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Online vision-based inspection system for thermoplastic hot plate welding in window frame manufacturing

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Abstract

Current manual quality control processes in continuous production environments are limited in impact and reliability. An online automatic inspection system is proposed to generate quality-oriented information regarding the welding of frames in window manufacturing. Using novel edge detection techniques and the Hough transform, a novel algorithm is presented to accurately estimate in real-time welding angles and the overall squareness of the window frame. The inspection system presented is integrated in an automated four-point welding machine and provides decision support to quality control operators regarding the conformity of welded frames. The system is validated in a real scenario and the proposed algorithm estimates welding angles and overall frame squareness with an accuracy of 98.38%, indicating an average error less than 0.8 degrees.

Keywords: inspection system; machine vision; thermoplastic welding; hot plate welding; window manufacturing.

1. Introduction

1.1. Background

Hot plate welding is one of the simplest welding techniques available and is a commonly used technology in industrial environments to fuse certain thermoplastic components together in mass production environments [1]. Hot plate welding can be used for joining all thermoplastics and thermoplastic elastomers whose melting temperature range lies below their decomposition temperature. In window manufacturing, such technology has been adopted to enable the transition from metallic, i.e. aluminum or steel, to hard plastic frames. Thermoplastic polymers are interesting materials for window manufacturers because of their particular physical properties, e.g., light weight, better thermal insulation, flexibility, good fatigue resistance, and high fracture toughness [2].

In most industrial setups, hot plate welding is an automated sequential manufacturing process. It can be divided in 4 phases: squaring, heating, welding, and cooling. Initially, the window profiles are manually or automatically loaded onto the welder, where clamps will secure the placement of the window profiles previous to any irreversible process. Then, the heated plate advances and the window profiles are pushed towards the hot plate. The surface of the window profiles that is in contact with the hot plate melts in a few seconds, creating a small layer (few millimeters deep) of fluid thermoplastic material. Finally, the hot plate is removed and both melted surfaces are pressed against each other. Maintaining the pressure over the profiles for a few seconds secures the welding process and to ensure a lasting weld performance the weld is left to cool down for around a minute. The stages of the hot welding process are illustrated in Figure 1 and further details on this process can be found in the literature [3].

The welding process has a significant impact on the

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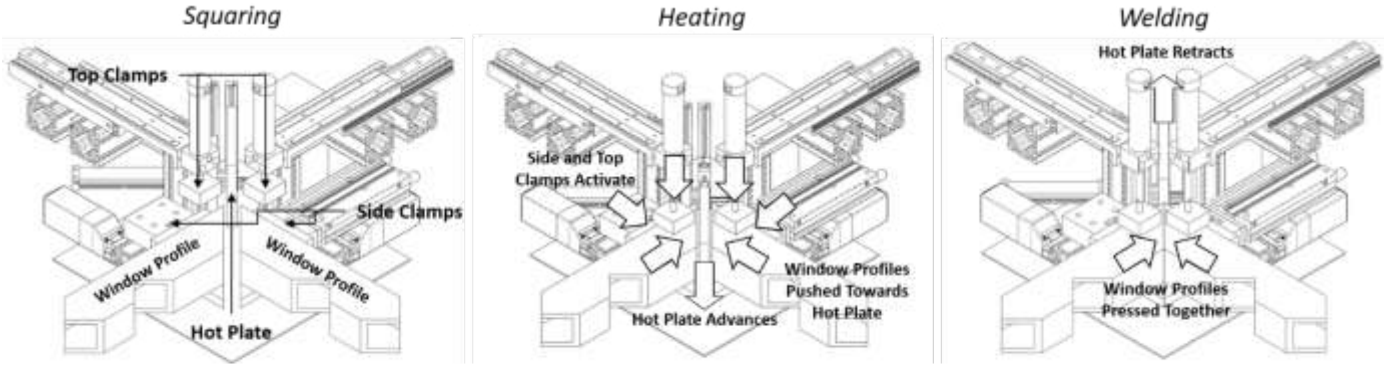

Figure 1. Automated hot plate welding process illustration.

manufacturing quality and final thermal performance. At this stage, manufacturing quality relates to two main frame characteristics: weld strength and frame squareness. Machine related and environmental parameters, such as hot plate temperature, air humidity and temperature, cooling time, and clamping force and time, have reported effects on the final weld strength and frame squareness [4]. Due to the variability and complexity of the design of window frame profiles, a reliable inspection is necessary to ensure the quality of the manufacturing process.

