

Article

Optical Reconstruction and Quantitative Evaluation of Arc Position in Stud Welding

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Abstract

This study presents an optical reconstruction method for the quantitative evaluation of arc position in stud welding. Knowledge of the instantaneous arc position is essential for understanding arc dynamics and enabling process monitoring and control. The relative spatial position of the arc is determined from the geometric centroid of an intensity distribution recorded by eight directionally arranged photodiodes. Calculated using area-weighted polygon decomposition, the centroid provides a consistent two-dimensional representation of arc motion and enables the derivation of angular and amplitude-related quantities. The method is not intended to deliver absolute metric arc positions but to provide a reliable relative description of arc movement. Whereas laser-based stereoscopic systems require an additional illumination arrangement and high-speed camera systems rely on the acquisition and processing of image sequences, the proposed method evaluates photodiode signals acquired directly within the welding hardware. This enables a compact, process-integrated implementation suitable for real-time arc monitoring. The proposed reconstruction method is evaluated under conventional direct-current, magnetically influenced direct-current, and alternating-current welding conditions. Validation against stereoscopic high-speed camera measurements showed good agreement in trajectory shape and dynamic behaviour, with mean Pearson correlation coefficients above 0.97 and a mean Euclidean deviation of 0.59 mm, corresponding to 10.4%, for rotational arc motion. The approach thus enables reliable analysis of arc movement and spatial energy distribution over the entire welding duration. Overall, the proposed methodology provides a robust and efficient tool for quantitative arc motion analysis in stud welding.

Keywords: stud welding; arc motion; position detection; photodiode sensor; process monitoring



Academic Editor: Lucas F. M. da Silva

Received: 5 June 2026

Revised: 24 July 2026

Accepted: 28 July 2026

Published: 4 August 2026

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1. Introduction

The spatial motion of the welding arc represents a key factor influencing process stability and joint quality in stud welding. The arc position governs the spatial distribution of energy input and thereby influences molten pool formation as well as the metallurgical properties of the resulting joint. Under normal operating conditions, arc motion is primarily driven by electromagnetic (Lorentz) forces, self-induced magnetic forces (pinch effect), arc pressure, and plasma flow dynamics [1]. However, unfavorable boundary conditions—such as misalignment between stud and workpiece, surface irregularities, variations in

electrical contact, or external magnetic disturbances—may cause the arc motion to become asymmetric or stationary. The resulting localized heat input can lead to uneven fusion, localized overheating, reduced weld quality, and diminished process reproducibility [2].

Accurate knowledge of the instantaneous arc position is therefore of fundamental importance. With increasing stud diameter and welding current, the arc tends to stabilize in a stationary configuration, promoting localized energy input and asymmetric heat distribution. To mitigate this effect, external magnetic field systems—such as rotating magnetic arc control modules—are employed to actively enforce arc motion and homogenize the energy distribution [3–5]. However, these systems typically do not provide direct, position-resolved feedback of the actual arc trajectory. More generally, recent reviews highlight persisting gaps in process understanding, parameter standardization, and quality monitoring in stud welding, despite the industrial relevance of the process [2].

Obtaining spatially resolved arc information in stud welding is experimentally challenging. The short process duration combined with high arc dynamics, strong magnetic fields, intense radiation, elevated temperatures, and limited installation space within the process module significantly complicates direct measurement of the arc position. In addition, diagnostic systems must operate reliably under practical process conditions while remaining insensitive to electromagnetic interference and mechanical stress. These constraints necessitate compact and robust sensor concepts capable of providing high temporal resolution of arc motion, particularly since process monitoring is regarded as essential for quality assurance and early defect detection in stud welding [2].

Various measurement approaches have been employed to analyze arc motion. High-speed imaging systems enable spatially resolved observation of arc position and, with appropriate calibration, can also be used to determine its absolute position. They are therefore frequently used as a reference method in experimental investigations [6–8]. High-speed imaging allows detailed analysis of arc trajectory and size, but it involves considerable experimental effort and generates large data volumes. As a result, detailed trajectory analysis is often restricted to short observation intervals and primarily laboratory-based investigations. Accordingly, high-speed imaging is used primarily to elucidate arc welding phenomena under controlled experimental conditions rather than for routine industrial implementation [9,10]. Related work in welding and robotic arc guidance has shown that calibrated multi-view and stereo vision imaging systems can be used for three-dimensional geometric reconstruction through triangulation of features from multiple viewpoints [11–13]. In principle, similar reconstruction strategies could also be used to assess spatial arc motion in stud welding. However, these camera-based methods rely on extensive calibration and post-processing to recover position information for visualization or robot guidance. In addition to imaging techniques, electrical signal-based methods are applied, in which current and voltage waveforms are evaluated to assess process stability [14]. Acoustic and magnetic-field-based measurement approaches have likewise been investigated to characterize dynamic phenomena within the arc plasma [15]. While these methods provide valuable information about process dynamics and stability, they generally do not provide direct geometrically resolved arc position information.

Optical intensity measurements using directionally sensitive sensors present another approach for evaluating the spatial light distribution within the welding zone and deriving information about arc motion [16–18]. Such concepts are particularly promising for compact and process-integrated solutions, as their directional sensitivity enables spatial discrimination of arc radiation.

Delzant et al. [17] reported a photodiode-based approach for analyzing arc motion in vacuum arc remelting processes, while Jilg [18] disclosed a conceptually related sensor approach for stud welding in the context of position-based arc control. In conjunction

with magnetic arc control concepts such as those described in [3,4], directionally resolved optical sensing could provide the process-near position information required for closed-loop control of arc motion. However, to use this type of sensing for quantitative arc motion analysis and potentially for active arc control, the measured intensity distribution must be translated into a geometrically defined trajectory.

A method that allows quantitative reconstruction of arc motion while retaining low hardware complexity and enabling real-time evaluation is still lacking for process-near stud-welding applications. This limitation becomes particularly relevant under the short process durations and dynamically excited arc conditions characteristic of stud welding, where sensor systems must operate reliably under restricted optical access. A suitable reconstruction strategy must therefore provide a robust and consistent geometric description of arc motion from directionally resolved optical intensity signals across varying process conditions while remaining compatible with compact hardware and real-time evaluation.

This work presents an optical reconstruction method for the quantitative characterization of arc motion in stud welding. The proposed framework converts directionally resolved optical intensity signals into a two-dimensional position variable using a geometric centroid formulation. In this way, discrete directional intensity measurements are transformed into a continuous geometric representation of arc motion, enabling direction- and amplitude-resolved evaluation of arc dynamics. The implementation is based on eight directionally arranged photodiodes that capture the spatial intensity distribution of the arc with high temporal resolution. The eight-channel configuration provides uniform angular sampling at intervals of 45° and was selected as an engineering compromise between directional resolution, robustness against individual-channel disturbances, hardware complexity, and integration space. While the method does not yield absolute metric position measurements, it enables consistent assessment of directional characteristics, relative arc displacement, and the geometric distribution of arc motion throughout the welding process. The sensor architecture requires only limited hardware and produces comparatively little data. In combination with the proposed reconstruction method, this enables real-time analysis and facilitates integration into industrial stud welding equipment. The reconstruction results are validated by comparison with stereoscopic high-speed imaging reference measurements. The approach is evaluated experimentally for conventional direct-current stud welding, alternating-current stud welding, and stud welding with externally applied rotating magnetic fields for active arc motion control. These investigations demonstrate the robustness of the proposed method across different operating modes and highlight its suitability for actively controlled arc processes.

