

SMART GUIDANCE SYSTEM FOR MANUAL WELDING PROCESSES: SEQUENTIAL SURFACE MAPPING AND REAL-TIME TORCH ORIENTATION

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<https://doi.org/10.37904/metal.2026.5269>

Abstract

This study presents 'WeldTrack: Smart Guidance System,' developed to minimize operator-induced errors in manual laser welding operations and to protect device longevity against the risk of 'back-reflection,' a critical issue particularly in highly reflective metals such as AISI 304 stainless steel. The system architecture consists of two main units communicating via Wi-Fi. The first unit is a reference apparatus equipped with a BNO055 absolute orientation sensor and an ESP32-S3 microcontroller, designed to measure the spatial orientation of the surfaces to be joined by touching them sequentially prior to welding. Data obtained from these surfaces are used to calculate the three-dimensional digital twin of the joint geometry and its absolute orientation relative to the gravity axis. The second unit is a tracking module integrated into the welding torch. Based on the bisector plane and target orientation data received from the reference unit, the torch module provides real-time guidance to the operator through a visual interface (LCD-based spirit level) to maintain the correct angular position along the welding line. Experimental results demonstrate the feasibility of the proposed digital twin generation and real-time operator guidance approach, enabling orientation-aware manual laser welding while providing a digital framework compatible with Industry 4.0-based process monitoring.

Keywords: Hand-held Laser Welding, Dual-Sensor Fusion, Digital Twin, Joint Geometry Mapping, Real-Time Guidance

1. INTRODUCTION

Laser welding technology has become an indispensable part of modern manufacturing thanks to its advantages of low heat input and a narrow heat-affected zone (HAZ) [1, 2]. Early studies proved the effectiveness of Nd:YAG lasers on thin foils and sensitive components [3]. The automotive industry is one of the areas where this technology is most intensively utilized. In the literature, it has been emphasized that the optimization of seam geometry in sheet metal joining [4, 5] and the cracking and softening problems encountered in the welding of high-strength steels can be overcome through parameter control [6, 7]. Furthermore, the critical role of microstructural phase changes on mechanical strength in the laser joining of nickel-based superalloys has been the subject of many investigations [8, 9].

In recent years, with the increasing need for flexibility in the industry, a significant trend from fixed systems toward hand-held laser welding (HHLW) systems has been observed. The growing popularity of handheld systems since 2023 is seen particularly as a solution to the shortage of qualified labor [10]. By evaluating the applicability of these systems in the production of components with aesthetic requirements, it has been stated that they constitute a strong alternative to traditional arc welding [11]. However, welding quality in these systems is directly dependent on parameters such as laser power, wire feed speed, and oscillation frequency [12, 13].

In contrast, the "operator factor" in handheld systems remains one of the greatest challenges. Variations in optical characteristics and focal shifts of different commercial systems make the direct transfer of parameters

between devices difficult and can lead to welding defects [14]. Moreover, reflected radiation generated during the use of these Class 4 laser category devices poses serious risks to operator safety [15, 16]. By drawing attention to the optical hazards created by systems used in small workshops, it has been emphasized that traditional protection methods may remain insufficient [17]. Smart torch systems developed to minimize these risks and user errors are of great importance for the traceability and reliability of the process [18].

The operator assistance device developed within the scope of this study aims to reduce operator-induced variability by supporting the parameter sensitivity and safety requirements specified in the literature. In this direction, the presented 'WeldTrack: Smart Guidance System' provides real-time guidance using dual-sensor fusion and a dynamic referencing algorithm, supporting safer torch orientation.

2. MATERIALS AND METHODS

The experimental validation of the WeldTrack system was performed using an industrial laser welding platform and a dual-sensor orientation measurement architecture. The proposed methodology focuses on generating a weld seam digital twin from measured joint geometry and calculating the corresponding reference torch orientation to provide real-time guidance during manual laser welding operations.

