threshold for binary image conversion, crucial for distinguishing the laser stripe from the background.

- **Feature Point Identification:** Uses advanced methods such as the least square method and Hough transform to pinpoint weld features accurately, ensuring precise tracking even under challenging conditions.

### Experimental Results

Experimental validation demonstrated the system's capability to accurately track weld feature points and improve detection speed. The use of the laser vision sensor, combined with advanced image processing techniques, allowed for real-time monitoring and control of the welding process, significantly enhancing precision and reliability.

### Key Findings

- **Improved Precision:** The laser vision-based system significantly improves the precision of weld tracking compared to traditional methods.
- **Real-Time Performance:** The system can operate in real-time, providing immediate feedback and adjustments during the welding process.
- **Noise Reduction:** The median filter effectively reduces noise from arc and splash, improving image quality for better processing.
- **Advanced Segmentation and Identification:** The use of improved algorithms for image threshold segmentation and feature point identification enhances the system's ability to track welds accurately.
- **Increased Detection Speed:** The system demonstrated faster detection speeds in experimental setups, making it suitable for high-speed automated welding applications.

### Conclusion

This literature review highlights the advancements in weld tracking systems through the integration of laser vision technology. The development of a seam tracking system based on laser vision and advanced image processing techniques addresses the key challenges of real-time performance, applicability, and precision in automated welding. The experimental results confirm that the proposed system can accurately track weld feature points and improve detection speed, making it a valuable tool for enhancing the efficiency and quality of automated welding processes.

5.Literature Review on Fusing Optical Coherence Tomography and Photodiodes for Weld Feature Diagnosis

## Introduction

The advancement of remote laser welding, particularly in joining dissimilar metals such as copper and aluminum, necessitates precise monitoring and diagnosis of weld features to ensure high-quality welds. This literature review examines a study investigating the fusion of optical coherence tomography (OCT) and photodiodes to monitor and diagnose variations in laser weldments. The focus is on how these combined sensing techniques can enhance the detection and classification of weld features during the welding process.

## Sensing Technologies in Weld Monitoring

### Optical Coherence Tomography (OCT)

OCT is a non-invasive imaging technique that captures high-resolution cross-sectional images of the weld penetration depth. It provides direct measurements that are crucial for assessing the quality and integrity of the weld.

### Photodiodes

Photodiodes are sensors that detect process emissions such as plasma and back-reflection during welding. These emissions carry significant information about the welding process, including the presence of defects and variations in weld quality.

## Methodology

### Experimental Setup

The study utilized an adjustable ring mode laser integrated with a 1D oscillation head to weld 0.2 mm thick copper foils to 2 mm thick aluminum 1050 plates. Two manufacturing scenarios were considered: variations in laser power and focal offset. The process was monitored using OCT to measure weld penetration depth and photodiodes to capture process emissions.

### Data Acquisition

The acquisition frequency for all signals was set at 40 kHz, ensuring high-resolution data collection. Strong correlations ( $r > 0.75$ ) were observed between the plasma, back-reflection, and OCT signals with the measured weld depth and width. However, weak correlations ( $r < 0.5$ ) were noted for voids, cracks, and sensor signals.

## Results and Analysis

### Correlation of Signals

The study found that plasma is the predominant signal carrying most of the information about the welding process. The OCT measurements of penetration depth provided direct and accurate data. The integration of these signals resulted in an 87% classification accuracy for the tested welding scenarios.

### Misclassification Issues

The main misclassification occurred between "good weld" and "over weld," as defined by the measured weld depth. This suggests that while the combined sensor data improves overall classification, there are still challenges in distinguishing certain weld quality categories.

## Discussion

### Sensor Fusion Strategies

The fusion of OCT and photodiodes enhances the ability to diagnose and isolate variations in weld features. This combined approach leverages the strengths of both sensing technologies, offering a more comprehensive view of the welding process. The study discusses the potential of these sensor fusion strategies to improve manufacturing outcomes by providing real-time, accurate diagnostics.

### Manufacturing Implications

Implementing these advanced sensor fusion techniques in industrial settings can lead to significant improvements in weld quality and process control. The ability to accurately monitor and classify weld features in real-time enables better decision-making and reduces the likelihood of defects.

## Conclusion

The integration of optical coherence tomography and photodiodes for diagnosing weld features during remote laser welding shows promising results. The strong correlations between plasma, back-reflection, and OCT signals with weld depth and width highlight the potential of this approach. Despite some misclassification challenges, the overall classification accuracy of 87% demonstrates the effectiveness of sensor fusion in enhancing weld monitoring and diagnosis.