Despite its importance, the inspection of window frames is currently a manual process, relying on operator experience and visual inspection. In some cases, the weld strength is tested on randomly selected welded parts using destructive testing procedures, with their associated drawbacks. Nonetheless, results may give insight into potential maintenance issues or base product deficiencies [5]. Currently, a randomly selected window frame is tested from a 100-unit batch. If the tested frame does not achieve the minimum weld strength required by quality standards, then the whole batch is isolated for further analysis. Otherwise, the batch continues its manufacturing process. However, this testing approach does not provide real-time information regarding the quality of each window frame and is susceptible to false positives and false negatives, and further action to correct detected deficiencies in the manufacturing process increases overhead costs for the production line.

To apply an Industry 4.0 approach to the problem, an online automatic vision-based inspection system for thermoplastic hot plate welding of window frames is proposed in this study. The aim of this system is twofold: to provide quality-oriented results for each manufactured window frame in real-time, which facilitates decision-making by quality control operators on a case-by-case basis; and to continuously generate quality-oriented data that can be analyzed afterwards using data mining or artificial intelligence techniques to optimize the manufacturing process from a quality perspective.

1.2. Literature review

Thermoplastic welding joints have been researched thoroughly and numerous publications aim to model welding as a multi-input multi-output process [6]. Different types of welding processes for joining thermoplastic components are available, i.e., friction welding or ultrasonic welding; however, hot plate welding has proved to be the most reliable for hard thermoplastics, such as polyvinyl chloride (PVC). However, little research exists on the inspection of thermoplastic welding, given that the literature is found to focus heavily on metallic alloys. Existing inspection systems for plastic parts focus on surface defect detection. The automatic detection and control of surface defects was researched recently, aiming to ensure surface and aesthetic quality of plastic products [7]. In window frames, however, the potential inspection system has to consider structural and welding performance parameters, as the frame supports all the components of the window in later stages. Therefore, a robust inspection system is investigated herein to finally support mitigate defects in window frames to optimize resource usage and reduce unnecessary risks.

Automated online product inspection is currently a requirement for most manufacturing processes, especially when real-time communication and connectivity are the mainstays of an Industry 4.0 approach [8]. Computer vision has been adopted globally as the preferred approach to solve such challenges [9]. In welding processes, non-destructive vision-based online inspection has been developed to measure and detect external defects in real-time [10], [11]. Recent works use different visual sensors, such as cameras or lasers, to provide feedback on the post-manufacturing state of the welded part. Subsequently, monitoring of weld quality in an industrial environment was achieved [12]. Results reported high accuracy measurements of weld dimensions and identification of defects associated with a robotic welding process, such as plate displacement and undercut welds.

Whereas most literature on welding defect inspection focuses on the weld area (weld seam), hot plate welding applies external forces during the weld phase that may cause defects outside the weld area. For window manufacturing, these applied forces may introduce deviations in the overall frame squareness and local angle connection. These deviations have been the source of issues in later stages of the window manufacturing process, especially during the glass installation. An unsquared frame causes increased glass stress and cracks occur during installation, causing unnecessary physical strain on operators and potential risks due to breaking glass [13].

2. Inspection system

The inspection system presented in this study aims to inspect the final state of the welding joint and final squareness of the window frame during/after the cooling down phase is finished. The workflow of the proposed system begins by obtaining visual data from each corner of the frame, where the weld seam is located, as illustrated in Figure 2. As the welding process occurs on all the corners of the frame simultaneously, four short range Basler ACE cameras with Optron 35 mm lenses are installed to obtain the required images. Each camera is mounted on the edge of the welding carriage, around 0.5 meters above the weld area, and provides a close view after the process has finished. The capture of the images is user triggered.

Figure 2. Illustration of the proposed inspection system on a VSM Sturtz four-point automated welding machine.