2. Materials and Methods

This section describes the experimental setup, the sensor arrangement, and the method used for reconstructing the arc position. First, the employed stud welding system is presented, including the integrated magnetic arc control system and the stereoscopic high-speed imaging used for validation. Subsequently, the operating principle of the optoelectronic sensor is described, and the geometric evaluation of the photodiode signals is derived. Finally, the validation concept is outlined.

2.1. Stud Welding System and Experimental Setup

The experimental investigations were conducted using a drawn-arc stud welding system. The setup was based on a direct-current stud welding inverter power supply (BMK-16i, Heinz Soyer Bolzenschweißtechnik GmbH, Wörthsee, Germany). To enable alternating-current operation, a full-bridge module was added to the inverter output and synchronized with a higher-level programmable logic controller (PLC) that controlled

the entire experimental setup. To deliberately influence the arc motion, a magnetic field system was integrated into the welding head. The system consists of four coils arranged concentrically with respect to the welding axis. It generates a rotating magnetic field of defined frequency, thereby enabling control of the rotation of the arc about the process axis. The relevant process parameters, in particular welding current, welding duration, and the rotational frequency of the magnetic field, were set via the PLC and kept constant throughout the experiments.

The optical diagnostic system used to detect the arc position is integrated into a compact process module that incorporates the shielding gas nozzle, an eight-element circular photodiode array, the magnetic field coil system, and the associated electrical and shielding gas connections. The process module can be mounted on different welding heads or welding guns. The photodiodes are arranged circumferentially around the process axis, as shown schematically in Figure 1. Photographs of the developed process module, including the integrated sensor and connector assembly, are shown in Figure 2. The photodiodes capture the radiation emitted by the arc from defined spatial directions relative to the process axis. The signals are digitized by the PLC at a sampling rate of up to 10 kHz and subsequently processed. This rate corresponds to the practical limit of the PLC-based acquisition system used in the present setup. For the magnetic field rotating at 500 Hz in the experiments, the sampling rate provides a temporal resolution of 0.1 ms, corresponding to 20 measurement points per rotation period. Since the aim of the analysis is to track the time-dependent position of the reconstructed arc centroid, rather than to resolve high-frequency plasma turbulence, this temporal resolution is sufficient to capture the relevant arc motion and to assess the resulting symmetry and stability of the trajectory. Faster local intensity fluctuations of the arc may still contribute to the residual variability of the reconstructed centroid. However, these fluctuations are not the target of the proposed trajectory reconstruction method, and their influence is reduced by the subsequent mean-value-based evaluation.

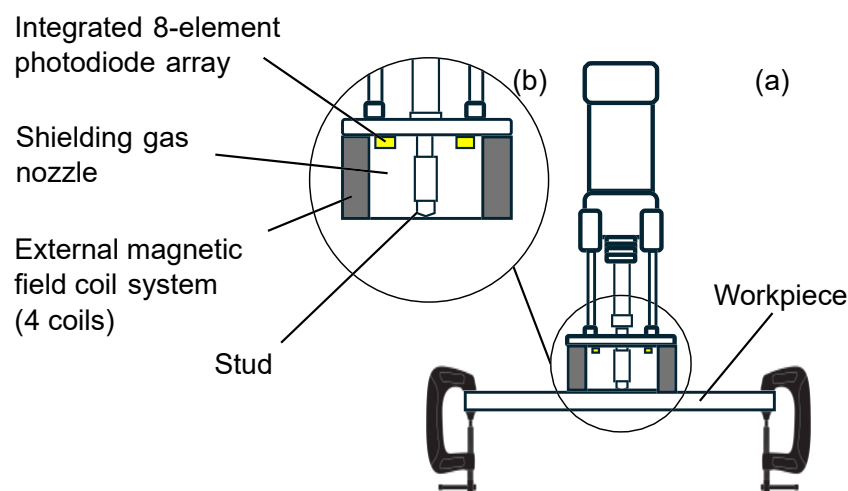


Figure 1. Experimental setup of the stud welding system: (a) Side view of the process module and workpiece, (b) Enlarged sectional view of the integrated eight-element photodiode array.

For validation of the reconstructed arc position, a stereoscopic high-speed camera system was used as an independent image-based reference measurement of the arc trajectory. The camera arrangement was based on the stereo imaging system described by Forster et al. [19] and is shown schematically in Figure 2c. In contrast to that study, however, the present work did not aim at a full three-dimensional reconstruction of the arc plasma. Instead, the evaluation was restricted to a single horizontal pixel line located between the stud and the workpiece in both camera views. For each image, the position of the intensity

maximum along this line was determined. The corresponding maxima from the left and right camera images were then matched to one another and triangulated, following the principle shown in Figure 3, to obtain the lateral arc position.

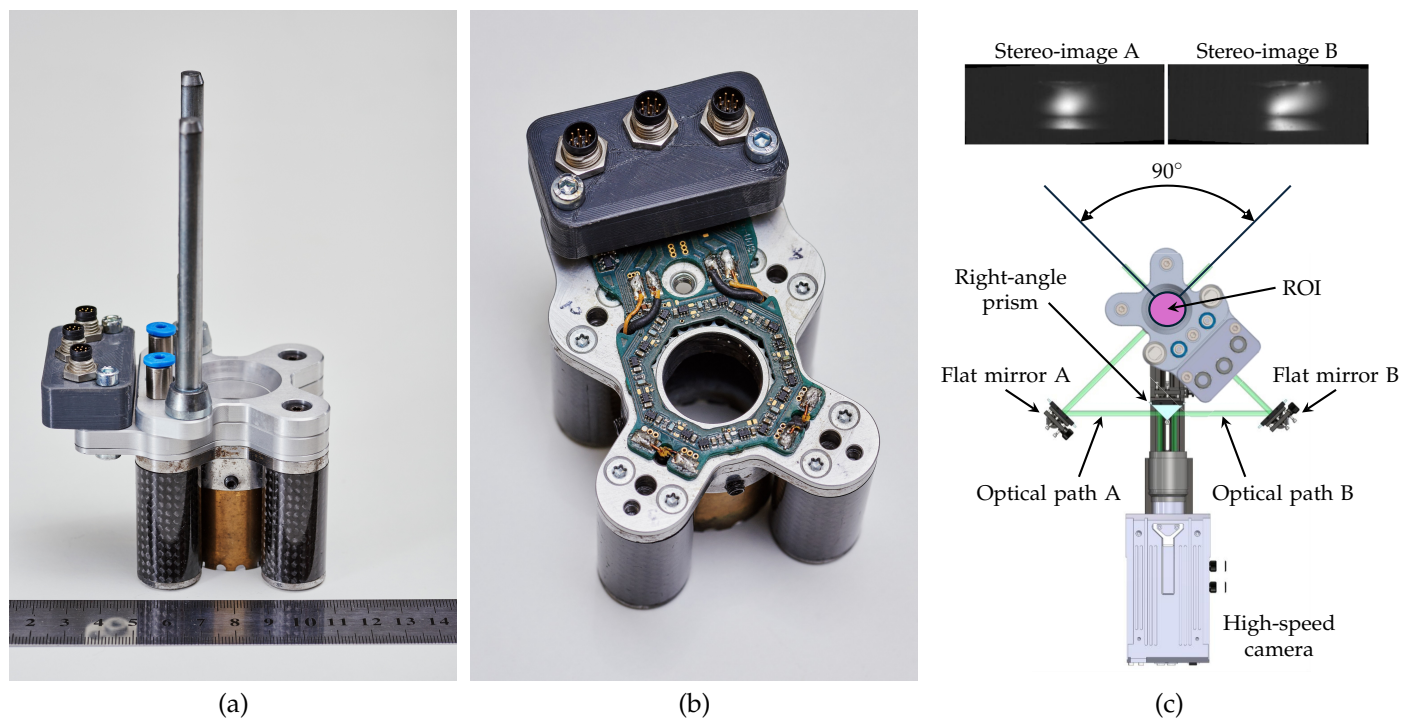


Figure 2. Photographs of the developed process module and schematic of the stereo-optical measurement setup: (a) side perspective view, (b) top view of the integrated photodiode sensor and connector assembly, (c) schematic of the stereo-optical high-speed camera setup.