2.1. Tactile Surface Mapping and Digital Twin Generation

The Master Unit (**Figure 1-1**) was developed to digitalize the physical joint geometry. It integrates a BNO055 absolute orientation sensor (**Figure 1-2**) and an ESP32-S3 control board (**Figure 1-3**), enabling quaternion-based orientation measurement, processing, and Wi-Fi communication. The measurement procedure consists of three sequential steps (**Figure 2**): first, the operator records the gravity-aligned reference quaternion q_{ref} using the trigger button (**Figure 1-4**), establishing the global coordinate frame (**Figure 2a-7,8**). Then, the sensor is placed on the first and second joint surfaces to acquire their orientations as quaternion vectors q_1 and q_2 (**Figure 2b-9** and **Figure 2c-10**). RGB LEDs indicate the current measurement stage (**Figure 1-5**).

The quaternion data are converted into surface normal vectors using equation (1):

$$\mathbf{n}_i = q_i(0,1,0)q_i^{-1} \quad (1)$$

where $\mathbf{n}_1$ and $\mathbf{n}_2$ are the unit normal vectors of the joint surfaces. The weld seam direction vector is calculated using equation (2):

$$\mathbf{l} = (\mathbf{n}_1 \times \mathbf{n}_2) / |\mathbf{n}_1 \times \mathbf{n}_2| \quad (2)$$

The normalized bisector vector is obtained using equation (3):

$$\mathbf{b} = (\mathbf{n}_1 + \mathbf{n}_2) / |\mathbf{n}_1 + \mathbf{n}_2| \quad (3)$$

The bisector plane normal is calculated using equation (4):

$$\mathbf{p} = (\mathbf{l} \times \mathbf{b}) / |\mathbf{l} \times \mathbf{b}| \quad (4)$$

where $\mathbf{p}$ defines the rotation axis. The target torch orientation vector is generated by rotating the bisector vector by 15° about the plane normal vector $\mathbf{p}$, remaining within the bisector plane, as given by equation (5):

$$\mathbf{t} = R(\mathbf{p}, \theta)\mathbf{b} \quad (5)$$

where $\theta = 15^\circ$. The rotation angle was fixed at 15° , corresponding to the target torch work angle used in the present study. Therefore, the generated digital twin includes both the weld seam geometry and the reference torch orientation required for operator guidance. Before each measurement, the Master Unit was calibrated by recording the gravity-aligned reference quaternion (q_{ref}) on a surface perpendicular to the gravity direction. According to the manufacturer's specifications, the BNO055 provides an orientation uncertainty below $\pm 0.5^\circ$. The generated digital twin was then transmitted to the Slave Unit for real-time guidance.

2.2. Industrial Platform and Real-Time Guidance Integration

The digital twin was integrated into the manual laser welding process through the Slave Unit. The experimental platform consists of a Turcweld LP300 Nd:YAG laser system (**Figure 3a**), operating at 1064 nm wavelength with a peak power of 9.9 kW and average power of 300 W. Welding parameters, including 200 ms pulse interval and 1–300 Hz frequency range, were controlled through the manual control unit (**Figure 3b**). The conventional torch (**Figure 3c**) was modified by integrating the Slave Unit (**Figure 3d**), which includes a second BNO055 sensor (**Figure 4b-15**) and an ESP32-S3 processor (**Figure 4b-16**). The sensor continuously acquires torch orientation data at 20 Hz, and the measured quaternion data are compared with the target orientation calculated from the digital twin. The generated digital twin and the calculated target orientation are transferred to the Slave Unit, which continuously updates orientation data at 20 Hz to provide real-time operator guidance. The developed user interface (**Figure 4c-17**) visualizes the deviation between the actual torch orientation and the calculated target orientation using a spirit-level display, enabling the operator to continuously adjust and maintain the recommended torch orientation during welding.

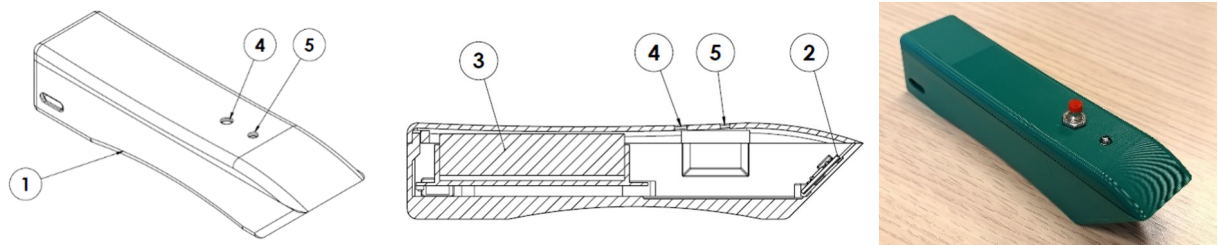


Figure 1 Tactile measurement unit (1) for pre-weld joint geometry mapping (Master Unit): (2) BNO055 absolute orientation sensor, (3) ESP32-S3 control board for data processing, (4) trigger button, and (5) status RGB LED.