Then, the images are processed to obtain the relevant information regarding the quality of the weld on the window frame, namely the weld seam angle and the squareness of the frame. The presented inspection system is a novel algorithm based on well-known image processing techniques, such as edge detectors, blurring filters, or the Hough transform. Such techniques have already been proven successful to provide highly accurate measurements for inspection processes for different industry sectors, from steel [14] to bottle [15] manufacturers. Finally, the inspection results determine the conformity of the recently welded window frame and communicate the decision to support quality control decision making of the operators. The following subsections will explain further each sub-process of the inspection system.

2.1. Image processing

For each one of the images, the same image processing algorithm is used, no matter the orientation of the window corner weld. To identify the angles that define the final weld quality, several steps are needed to process the image. Step (1): The original image is undistorted using the intrinsic camera matrix obtained by standard camera calibration [16]. Step (2): Gaussian blurring is used to remove unwanted edges (noise) that could be generated from the background afterwards. Step (3): The automatic threshold Canny edge detector is then applied to obtain a mask with the most relevant edges in the image [17]. Step (4): Hough transform is applied over the binary mask to obtain the parametric lines that are defined by the detected edges, following Equation (1) below.

$$L(\rho,\theta) \coloneqq \begin{cases} \rho = \sqrt{x^2+y^2} \\ \theta = \tan^{-1}(\frac{y}{x}) \end{cases} \qquad (1)$$

where $L(\rho,\theta)$ is the set of lines detected by the Hough transform in polar coordinates, and (x, y) are the pixel coordinates of the points belonging to each edge from the undistorted binary image. Step (5): Using k-means clustering around the θ value, the detected lines are separated into different sets. Step (6): The outliers of each cluster are removed. A line is defined as an outlier in a cluster if its parameters satisfy Equation (2).

$$\mu_\theta + 2.5\sigma_\theta \geq \theta \geq \mu_\theta - 2.5\sigma_\theta \qquad (2)$$

where μ_θ and σ_θ are the mean and standard deviation of the θ parameter of all the lines within the same cluster. A step-by-step overview of the image processing results can be found in Figure 3.

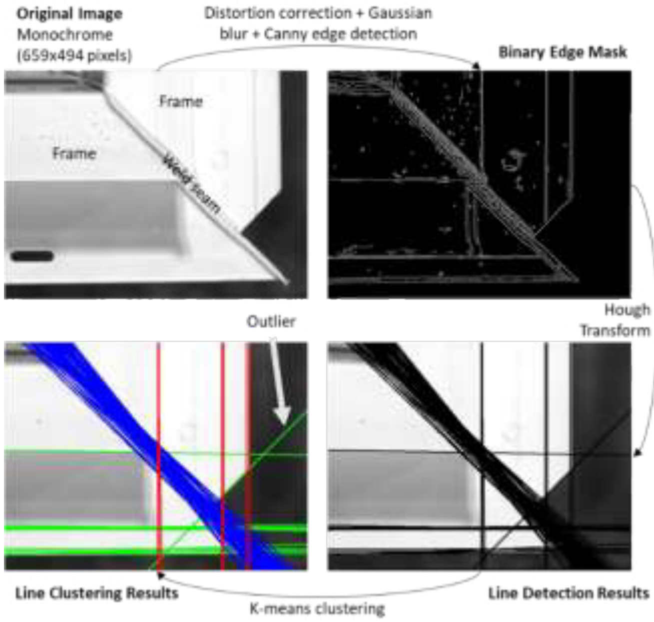

Figure 3. Image processing results obtained from the inspection of a weld seam on a uPVC window corner.

2.2. Interpreter

The line clusters provided by the image processing algorithm need to be associated with their corresponding location on the frame, namely the weld seam, the horizontal frame edges, and the vertical frame edges, to be able to give meaning to the results of the algorithm. As such, for this study, the clustering method is limited to a maximum of three clusters. Another characteristic to consider is that the orientation of the weld seam depends on the weld area selected. As the welded frame corners are in different orientations, the cluster identification needs to be independent of the orientation of the window frame. As such, each cluster needs to be identified accurately. To ease the calculation process, each cluster is represented by the ‘average’ line, $C(\rho_c, \theta_c)$, of the cluster as defined in Equation (3).