## 6. Literature Review on Application of Electrical Power Measurements for Process Monitoring in Ultrasonic Metal Welding

### Introduction

Ultrasonic metal welding is a widely used technique for producing e-mobility components, such as cable harnesses, battery cells, and power electronics. These applications demand high-quality welds, as single points of failure and lack of reparability post-installation are common. Ensuring high quality in this context is challenging due to numerous process variables, such as base material hardness, surface conditions, and cleanliness. This literature review examines a study that explores the application of electrical power measurements for process monitoring in ultrasonic metal welding. The study focuses on the potential of using electrical power signals and machine learning models to predict joint quality.

### Sensing Technologies in Ultrasonic Metal Welding

#### Ultrasonic Metal Welding

Ultrasonic metal welding involves high-frequency vibrations to join metal components. It is particularly suitable for e-mobility components due to its efficiency and ability to produce high-quality welds. However, understanding the binding mechanisms and their sensitivity to various process variables remains an area of active research.

#### Current Monitoring Methods

Existing monitoring methods, such as laser-doppler vibrometry and laser triangulation sensors, are used to observe process vibrations at the horn, anvil, and components. These methods require external accessibility, which is often not feasible in industrial environments. As a result, random destructive testing is commonly used to ensure weld quality, despite its limitations and inefficiencies.

### Methodology

#### Electrical Power Measurements

The study investigates the use of high-frequency power signal measurements from the welding system to monitor the welding process. This method does not require external accessibility and can be integrated into industrial production environments.

### Machine Learning Models

Several machine learning models were developed to predict weld quality based on the high-frequency power signal data. The robustness of these models was evaluated by incorporating various disturbances, such as changes in material hardness and cleanliness.

### Results and Analysis

#### High-Frequency Power Signal Monitoring

The study demonstrated that monitoring the high-frequency power signal of the welding system provides valuable insights into the welding process. This approach can help identify different process phases and features related to joint formation.

#### Machine Learning Predictions

The machine learning models showed promise in predicting weld quality based on the power signal data. By accounting for disturbances, the models were able to provide robust predictions, highlighting the potential for implementing these models in industrial settings.

### Discussion

#### Benefits of Electrical Power Measurements

Using electrical power measurements for process monitoring offers several advantages. It allows for non-invasive, real-time monitoring of the welding process, which is more suitable for industrial applications compared to existing methods that require external accessibility.

#### Improvement over Current Methods

The study suggests that electrical power measurements, combined with machine learning models, can provide more accurate and reliable quality predictions than the internal monitoring methods currently available in welding systems. This approach can reduce the need for random destructive testing and improve overall process efficiency.

### Manufacturing Implications

Implementing electrical power measurement-based monitoring in ultrasonic metal welding can significantly enhance process control and weld quality. This method offers a practical and effective solution for real-time quality monitoring in industrial

production environments, leading to better decision-making and reduced defect rates.

## Conclusion

The application of electrical power measurements for process monitoring in ultrasonic metal welding shows significant potential. The integration of high-frequency power signal monitoring with machine learning models can provide accurate and robust predictions of weld quality. This approach addresses the limitations of current monitoring methods and offers a viable solution for improving weld quality in the production of e-mobility components.

## 7.Literature Review on Modeling of Predictive Maintenance Systems for Laser-Welders in Continuous Galvanizing Lines Based on Machine Learning

### Introduction

Predictive maintenance is essential in modern manufacturing environments to prevent equipment failures and reduce downtime. This literature review explores a study focused on developing a predictive maintenance model using machine learning (ML) techniques for laser welders in continuous galvanizing lines (CGLs) of a steel plant in Korea. The study aimed to detect equipment failures before they lead to line shutdowns, thereby improving operational efficiency and reducing maintenance costs.

### Predictive Maintenance in Manufacturing

#### Importance of Predictive Maintenance

Predictive maintenance involves using data-driven techniques to predict equipment failures before they occur. This approach is crucial in high-demand manufacturing environments, such as steel production, where unexpected equipment failures can lead to significant downtime and financial losses.

#### Machine Learning in Predictive Maintenance

Machine learning techniques, particularly deep learning models, have shown great promise in predictive maintenance due to their ability to analyze complex datasets and identify patterns indicative of equipment failures. These models can be trained on historical operation data to predict future failures with high accuracy.

## Methodology

### Data Collection and Preprocessing

The study collected approximately 1500 types of data from the laser welders' operation, selecting around 200 relevant data types through preprocessing. The dataset was then split into training and testing sets at an 8:2 ratio.