The recorded high-speed camera data were scaled using the known stud diameter of 12.6 mm, determined from pixel-resolved measurements of single high-speed camera images of the welded stud after the welding process. Since the photodiode-based reconstruction provides relative positional information rather than absolute metric coordinates, the resulting photodiode trajectories were scaled to match the metric reference trajectory obtained from the stereoscopic camera measurements. Apart from this scaling, no further geometric corrections were applied. Accordingly, the validation focuses on the consistency of motion shape, symmetry, and directional characteristics rather than absolute metric accuracy.

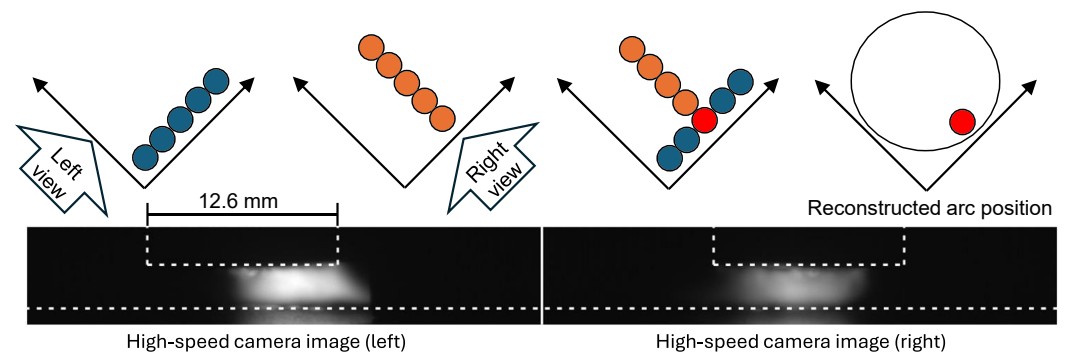


Figure 3. Principle of stereoscopic reconstruction of the arc position from corresponding image points in the left and right camera images. Metric scaling is based on the known stud diameter (12.6 mm).

2.2. Operating Principle of the Optoelectronic Sensor

The optical sensor system consists of an eight-element photodiode array arranged circumferentially around the process axis. The photodiodes are integrated into the shielding gas nozzle and positioned at uniform angular intervals of 45° . This configuration establishes a fixed geometric reference with respect to the welding axis. The sensors are indexed in a clockwise direction, starting at 90° relative to the positive x -axis, as shown in Figure 4.

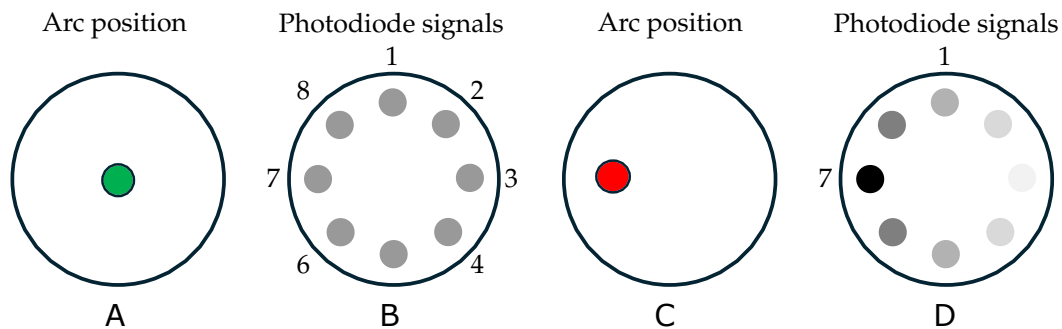


Figure 4. Principle of arc position detection using a circular photodiode array. The sensors are numbered clockwise starting from the top position. Darker sensor symbols correspond to higher light intensity. (A) Centered arc position marked in green. (B) Resulting symmetric spatial light intensity distribution. (C) Laterally displaced arc position marked in red. (D) Resulting asymmetric photodiode signal distribution, with the maximum signal intensity recorded by sensor 7.

Although a circular sensor arrangement with three uniformly spaced measurement directions represents the geometric minimum required to form a closed two-dimensional intensity polygon, such a configuration would provide only coarse directional sampling and would be highly sensitive to disturbances in individual channels. Eight uniformly distributed photodiodes provide full circumferential coverage and sufficient angular redundancy to reduce sensitivity to individual-channel disturbances, local shadowing, and intensity fluctuations in the arc. This configuration also keeps the required analog electronics, calibration effort, signal acquisition, and mechanical integration compatible with a compact process-integrated sensor system.

Each photodiode detects radiation emitted by the welding arc from a defined spatial direction. The resulting measurement signals represent a direction-dependent sampling of the spatial light intensity distribution within the welding zone. Owing to the circular geometry of the array and potential shadowing effects caused by the stud, any lateral displacement of the arc leads to asymmetric irradiation of opposing photodiodes. Figure 5 presents a cross-sectional view illustrating the fundamental sensing principle. A laterally displaced welding arc produces a non-uniform spatial intensity distribution, resulting in different signal levels in two opposing photodiodes. This asymmetry provides the basis for detecting and quantifying deviations of the arc position relative to the process axis.

The photodiode signals were acquired with temporal resolution and evaluated as relative intensity values. Before evaluation, the gain of each photodiode channel was calibrated using a homogeneous external light source to compensate for sensor-specific differences in sensitivity. The photodiode gain was adjusted so that the maximum process brightness under reference conditions, namely helium shielding gas, a welding current of 1000 A, and a lift height of 4.0 mm, could still be recorded without signal saturation. These gain settings were then kept constant for all measurements.

The measured photodiode signals were not calibrated to absolute radiometric units. Instead, the corrected signal amplitudes were used as relative direction-dependent intensity values L_i for the geometric reconstruction. Thus, L_i represents a relative sensor signal assigned to the angular position of the corresponding photodiode, rather than an absolute

radiometric quantity. No separate pre-normalization of the photodiode signals to the sum or maximum of all channels was applied prior to the centroid calculation, since the geometric centroid formulation itself provides a relative weighting of the direction-dependent intensity contributions.