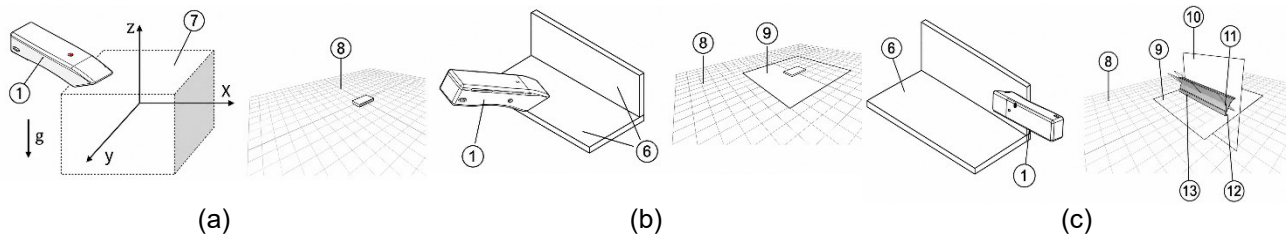


Figure 2 Representative illustration of the tactile measurement steps for joint digitalization: (a) Calibration phase to establish the global reference frame (8) relative to the gravity axis (7). (b) Measurement of the first surface orientation angle (9) by contacting the primary workpiece surface (6). (c) Measurement of the second surface orientation angle (10) and subsequent calculation of the weld seam digital twin (11), including the ideal bisector plane (12) and target torch direction (13).

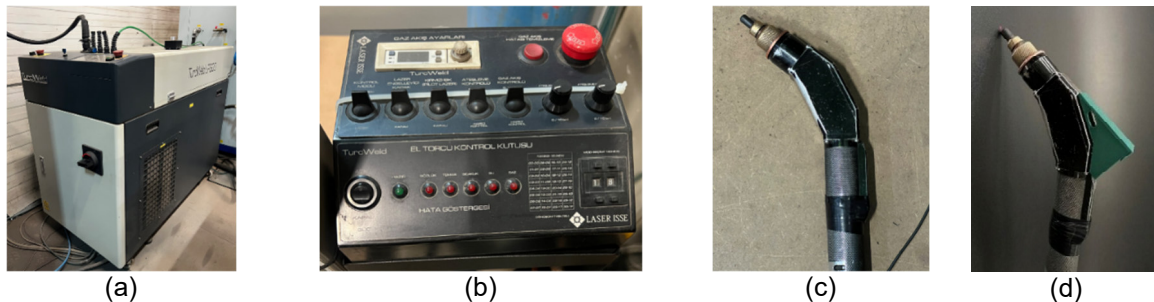


Figure 3 (a) Turcweld LP300 laser welding machine, (b) manual control interface, (c) standard hand-held laser torch, and (d) upgraded torch integrated with the WeldTrack angular positioning assistant.