### Model Selection and Training

The study selected an auto-encoder (AE) model for handling normal data and a long short-term memory (LSTM) model for analyzing time series data. The combination of these models, known as the LSTM-AE algorithm, was chosen for its technical advantages. Model parameters were optimized using 10-fold cross-validation to ensure robust performance.

### Results and Analysis

#### Performance Metrics

The performance of the Laser Welder Predictive Maintenance Model (LW-PMM) was evaluated using several metrics:

Accuracy: 97.3%

Precision: 79.8%

Recall: 100%

F1-Score: 88.8%

#### Interpretation of Results

The high recall rate indicates that the model effectively identified all equipment failures. However, the precision rate of 79.8% suggests that some of the predicted failures were false positives. Despite this, the model significantly improved early detection of equipment abnormalities, identifying issues 27 hours before failure, which is 18 hours earlier than the existing process.

#### Application in Industrial Settings

When applied to an actual CGL operation site, the LW-PMM model successfully detected equipment abnormalities well before failure, demonstrating its potential for real-world applications. This early detection capability can significantly reduce downtime and maintenance costs.

## Discussion

### Advantages of LSTM-AE Model

The combination of AE and LSTM models leverages the strengths of both algorithms, making the LW-PMM model particularly effective for handling normal and time series data. This hybrid approach enhances the model's ability to predict equipment failures accurately.

### Challenges and Limitations

One limitation is the possibility of overfitting due to setting thresholds by facility engineers. Additionally, the model may not learn all possible failure scenarios during its training phase, potentially limiting its robustness in new or unforeseen situations.

### Future Research Directions

Further research could focus on improving the precision of the model by refining data preprocessing techniques and exploring additional machine learning algorithms. Expanding the model to other equipment and processes within the steel industry could also enhance its applicability and impact.

### Manufacturing Implications

Implementing predictive maintenance models like LW-PMM in industrial settings can lead to significant improvements in operational efficiency and equipment reliability. By reducing unplanned downtime and maintenance costs, these models contribute to the digital transformation and innovation of the steel industry.

## Conclusion

The study demonstrates the effectiveness of using machine learning techniques for predictive maintenance in laser welders. The LW-PMM model achieved high accuracy and recall rates, detecting equipment abnormalities well before failure. This approach offers a viable solution for improving maintenance practices and operational efficiency in the steel industry.

## 8.Literature Review on Accurate Detection of Weld Seams for Laser Welding in Real-World Manufacturing

### Introduction

Welding is a critical fabrication process in various manufacturing industries, enabling the joining or fusing of mechanical parts to form a strong bond. With advancements in technology, modern welding machines utilize automated lasers to follow pre-defined weld seam paths. However, the reliability and accuracy of weld seam detection have been a persistent challenge. Traditional methods, relying on simple computer vision edge detectors, often necessitate manual human verification due to their limitations. This literature review focuses on the state-of-the-art approaches to weld seam detection, with an emphasis on the neural network-based methodology proposed in the article "Accurate Detection of Weld Seams for Laser Welding in Real-World Manufacturing" by Rabia Ali, Muhammad Sarmad, Jawad Tayyub, and A. Vogel.

### Traditional Weld Seam Detection Techniques

Traditional weld seam detection systems primarily use basic edge detection algorithms such as the Sobel operator, Canny edge detector, and Hough transform. These methods, although computationally inexpensive, struggle with robustness and accuracy in complex industrial environments. Factors such as variations in lighting, surface reflections, and the presence of noise adversely affect their performance. As a result, these systems often require manual verification to ensure correct weld seam identification, leading to inefficiencies and increased labor costs.

### Limitations of Traditional Methods

**Sensitivity to Environmental Conditions:** Traditional edge detectors are highly sensitive to variations in lighting and surface conditions, which are common in industrial settings.

**Inadequate Accuracy:** Simple edge detection techniques often fail to accurately delineate weld seams, especially in the presence of noise and reflections.

**Need for Manual Intervention:** Due to their limited reliability, these systems necessitate frequent manual checks, reducing overall automation efficiency.

### Neural Network-Based Approaches

In recent years, deep learning techniques have revolutionized various fields, including computer vision. Convolutional neural networks (CNNs) and

other deep learning architectures have demonstrated significant improvements in object detection and classification tasks, making them suitable candidates for weld seam detection.

#### Proposed Neural Network Architecture

The article under review introduces a novel neural network architecture designed specifically for weld seam detection. This architecture aims to address the shortcomings of traditional methods by providing high accuracy and robustness in real-world manufacturing environments. Key features of this approach include:

- **High Accuracy:** The neural network architecture achieves superior accuracy in detecting weld seams compared to traditional edge detectors.
- **Pre-Classifier for Anomalous Workpieces:** The system incorporates a pre-classifier that filters out anomalous workpieces, such as those with incorrect placement, further enhancing detection reliability.
- **Real-World Deployment and Evaluation:** The proposed system is thoroughly evaluated on a real-world shop floor, demonstrating its practical applicability and robustness.