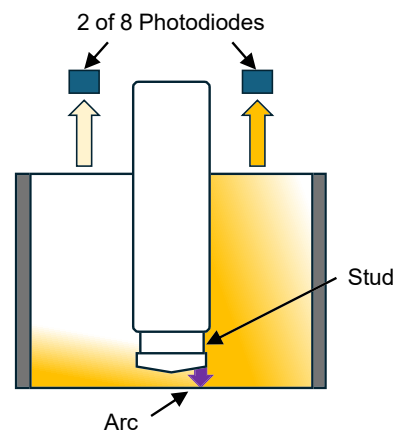


Figure 5. Arc displacement leads to an asymmetric spatial light distribution, causing the photodiode on the right side to detect a higher intensity than that on the left side.

Due to the optical intensity of the welding arc being much higher than that of the ambient illumination, background light contributions and photodiode dark currents had only a minor influence on the measured signals under the investigated experimental conditions and were therefore not compensated separately.

To estimate the practical detection limit of the reconstruction method, the reconstructed centroid trajectory was evaluated during the pilot-current phase over a period of 50 ms. During this phase, the arc was approximately centered on the welding axis at 80 A. The mean radial position fluctuation was approximately 0.21 mm. This value describes the residual fluctuations of the reconstructed position signal under comparatively stable arc conditions and therefore provides an estimate of the practical noise floor of the reconstruction method. It should be noted that this value does not represent purely electronic signal noise, but also includes residual arc-related intensity fluctuations.

2.3. Geometric Reconstruction Method

To quantitatively determine the arc position, the time-dependent photodiode signals are interpreted as direction-resolved intensity vectors. The magnitude of each vector corresponds to the relative signal intensity L_i , while its orientation is defined by the fixed angular position ϕ_i of the respective photodiode. Connecting the vector endpoints according to their circumferential sequence produces a polygonal representation of the direction-dependent intensity distribution, as illustrated in Figure 6.

More generally, for N photodiodes distributed uniformly around the process axis, the angular sampling interval is given by

$$\Delta\phi = \frac{360^\circ}{N}. \quad (1)$$

The angular position of sensor i can therefore be expressed as

$$\phi_i = \phi_0 + (i - 1)\Delta\phi, \quad i = 1, \dots, N, \quad (2)$$

where ϕ_0 defines the angular position of the first sensor. In the present configuration, $N = 8$, resulting in an angular sampling interval of 45° . Increasing N provides a finer discretization of the direction-dependent intensity distribution and increases the number

of vertices used to approximate its geometric shape. However, the resulting reconstruction accuracy is not determined by N alone. It also depends on the angular sensitivity of the photodiodes, channel calibration, signal-to-noise ratio, optical shadowing, and the spatial intensity distribution of the arc. The diameter of the sensor arrangement may also affect the mapping between angular intensity differences and reconstructed position error. Consequently, no universal analytical relationship between the number of photodiodes and the metric position error can be specified for the present centroid-based method.

For each sensor at the angular position ϕ_i , the Cartesian coordinates of the corresponding polygon vertices are given by

$$X_i = L_i \cos(\phi_i), \quad (3)$$

$$Y_i = L_i \sin(\phi_i), \quad (4)$$

where $i = 1, \dots, N$ denotes the sensor index. In the present system, $N = 8$. Connecting adjacent vertices results in an octagonal polygon that represents the direction-dependent intensity distribution. To close the polygon, cyclic indexing is used, such that $X_{N+1} = X_1$ and $Y_{N+1} = Y_1$.

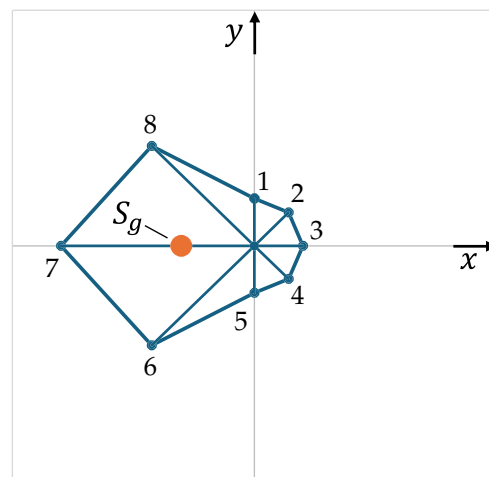


Figure 6. Geometric reconstruction principle based on the polygon formed by the direction-dependent intensity vectors of the eight-element photodiode array, with the photodiodes numbered in the figure. The length of the vector from the origin to each sensor index corresponds to the recorded signal intensity. With the process axis located at the origin, the centroid S_g of the polygon represents the reconstructed arc position in Cartesian coordinates.

The geometric centroid of the polygon is used as a representative measure of the arc position. For its calculation, the polygon is decomposed into triangular subareas, each spanned by two adjacent vertices and the coordinate origin. The centroid coordinates are obtained by area-weighted averaging according to

$$S_x = \frac{1}{3A} \sum_{i=1}^N (X_i + X_{i+1}) F_i, \quad (5)$$

$$S_y = \frac{1}{3A} \sum_{i=1}^N (Y_i + Y_{i+1}) F_i, \quad (6)$$

where F_i denotes the area of the respective subtriangle and

$$A = \sum_{i=1}^N F_i \quad (7)$$

represents the total area of the polygon.

The time-dependent centroid coordinates $x_S(t)$ and $y_S(t)$ describe the lateral arc position relative to the process axis. In addition, the associated angle

$$\varphi(t) = \text{atan2}(y_S(t), x_S(t)) \quad (8)$$

can be determined to quantify the instantaneous directional deviation. Here, atan2 denotes the four-quadrant inverse tangent function, yielding angular values over the full angular range from 0° to 360° .

Alternative formulations, including simple arithmetic averaging of the vector end-points and related centroid-based evaluations of photodiode signals reported in the literature [17], were considered for arc position reconstruction. However, such formulations do not explicitly account for the geometric shape of the resulting intensity distribution, which may limit their ability to provide a consistently robust representation across a broad range of arc motion patterns. This aspect is particularly important in the context of actively influenced arc motion, where the reconstruction must remain geometrically consistent under varying intensity distributions. The area-weighted centroid of the polygon introduced above was therefore adopted as the reconstruction method for the following analysis.

2.4. Determination of Relative Position Deviation

To illustrate the reconstructed arc motion, Figure 7 shows a representative temporal evolution of the centroid coordinates $x_S(t)$, $y_S(t)$, and the associated angle $\varphi(t)$.