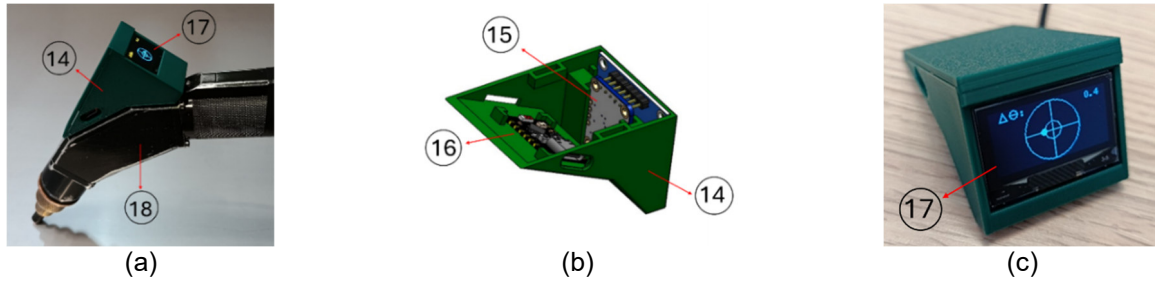


Figure 4 Welding Torch Module (Slave Unit): (a) Integration of the module (14) onto the torch body (18), (b) Internal architecture showing the tracking sensor (15) and receiver processor (16), (c) Real-time User Feedback Interface (17) for angular deviation monitoring.

3. RESULTS AND DISCUSSION

3.1. Joint Geometry Identification and Digital Twin-Based Torch Orientation Calculation

Two different measurement scenarios were performed to demonstrate the capability of the proposed system to identify joint geometries and calculate the reference torch orientation independently of the workpiece position relative to gravity. The preparation and guidance processes for these scenarios are presented step-by-step in **Table 1**. In the first scenario, two sheet metal components were positioned to form an internal corner joint with arbitrary spatial orientation. During the pre-welding preparation stage, the Master Unit sequentially measured the reference surface and both joint surfaces. The acquired quaternion data were processed using the algorithm described in Section 2 to reconstruct the three-dimensional digital representation of the joint geometry. The generated digital twin represents the weld seam direction, bisector plane, and target torch orientation obtained by applying the predefined 15° inclination angle within the bisector plane. This calculated orientation was transferred to the Slave Unit to provide real-time guidance during manual welding.

The second scenario involved a more complex joint orientation with multi-axis inclination, where predefined geometric references such as 45° or 90° positions are insufficient. As illustrated in **Table 1**, the proposed mapping approach successfully reconstructed the spatial relationship between the joint surfaces without requiring external references. These results demonstrate the capability of the WeldTrack system to transform physical joint geometry into a digital representation and generate a corresponding torch orientation reference for manual welding operations.

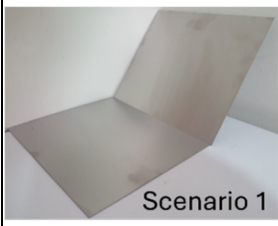
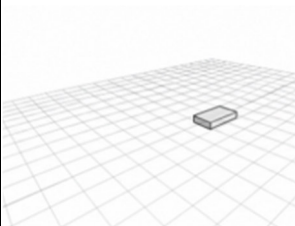
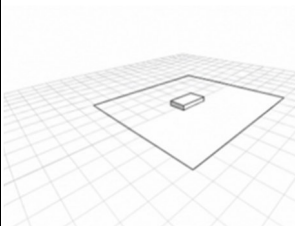
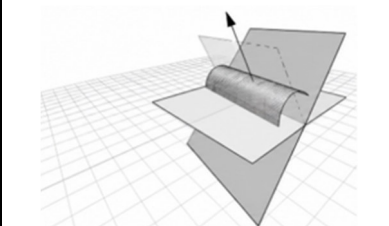
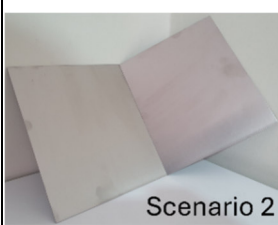
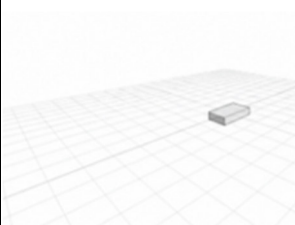
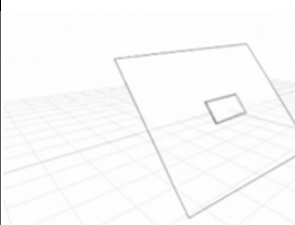
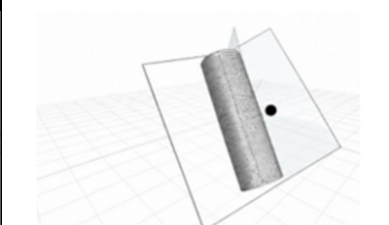
3.2. Preliminary Evaluation of Operator Guidance Performance