#### Evaluation Against Existing Deep Network Pipelines

The authors conduct a comprehensive evaluation of their neural network architecture against several existing deep learning pipelines. This comparative analysis highlights the advantages of the proposed method in terms of accuracy, robustness, and operational efficiency.

#### Deployment in Real-World Manufacturing

One of the significant contributions of the article is the detailed description of deploying the neural network-based weld seam detection system in an actual manufacturing environment. The authors provide insights into the challenges and considerations involved in real-world deployment, including system integration, performance monitoring, and continuous improvement.

#### Public Dataset for Laser Seam Detection

The authors also contribute to the research community by making publicly available a large, well-labeled laser seam dataset. This dataset is crucial for training and evaluating deep learning

models for weld seam detection, fostering further advancements in this field.

#### Conclusion

The neural network-based approach to weld seam detection presented in the article "Accurate Detection of Weld Seams for Laser Welding in Real-World Manufacturing" represents a significant advancement over traditional methods. By leveraging deep learning techniques, the proposed system offers high accuracy and robustness, addressing the limitations of simple edge detectors. The inclusion of a pre-classifier to filter out anomalous workpieces further enhances the system's reliability. The real-world deployment and availability of a comprehensive dataset underscore the practical applicability and potential for broader adoption of this innovative approach in industrial welding operations.

#### 9.Literature Review on Efficient Method for Laser Welding Depth Determination Using Optical Coherence Tomography

##### Introduction

In the field of power battery manufacturing for new energy vehicles, precise control and monitoring of laser welding depth are critical. Accurate welding depth ensures the structural integrity and performance of the batteries. Traditional indirect methods of measuring welding depth, which rely on optical radiation, visual images, and acoustic signals, often fail to provide the required accuracy for continuous monitoring. The use of Optical Coherence Tomography (OCT) offers a promising alternative, providing direct and highly accurate measurements. This review examines the recent advancements and methodologies, particularly focusing on the efficient method proposed in the article "An Efficient Method for Laser Welding Depth Determination Using Optical Coherence Tomography" by Guanming Xie et al.

##### Traditional Methods for Welding Depth Measurement

Traditional indirect methods for welding depth measurement include:

- **Optical Radiation:** Utilizes the emission of light during welding to infer depth, but accuracy is compromised by environmental factors.

- Visual Imaging: Captures images of the welding process, but precision is limited by image resolution and noise.
- Acoustic Signals: Measures sound waves generated during welding, but results are often inconsistent and affected by ambient noise.

These methods, while useful in some contexts, are generally insufficient for the high precision required in continuous industrial monitoring.

#### Limitations of Traditional Methods

- Low Accuracy: Traditional methods are often inaccurate due to interference from environmental factors and noise.
- Inconsistent Monitoring: The reliability of continuous monitoring is compromised, necessitating periodic manual checks.
- Complexity and Cost: Implementing and maintaining these systems can be complex and costly.

#### Optical Coherence Tomography (OCT) for Welding Depth Measurement

OCT has emerged as a robust solution for direct measurement of laser welding depth. It leverages low-coherence interferometry to produce high-resolution cross-sectional images of the weld, allowing for precise depth determination.

- Advantages of OCT
- High Accuracy: OCT provides highly accurate depth measurements, essential for quality control in battery manufacturing.
- Direct Measurement: Unlike indirect methods, OCT offers a direct measurement approach, reducing the likelihood of errors.
- Continuous Monitoring: OCT is well-suited for continuous, real-time monitoring, which is crucial for industrial applications.
- Proposed Method: DBSCAN and Percentile Filter

The article under review presents a novel method for determining laser welding depth by combining Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and a percentile filter. This approach aims to enhance the accuracy and efficiency of depth measurement by addressing the noise issues inherent in OCT data.

#### Methodology

Noise Detection with DBSCAN: The DBSCAN algorithm is employed to identify and eliminate noise from the OCT data. By treating noise as outliers, DBSCAN effectively enhances the quality of the data.

Percentile Filter for Depth Extraction: After noise removal, a percentile filter is applied to accurately extract the welding depth. This method ensures that the depth measurement is precise and reliable.

#### Evaluation and Results

The proposed method was evaluated by comparing the determined welding depth with the actual weld depth from longitudinal cross-sections. The results indicated an average error of less than 5%, demonstrating the method's high accuracy and efficiency.