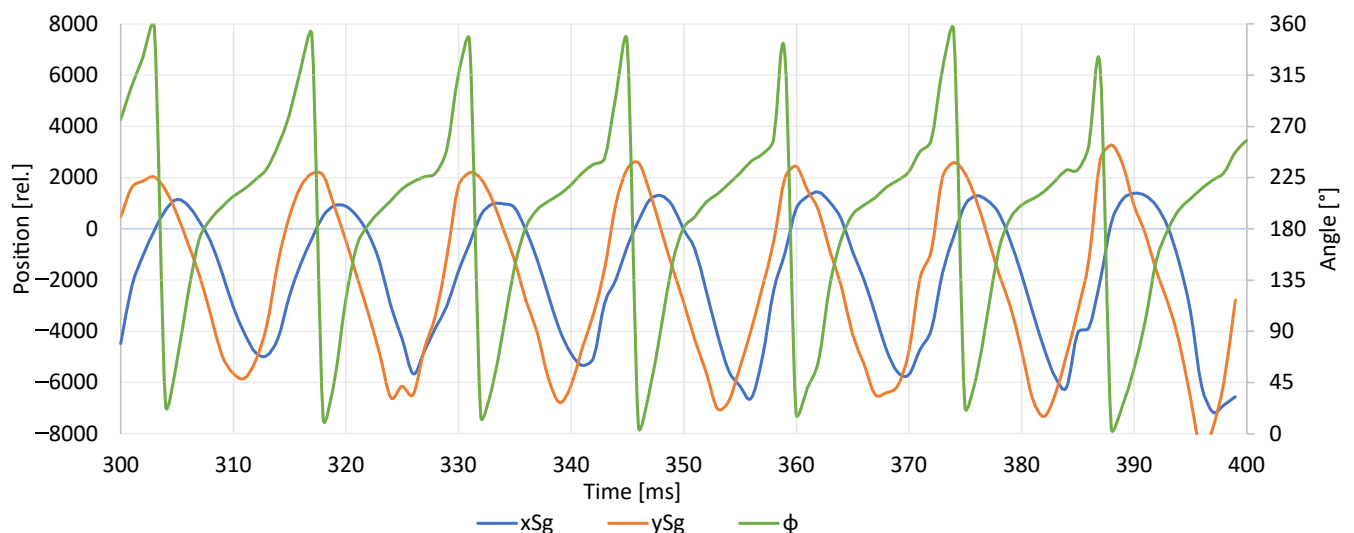


Figure 7. Time evolution of the reconstructed centroid coordinates $x_S(t)$ and $y_S(t)$ together with the corresponding angular position $\varphi(t)$ during excitation of the arc by a rotating magnetic field. Deviations from ideal sinusoidal and triangular waveforms indicate a non-centered and non-ideal rotational arc motion.

The presented dataset was acquired under magnetic excitation by an externally applied rotating magnetic field, allowing the arc position to evolve freely without active control. The periodic structure of the motion is clearly observable. Both $x_S(t)$ and $y_S(t)$ exhibit approximately sinusoidal waveforms. At the same time, both signals show a shifted mean

value, indicating an eccentric rotation of the arc. For an ideal uniform circular motion, the angular trajectory $\varphi(t)$ would exhibit a sawtooth-like progression. Such behavior is not observed in the present case. Instead, the measured $\varphi(t)$ deviates from the expected linear increase, indicating a non-centered and geometrically distorted rotational motion.

For further analysis, the same dataset is presented in Figure 8 using two different visualization approaches. Figure 8a shows the time-discrete photodiode signals as polygons in the sensor coordinate system. Each polygon corresponds to a single sampling instant and represents the direction-dependent intensity distribution. Figure 8b depicts the corresponding trajectory of the geometric centroid in the Cartesian coordinate system. In contrast to the polygon-based visualization, this representation enables a direct geometric assessment of the rotational center and the eccentricity of the motion. Both visualizations are derived from identical measurement data.

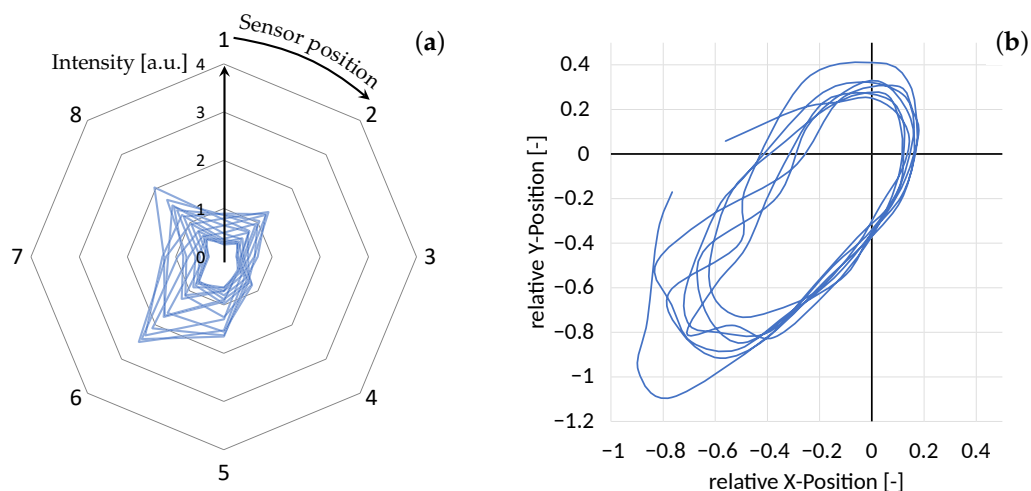


Figure 8. (a) Radar representation of direction-dependent photodiode intensities at exemplary time instants within one rotation period. Although asymmetries are qualitatively visible, a direct geometric interpretation of the arc motion remains limited. (b) Reconstructed arc trajectory in the Cartesian coordinate system based on the geometric centroid method. The elliptical shape and the offset from the origin reveal a non-centered and non-ideal rotational motion of the arc.

2.5. Validation Procedure

To verify the geometric consistency of the reconstructed arc position, the proposed method was compared with stereoscopic high-speed camera measurements [20], which provide a geometrically resolved reference trajectory of the arc motion. As described in Section 2.1, the high-speed camera data were converted to metric scale using the known stud diameter of 12.6 mm, and the photodiode trajectories were subsequently scaled to the resulting stereoscopic reference. The validation therefore focuses on agreement in trajectory shape, symmetry, and directional characteristics rather than on absolute metric accuracy.

The comparison was performed for two representative magnetically induced motion types under active position control: rotational arc motion and directed oscillatory arc motion. These cases were selected to evaluate whether the reconstruction method captures both circular trajectories with an eccentric rotational center and non-circular trajectories with pronounced directional reversals. The control strategy itself is not discussed here, as the focus of the present work is the validation of the optical reconstruction of the arc position. For each measurement, the comparison was based on signal sections with a duration of 50 ms, starting 20 ms after the onset of the main welding current phase. Agreement between the reconstructed and reference trajectories was quantified using

Pearson correlation coefficients for the time-dependent x - and y -components, together with the mean Euclidean deviation between both trajectories.

First, both trajectories were centered around their respective centroids. This allowed the relative arc motion to be compared independently of global position offsets between the measurement systems. Subsequently, the mean diameter of the high-speed reference trajectory was determined. This diameter was defined as twice the mean radial distance of all trajectory points from the centroid of the corresponding high-speed reference trajectory. Since the photodiode-based reconstruction provides the arc motion on a relative spatial scale rather than directly in the physical coordinate scale of the high-speed camera, spatial scaling was required before calculating Euclidean deviations between both trajectories. The scaling therefore served as a fixed calibration step and was not optimized individually for each measurement. For the rotational motions, the scaling factor was determined from the first reference measurement and then kept constant for all subsequent rotational measurements. Similarly, a separate scaling factor was determined for the oscillatory motions and was used unchanged for all oscillation measurements. The mean Euclidean deviation therefore primarily describes the remaining geometric difference in trajectory shape rather than an absolute positional offset between both measurement systems. The resulting mean Euclidean deviation was additionally normalized by the mean diameter of the reference trajectory obtained from the high-speed recordings. This expresses the reconstruction error relative to the characteristic spatial extent of the arc motion.