A preliminary welding experiment was conducted to evaluate the practical guidance capability of the developed system. The objective of this experiment was not to statistically quantify the effect of the system on weld quality, but rather to demonstrate its capability to assist an inexperienced operator in maintaining the calculated torch orientation. The welding samples were produced using 304 series matte stainless steel sheets with dimensions of $20 \times 40 \times 1.2$ mm, configured as 90° internal corner joints. The operator received one day of basic welding training before the experiments. A total of twenty specimens were welded, including ten samples without WeldTrack guidance and ten samples with WeldTrack guidance. Representative microscope images of three samples and one general appearance image for each condition are presented in **Figure 5**.

As shown in **Figure 5a**, samples produced without guidance exhibited visible burn marks on the opposite surface of the welding direction, which were associated with difficulties in maintaining a stable torch orientation by an inexperienced operator. In contrast, the samples produced with WeldTrack guidance (**Figure 5b**) did not exhibit the same visible marks, suggesting that the visual feedback provided by the system helped the operator maintain the recommended torch orientation more consistently. These preliminary observations suggest that the proposed system has the potential to improve the consistency of manual torch positioning by assisting

operators in maintaining the calculated reference torch orientation; however, comprehensive statistical studies involving different operators, materials, welding conditions, and quantitative weld characterization are required to determine its overall influence on welding performance.

Table 1 Identification of joint geometries with different spatial orientations via sequential surface mapping and calculation of torch guidance data.

Welding Scenario	Calibration	Measurement of the first surface	Second surface measurement and the weld seam digital twin reconstruction
 Scenario 1			
 Scenario 2			

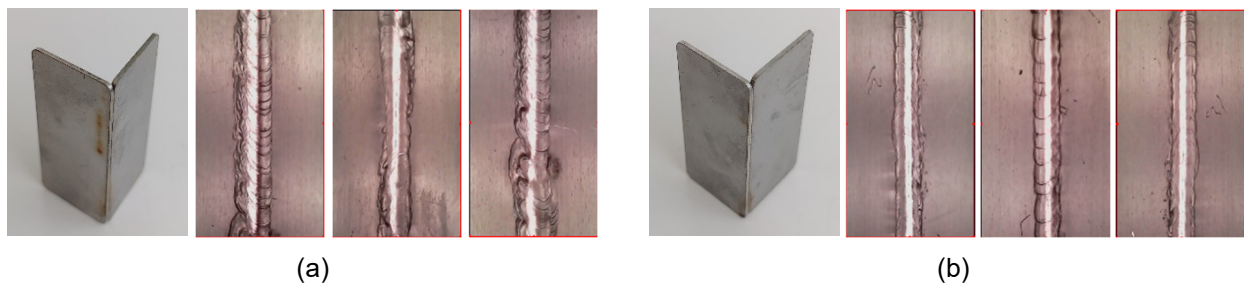


Figure 5 Comparison of representative weld seam appearances: (a) welds produced without guidance exhibiting visible surface irregularities and burn marks, (b) welds produced using WeldTrack guidance.

4. CONCLUSION

This study presents the development and experimental demonstration of WeldTrack, a mechatronic guidance system designed to generate a digital twin of a weld seam and provide real-time guidance for maintaining the calculated torch orientation during manual laser welding operations. The proposed system integrates tactile surface mapping, quaternion-based orientation calculation, and a dual-sensor architecture to reconstruct the spatial geometry of the joint and determine the reference torch orientation based on the calculated bisector plane and predefined inclination angle. Experimental results show that the developed approach can successfully convert physical joint geometry into a digital representation and provide real-time orientation feedback to the operator.

A preliminary welding experiment performed by an inexperienced operator demonstrated that the proposed guidance system has the potential to assist in maintaining torch positioning compared with unguided manual operation. The present study primarily focuses on the development and validation of the digital twin generation

and operator guidance methodology. The quantitative effects of the system on weld quality parameters, penetration characteristics, defect formation, and operator performance require further investigation through comprehensive statistical studies involving different operators, materials, welding conditions, and measurement techniques.

ACKNOWLEDGEMENTS

The authors would like to thank EVINOKS SERVIS EKIPMANLARI SAN. VE TIC. A.S. for their financial support of this research.