#### Comparative Analysis with Existing Methods

The proposed DBSCAN and percentile filter method offers significant improvements over traditional statistical evaluation approaches, which often suffer from complexity in noise removal. The combination of DBSCAN for noise detection and the percentile filter for depth extraction simplifies the process while maintaining high precision.

#### Key Advantages

- Improved Accuracy: The method achieves an average error of less than 5%, making it highly reliable for industrial applications.
- Efficiency in Noise Removal: DBSCAN effectively identifies and removes noise, which is a major challenge in OCT data analysis.
- Applicability to Real-World Settings: The method has been validated in real-world scenarios, demonstrating its practical viability for continuous monitoring in manufacturing environments.

#### Conclusion

The method proposed by Guanming Xie et al. for laser welding depth determination using OCT, coupled with DBSCAN and a percentile filter, represents a significant advancement in the field. By addressing the limitations of traditional indirect methods and improving upon existing statistical approaches, this method provides a robust, accurate, and efficient solution for continuous welding depth monitoring. This innovation is particularly relevant

for the manufacturing of power batteries for new energy vehicles, where precision and reliability are paramount.

#### 10. Literature Review on Evaluation of a Cut Interruption Algorithm for Laser Cutting Steel and Aluminum with a High-Speed Camera

##### Introduction

Laser cutting is a widely used manufacturing process, particularly in the fabrication of steel, zinc-coated steel, and aluminum components. Ensuring the quality and precision of laser cuts is crucial for various industrial applications. Traditional monitoring methods often lack the spatial and temporal resolution required for accurate evaluation. This literature review examines the advancements in laser cutting monitoring systems, focusing on the evaluation presented in the article "Evaluation of a Cut Interruption Algorithm for Laser Cutting Steel and Aluminum with a High-Speed Camera" by Max Schleier et al.

##### Traditional Monitoring Systems for Laser Cutting

Traditional monitoring systems for laser cutting often rely on external illumination or sensors, which may not provide sufficient resolution or accuracy. These systems typically face challenges in detecting subtle variations in the melt pool area and distinguishing between complete and incomplete cuts.

##### Limitations of Traditional Methods

- **Limited Resolution:** Conventional monitoring systems may lack the spatial and temporal resolution needed to accurately capture the dynamic process of laser cutting.
- **External Dependencies:** Systems requiring external illumination or retrofitting of cutting heads may introduce additional complexities and limitations.
- **Detection Challenges:** Distinguishing between complete and incomplete cuts, especially in materials like aluminum, can be challenging with traditional methods.

##### High-Speed Camera-Based Monitoring System

The article under review introduces a monitoring system based on a high-speed camera for fiber laser fusion cutting. This system offers several advantages over traditional methods, including direct, spatially, and temporally resolved detection of the melt pool

area without the need for external illumination retrofitting.

##### Key Features

- **Direct Monitoring:** The high-speed camera allows for direct observation of the melt pool area from a top view, providing detailed spatial and temporal information.
- **Material Evaluation:** The system evaluates the melt pool area for different materials, including stainless steel, zinc-coated steel, and aluminum, enabling comprehensive process characterization.
- **Cut Interruption Algorithm:** An ad hoc developed image processing algorithm analyzes spectral and geometric information from high-speed camera images to distinguish between complete and incomplete cuts.

##### Methodological Approach

The monitoring system captures images of the melt pool area and analyzes the signal characteristics in the visible spectral range of the emitted secondary thermal radiation from the process zone. The image processing algorithm then utilizes this information to differentiate between complete and incomplete cuts.

##### Performance Evaluation and Results

The proposed cut interruption algorithm was evaluated for its effectiveness in distinguishing between complete and incomplete cuts. The results demonstrated reliable detection capabilities, particularly for aluminum, where traditional methods often face challenges. The adaptation of threshold values in the algorithm improved the accuracy of the detection process.

##### Comparative Analysis with Traditional Methods

Compared to traditional monitoring systems, the high-speed camera-based approach offers enhanced resolution and accuracy in evaluating the melt pool area and detecting cut interruptions. By directly observing the laser cutting process, this system provides valuable insights for in-situ quality control, particularly in materials like aluminum where precision is critical.

##### Conclusion

The monitoring system based on a high-speed camera, as presented in the article by Max Schleier et al., represents a significant advancement in laser

cutting process evaluation. By leveraging the spatial and temporal resolution of high-speed cameras, coupled with an ad hoc developed cut interruption algorithm, the system offers reliable and accurate monitoring capabilities. This innovation holds promise for improving quality control and efficiency in laser cutting processes, particularly for materials like aluminum where precision is paramount.

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