The results of the quantitative validation are summarized in Table 1. For the investigated rotational motions, the mean Pearson correlation coefficients were $r_x = 0.974 \pm 0.005$ and $r_y = 0.986 \pm 0.004$. The mean Euclidean deviation was 0.59 ± 0.10 mm, corresponding to a relative mean deviation of approximately $10.4 \pm 1.8\%$ of the mean high-speed reference trajectory diameter. The investigated oscillatory motions also showed good agreement between the reconstructed and camera-based trajectories. The mean Pearson correlation coefficients were $r_x = 0.911 \pm 0.073$ and $r_y = 0.927 \pm 0.084$. The mean Euclidean deviation was 1.70 ± 0.05 mm, corresponding to a relative mean deviation of approximately $12.9 \pm 0.7\%$. The lower correlation coefficients compared with the rotational motions can mainly be attributed to the low variance of the orthogonal signal component in directed oscillatory motion.

Representative examples from the validation data are shown in Figures 9 and 10. The reconstructed trajectories shown in these figures were visually scaled for qualitative comparison, but were not centered around their centroids. They therefore retain the original relative position of the reconstructed motion with respect to the high-speed reference trajectory. Figure 9 shows the rotational case used to determine the fixed scaling factor for the rotational measurements. The reconstructed trajectory captures both the circular motion pattern and the eccentric position of the rotational center. Local deviations of individual points are visible, but they do not substantially affect the overall geometric structure.

Figure 10 shows a representative oscillatory trajectory from the corresponding validation set. The reconstructed trajectory captures both dominant end positions and the transition path between them, indicating that non-circular motion patterns and changes in direction are also resolved by the reconstruction method.

Table 1. Quantitative validation results for the reconstructed arc trajectories. Here, r_x and r_y denote the Pearson correlation coefficients of the time-dependent x - and y -components, d_{HS} is the mean diameter of the high-speed reference trajectory, $\overline{\Delta r}$ is the mean Euclidean deviation, and $\overline{\Delta r}_{rel}$ is the relative mean deviation normalized by d_{HS} .

No.	Motion	r_x	r_y	d_{HS} [mm]	$\overline{\Delta r}$ [mm]	$\overline{\Delta r}_{rel}$ [%]
1	Rotation	0.970	0.979	5.26	0.58	11.0
2	Rotation	0.980	0.988	5.38	0.43	8.1
3	Rotation	0.973	0.987	5.29	0.49	9.2
4	Rotation	0.977	0.983	5.55	0.65	11.7
5	Rotation	0.977	0.986	5.63	0.66	11.8
6	Rotation	0.967	0.989	5.39	0.60	11.1
7	Rotation	0.966	0.986	5.71	0.69	12.1
8	Rotation	0.978	0.990	6.49	0.52	8.0
9	Rotation	0.978	0.991	6.16	0.53	8.5
10	Rotation	0.973	0.985	6.08	0.77	12.6
Mean		0.974	0.986	5.694	0.59	10.4
Std. dev.		0.005	0.004	0.417	0.10	1.8
11	Oscillation	0.974	0.803	13.23	1.66	12.5
12	Oscillation	0.974	0.951	13.63	1.67	12.2
13	Oscillation	0.842	0.975	13.08	1.77	13.6
14	Oscillation	0.852	0.979	12.85	1.71	13.3
Mean		0.911	0.927	13.198	1.70	12.9
Std. dev.		0.073	0.084	0.328	0.05	0.7

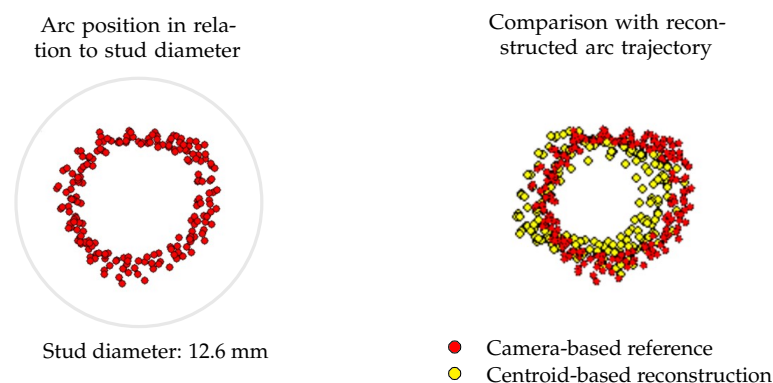


Figure 9. Validation of the reconstructed arc position during magnetically driven arc rotation with active position control. High-speed camera reference data are shown on the left (red dots), and the corresponding reconstruction on the right (yellow dots).

Together, the quantitative values in Table 1 and the representative trajectory comparisons in Figures 9 and 10 show that the proposed reconstruction method captures both rotational and oscillatory arc motion with consistent geometric agreement. The results support the suitability of the area-weighted centroid approach for direction-resolved analysis of dynamic arc behavior.

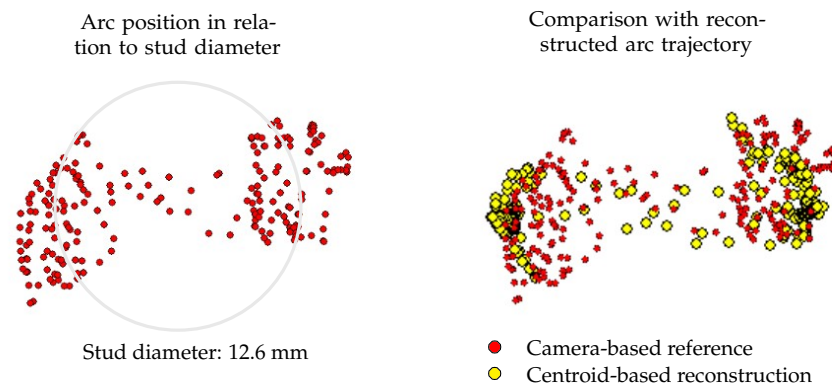


Figure 10. Comparison of high-speed camera reference data (red dots) and reconstructed arc position (yellow dots) for magnetically driven oscillatory arc motion.

3. Results

In this section, deliberately defined process states with expected characteristic arc motions are examined to assess the plausibility of the proposed arc trajectory reconstruction method. These include arc deflection caused by asymmetric current paths, rotation induced by an externally applied magnetic field, and transient displacements during polarity reversal under alternating-current (AC) welding. The resulting three-dimensional trajectories, in which temporal evolution is mapped along the vertical axis, serve as validation cases for evaluating whether the reconstructed arc position reproduces physically consistent motion patterns. This space–time representation combines spatial displacement and temporal progression in a single visualization, making motion patterns such as rotation, drift, and transient deviations easier to identify.

3.1. DC Welding—Influence of the Magnetic Rotating Field and Control

Figure 11 presents three representative DC welding processes under identical geometric boundary conditions. The experiments were conducted with a welding current of 600 A and a welding duration of 300 ms. When magnetic excitation was applied, the rotating magnetic field frequency was set to 500 Hz. In all cases, the ground connection is positioned on the right-hand side. The reconstructed arc trajectories are used to assess the plausibility of the position reconstruction under defined electromagnetic influences.

Figure 11a shows the reference case without an external magnetic field. The reconstructed trajectory exhibits a clear lateral deflection to the left. This behavior corresponds to the expected arc blow resulting from the asymmetric current path caused by the right-sided ground connection. The reconstruction therefore reproduces a physically plausible drift of the arc. When an external rotating magnetic field is applied (Figure 11b), the induced rotational component superimposes the previously dominant lateral drift. The reconstructed trajectory shows a rotational motion while a reduced asymmetry remains visible. This behavior is consistent with the physical expectation for the superposition of arc blow and magnetic excitation. With position control activated (Figure 11c), the lateral arc blow is largely compensated. The reconstructed arc trajectory exhibits a significantly more symmetric and stabilized pattern. The previously observed drift is reduced, and the motion is centered around the process axis.