REFERENCES

- [1] PÜSKÜLCÜ, G., KOÇLULAR, F. Laser Welding Method and Applications. Mühendis ve Makine. 2009, vol. 50, no. 599, pp. 43-52.
- [2] AYDIN, K., KARAAĞAÇ, İ. Laser Welding and Principal Applications of Laser Welding. El-Cezerî Fen ve Mühendislik Dergisi. 2018, vol. 5, no. 2, pp. 693-705.
- [3] VENTRELLA, V.A., BERRETTA, J.R., DE ROSSI, W. Pulsed Nd:YAG laser seam welding of AISI 316L stainless steel thin foils. Journal of Materials Processing Technology. 2010, vol. 210, pp. 1838-1843.
- [4] ÇAKMAKKAYA, M., ÇOLAK, F., KARA, R., KARAAĞAÇLI, A. The Effect of Welding Parameters on Weld Seam Geometry and Penetration of Different Types of Steels Used in the Automotive Industry Joined by Laser Welding Method. Journal of Materials and Mechatronics: A. 2020, vol. 1, no. 1, pp. 1-11.
- [5] ERGİN, D. Investigation of the Effects of Laser Weld Seam Forms on Welding Properties in Sheet Metal Joining. Bursa, 2021. Master's Thesis. Bursa Uludağ University.
- [6] ALPAR, T., ÇELENK, O., ÇAVDAR, K. Laser Welding Applications in High Strength Steels. Bursa Uludağ University Journal of the Faculty of Engineering. 2021, vol. 26, no. 3, pp. 883-896. Available from: <https://doi.org/10.17482/uumfd.960795>.
- [7] KARŞI, A. Investigation of the Effects of Laser Cladding Welding Parameters in Automotive. Bursa, 2019. Master's Thesis. Bursa Uludağ University.
- [8] LERTORA, E., MANDOLFINO, C., GAMBARO, C. Mechanical Behaviour of Inconel 718 Thin-Walled Laser Welded Components for Aircraft Engines. International Journal of Aerospace Engineering. 2014, Art. 721680.
- [9] YAN, L., et al. Effect of laser welding parameters on the temperature distribution, microstructure and mechanical properties of dissimilar weld joint of Inconel 625 and stainless steel 304. International Communications in Heat and Mass Transfer. 2022, vol. 131, 105859.
- [10] JAHN, S., et al. Potential of handheld laser beam welding. Archive of Mechanical Engineering. 2025. DOI: 10.21595/amr.2025.24840.
- [11] CAPRIO, L., et al. Experimenting with handheld laser welding for the flexible production of components with aesthetic requirements. Laser Systems Europe. 2022, Winter Issue, pp. 28-31.
- [12] MARQUARDT, R., et al. Influence of laser power on the melt pool shape of handheld laser beam welding. In: IOP Conference Series: Materials Science and Engineering. Bristol: IOP Publishing, 2025, vol. 1332, pp. 12-15.
- [13] MASLAREVIĆ, A., et al. Influence of welding parameters on the geometric characteristics of surface weld metal obtained by handheld laser welding. Structural Integrity and Life. 2025, vol. 25, no. 2, pp. 245-248.
- [14] JAHN, S., et al. Laser beam characteristics of handheld laser beam welding systems. Welding in the World. 2026. Available from: <https://doi.org/10.1007/s40194-026-02377-3>.
- [15] PÖLLÄNEN, L. Occupational Safety and Equipment of a Handheld Laser Welding. Lappeenranta, 2024. Master's Thesis. LUT University.
- [16] STANISZ, D., et al. Angular dependence of reflected laser radiation intensity during handheld laser welding. Advances in Science and Technology Research Journal. 2026, vol. 20, no. 4, pp. 213-226.
- [17] SLINEY, D., EARLEY, D. Optical Safety for Handheld Laser Welding. Welding Journal. 2024, June, pp. 58-61.
- [18] REIS, M., ŞERİFAĞAOĞLU, E. A Smart Handheld Welding Torch Device for Manual Spot Laser Welding. Applied Sciences. 2022, vol. 12, no. 11, pp. 1-14.