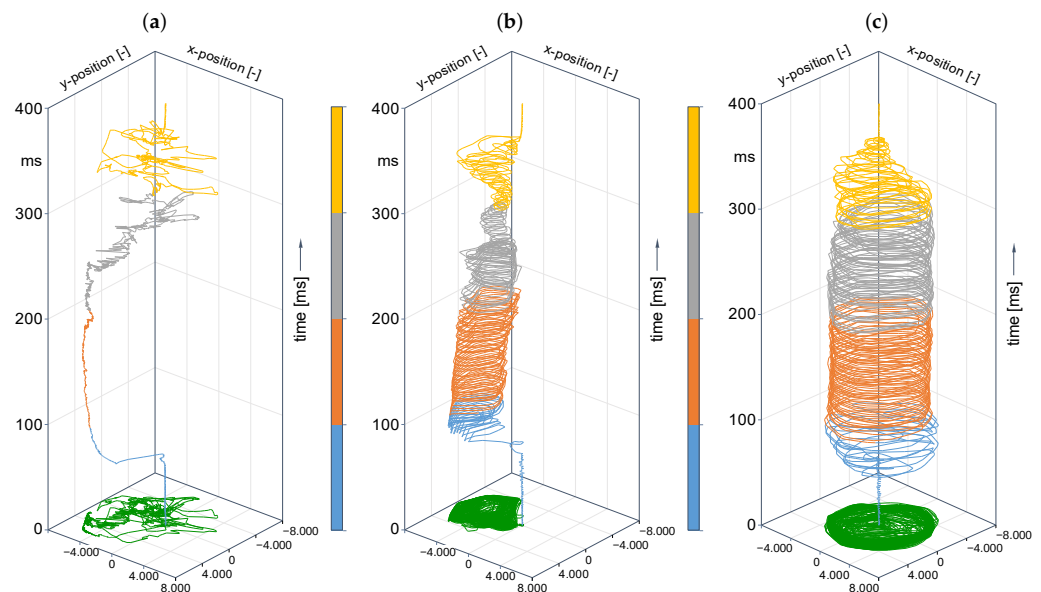


Figure 11. Influence of the rotating magnetic field and position control on the reconstructed arc trajectory under DC welding conditions. (a) DC welding without an external magnetic field. (b) DC welding with an externally applied rotating magnetic field. (c) DC welding with a rotating magnetic field and active position control. Color coding indicates the temporal progression along the spatial trajectory over the entire welding duration, with each color step representing 100 ms.

The differences between the three process states are consistent with the expected physical effects and confirm the consistency of the position reconstruction under DC welding conditions.

3.2. AC Welding—Influence of Polarity Reversal

The AC welding experiments were performed with a welding current of 600 A and a welding duration of 400 ms. The rotating magnetic field frequency was again set to 500 Hz. Under AC conditions, the arc is influenced by periodic current polarity reversals that introduce short transient disturbances in the immediate vicinity of each polarity change. These effects impose increased demands on the temporal resolution and geometric consistency of the reconstruction. The observed arc motion results from the superposition of intrinsic arc dynamics, transient deflections during polarity reversal, and rotational motion induced by the externally applied magnetic field, on which active position control can be implemented.

Figure 12 shows the reconstructed arc trajectory for an AC welding process with an externally applied rotating magnetic field and active position control, including a total of eight polarity reversals. The overall rotational motion remains clearly visible. Superimposed on this motion, short periodic lateral deviations occur at each polarity reversal. These transient positional changes are particularly evident in the projections onto the x - t and y - t planes.

The reproducible occurrence of these deviations at each polarity reversal indicates that the reconstruction captures not only stationary or quasi-stationary motion components but also rapid dynamic effects with sufficient temporal resolution. These results further confirm that the reconstruction provides a geometrically consistent representation of the arc position while resolving rapid dynamic effects under AC welding conditions.

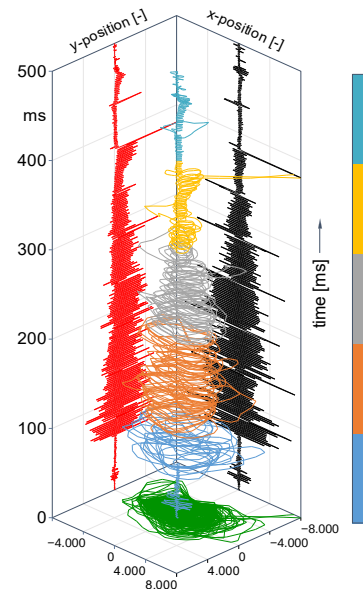


Figure 12. Reconstructed arc trajectory under AC welding conditions with an externally applied magnetic field and active position control. Color coding indicates the temporal progression along the trajectory, with each color step representing 100 ms. The projections onto the x-t and y-t planes reveal short transient lateral deviations occurring at polarity reversal.

4. Discussion

The experimental results show that the photodiode-based reconstruction method yields reproducible and physically plausible position signals under realistic welding conditions. In particular, the method enables reliable reconstruction of relative positional deviations with low experimental complexity, making it well suited for real-time, process-integrated applications. On this basis, the following discussion addresses the interpretation of the scaling procedure, the robustness of the reconstruction approach with respect to varying process conditions, potential error sources and optical disturbances as well as the applicability of the method beyond the investigated process window.

For the intended application, absolute metric position information is not necessarily required. The reconstruction method primarily provides direction-resolved relative positional information with respect to the process symmetry axis. This information is sufficient to detect asymmetric arc displacement and can therefore be used to restore or maintain a symmetric energy distribution during the welding process. A metric scaling factor is therefore not required for operating the photodiode-based system, but was introduced only for the quantitative validation against the high-speed-camera reference trajectories, where the relative photodiode reconstruction and the metric camera reference had to be compared on a common spatial scale. Accordingly, the scaling factor introduced in Section 2.5 should not be interpreted as a direct physical system parameter or a purely geometric quantity, but as a validation-specific comparison factor.

The reconstruction method proposed in this study was investigated for a stud diameter of 12.6 mm and a welding current of 600 A. This parameter combination was selected as a representative process condition for demonstrating the feasibility of the photodiode-based reconstruction principle. Within this process window, different operating states were examined, including variations in welding current polarity and the effect of an external magnetic field on arc motion. These cases consistently showed reproducible trajectory reconstruction. Together with the quantified deviations from the high-speed-camera reference trajectories and the estimated practical noise floor of the reconstructed centroid signal, these results support the method as a proof of concept.

The achievable reconstruction accuracy further depends on process stability. The results showed that the proposed method was capable of reliably tracking dynamic arc motion under normal process-related fluctuations. By varying the externally applied magnetic field strength, different arc displacement amplitudes, ranging from small to pronounced deflections, were generated and successfully reconstructed. This indicates that the reconstruction method is applicable over a broad range of arc displacement amplitudes within the investigated process window. However, severe process instabilities, such as persistent droplet short circuits, excessive arc blow, or pronounced degradation of the arc geometry, may alter the measured intensity distribution to an extent that reduces the accuracy of the reconstructed arc position. Reliable position reconstruction therefore requires that the welding process is operated within an appropriate process window using suitable welding parameters and boundary conditions.

The number of photodiodes influences the angular sampling and geometric discretization of the measured intensity distribution, as given by Equation (1). A larger number of measurement directions can generally provide a finer representation of the spatial intensity distribution and may reduce the relative influence of disturbances affecting individual channels. However, the resulting reconstruction accuracy cannot be described solely as a function of the number of photodiodes, as discussed in Section 2.3. The chosen arrangement represented the optimal compromise between the highest achievable directional sampling resolution and the installation space available for integration. Different sensor counts or different angular arrangements may lead to different reconstruction performance and accuracy. A systematic investigation of sensor count and angular arrangement, combined with stereoscopic reference measurements, would require a dedicated study and is therefore beyond the scope of this paper.

Despite this, the reconstruction principle itself is not restricted to the investigated stud diameter, welding current, or eight-channel sensor geometry, since it is based on direction-resolved relative intensity differences rather than on absolute radiometric values. Even though other stud diameters than 12.6 mm were not examined, and the quantitative performance of the method across different stud diameters remains to be investigated, the estimated practical detection limit of approximately 0.21 mm suggests that the method should be sufficiently sensitive to resolve arc movement even for smaller diameter studs. Changes in stud diameter may modify the measured intensity distribution owing to altered optical shadowing and viewing conditions. Depending on the stud diameter, these effects may require adjustments to the sensor sensitivity and may influence the reconstruction performance. Thus, the application of the proposed method to other stud diameters or welding currents is considered feasible, provided that the photodiode signals remain within the usable dynamic range and saturation effects are avoided. For this purpose, the gain settings may need to be adapted to the expected process brightness. Changes in process conditions, such as arc length, current level, shielding gas composition, or magnetic excitation, may affect the absolute emission intensity and the spatial intensity distribution of the arc. However, as long as the resulting direction-resolved intensity distribution remains physically consistent and sufficiently resolved by the photodiode array, the qualitative reconstruction of relative arc displacement and trajectory shape is expected to remain applicable.

The centroid-based reconstruction method exhibits a finite sensitivity to measurement noise, since random fluctuations in the photodiode signals directly affect the estimated intensity centroid. However, under a sufficiently high signal-to-noise ratio and stable calibration, the method remained robust, as uncorrelated noise is partially averaged across the distributed sensor channels. External influences such as contamination of the optical access regions may asymmetrically distort the measured intensity distribution. Nevertheless,

experimental investigations involving several thousand test welds showed that relevant sensor-related impairments occurred only under unstable process conditions. A strongly asymmetric or inconsistent distribution of the measured intensities—for example, simultaneously high signal amplitudes at non-adjacent photodiodes combined with markedly reduced signals at the intermediate sensors—is physically implausible, since arc emission inherently forms a spatially coherent intensity distribution. Such patterns can therefore be interpreted as indications of sensor malfunction or contamination and may serve as the basis for plausibility checks during operation. As a result, the proposed reconstruction method provides a basis for identifying certain classes of sensor disturbances when implemented with the photodiode-based sensor system.

Beyond the detection of implausible intensity patterns during disturbed operation, the process itself may also provide a suitable reference state for sensor self-monitoring. Immediately after arc ignition, during the pilot-current phase, the arc is approximately centered at reduced welding current, so that a symmetric intensity distribution is expected. Systematic deviations from such a plausible symmetric signal pattern could therefore, in principle, be interpreted as indications of an impaired or faulty photodiode. This relationship provides a potential basis for condition-based self-checking of the sensor system without additional hardware.

5. Conclusions and Outlook

The proposed optical reconstruction method enables direction-resolved quantitative characterization of arc motion in stud welding based on photodiode intensity signals. Using a geometric centroid formulation, the measured spatial intensity distribution is converted into a continuous two-dimensional representation of relative arc motion. The method thereby provides information on the direction and relative magnitude of arc displacement with low hardware and computational complexity. The main conclusions are summarized as follows:

- The proposed method resolved the direction and relative magnitude of arc displacement under conventional direct-current, alternating-current, and magnetically influenced welding conditions. Characteristic rotational and oscillatory motion patterns were reconstructed consistently.
- Validation against stereoscopic high-speed camera measurements showed good geometric agreement. For rotational arc motion, mean Pearson correlation coefficients of $r_x = 0.974$ and $r_y = 0.986$ were obtained, together with a mean Euclidean deviation of 0.59 mm, corresponding to 10.4% of the mean reference trajectory diameter. For oscillatory motion, the mean Euclidean deviation was 1.70 mm, corresponding to 12.9%.
- Evaluation during the pilot-current phase yielded a mean radial position fluctuation of approximately 0.21 mm. This value provides an estimate of the practical detection limit under comparatively stable arc conditions and includes both sensor-related and residual arc-related fluctuations.
- The experimental results showed that the proposed reconstruction method can handle process-related fluctuations, provided that the welding process is operated within an appropriate process window with suitable welding parameters and boundary conditions.
- Optical contamination or strongly unstable process conditions may produce implausible signal intensity patterns, which can in turn be used for plausibility checks during operation.
- Based on the limitation analysis, the system is expected to be applicable to other stud diameters or welding currents. This, however, remains to be investigated and experimentally validated.

- The reconstructed arc trajectories indicate the potential of the approach for process-integrated monitoring under restricted optical access and real-time processing constraints occurring during stud welding.

A broader assessment of the industrial applicability of the proposed photodiode system and reconstruction method requires further investigation. In particular, the effects of position-controlled arc guidance on weld quality, the metallurgical properties of the joint, and process stability under varying boundary conditions need to be analyzed in greater detail. Future work will therefore focus on developing dedicated arc position control strategies and assessing their effect on weld formation, joint properties, and overall process behavior. Beyond position reconstruction and closed-loop welding control, the sensor concept could also be extended by multispectral or spectrally selective detection to extract additional information on arc and process conditions from the optical emission, as demonstrated more generally by optical diagnostic approaches reported in the literature [21,22].

Author Contributions: Conceptualization, A.W.J.; methodology, A.W.J.; software, A.W.J.; validation, A.W.J. and M.J.S.; formal analysis, A.W.J.; investigation, A.W.J. and M.J.S.; resources, A.W.J. and J.S.; data curation, A.W.J.; writing—original draft preparation, A.W.J.; writing—review and editing, M.J.S. and J.S.; visualization, A.W.J.; supervision, J.S.; project administration, A.W.J.; funding acquisition, A.W.J. and J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Bayerische Forschungsförderung (BFS) under grant numbers AZ-1363-18 and AZ-959-11.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author. The data are not publicly available due to industrial confidentiality.

Acknowledgments: The authors acknowledge the technical collaboration and support of Heinz Soyer Bolzenschweißtechnik GmbH and GSI—Gesellschaft für Schweißtechnik International mbH, SLV München, within the funded research project AZ-1363-18. The publication of this manuscript was financially supported by Universität der Bundeswehr München.

Conflicts of Interest: The corresponding author is employed by Heinz Soyer Bolzenschweißtechnik GmbH. The study was conducted within a publicly funded research project. The company provided technical collaboration/support but had no role in the design of the study, data collection, analysis, interpretation, or decision to publish.

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