$$C_j(\rho_{cj}, \theta_{cj}) \coloneqq \begin{cases} \rho_{cj} = \frac{1}{n}\sum_{i=0}^{n} \rho_i \\ \theta_{cj} = \frac{1}{n}\sum_{i=0}^{n} \theta_i \end{cases} \qquad (3)$$

Let C_1, C_2, and C_3 be the ‘average’ lines of each cluster such that $\theta_{c1} < \theta_{c2} < \theta_{c3}$. Cluster identification is then performed by looking at the values of θ_{cj} of each cluster. As the weld seam is always created between the two frame components that are being welded together, θ_{cj} values can determine its origin. Equation (4) characterizes each cluster based on the patterns of the welding process.

$$\begin{cases} V_l = C_1 \\ H_l = \begin{cases} C_2 \; if \; \theta_{c3} > \pi/2 \\ C_3 \; if \; \theta_{c3} < \pi/2 \end{cases} \\ D_l = \begin{cases} C_3 \; if \; \theta_{c3} > \pi/2 \\ C_2 \; if \; \theta_{c3} < \pi/2 \end{cases} \end{cases} \quad (4)$$

where V_l, H_l, and D_l correspond to the vertical, horizontal, and diagonal line clusters. To obtain both metrics, an initial estimation of the angles between line clusters is needed. Let α and β be the angles between line clusters as defined in Figure 4, where the clusters are represented by the 'average' lines as defined in Equation (3).
Next, a welded frame is considered correct when the frame is squared, and the weld seam is evenly separated from both frame components. Considering that ε is the tolerance of the welding process, as defined by the process quality standards, and ⊥ is the squareness of the window frame at a specific corner, the inspection system checks the conditions stated in Equation (5).

$$\begin{cases} \perp = \alpha + \beta \approx 90° \pm \varepsilon \\ \alpha = \beta = 45° \pm \varepsilon \end{cases} \quad (5)$$

Therefore, if both conditions stated in Equation (5) are within the process tolerance, then the inspection system considers that the window frame is correctly welded and may continue down the production line. Otherwise, the inspection system communicates the non-conformity of the inspected frame to the operator (currently, with a flashing red signal light). As such, the frame can be sorted out manually for further manual inspection if needed.

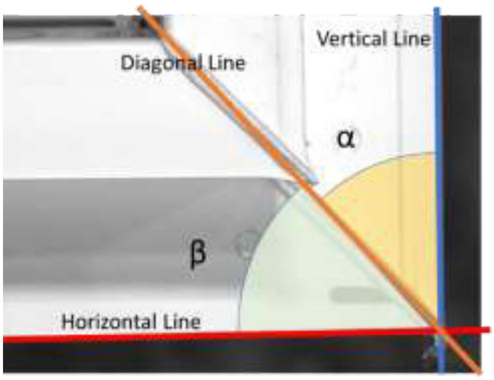

Figure 4. Definition of the angles between line clusters.

3. Results and discussion

This section aims to validate the proposed inspection system in two real scenarios. First, the experimental setup is defined, then the results are presented and analyzed, and finally the potential limitations are discussed in addition to the potential for integration of the inspection system in continuous production lines.

3.1. Experimental setup

To test the inspection system, two window frames of different size but having the same profile are welded automatically using a VSM Sturtz vertical four-point welder machine. The resulting frames are inspected after the cooling process is finished. The purpose of the experiment is to test the accuracy of the proposed system, as well as evaluate its real-time performance. The dimensional information regarding the welded frames is found in Figure 5. For both frames, all the welded areas are inspected.

Figure 5. Overview of the frames used for validation.

3.2. Inspection results

For each panel, the results obtained from the proposed inspection system are presented in

Table **1** and **Table 2**. The ground-truth results are obtained by manual measurements, using a manual protractor with 0.1 degrees of accuracy. These measurements are labeled as 'Real' in the following tables. Each welding corner is numbered for identification purposes while doing the manual measurements.

Table 1. List of the results obtained with the inspection system on window frame 1.

#	Welding Angle [°]				Squareness [°]	
	Alpha		Beta			
	Inspected	Real	Inspected	Real	Inspected	Real
1	45.7499	45.2	42.5185	44.1	88.2685	89.3
2	45.8169	46.3	43.3497	43.8	89.1667	90.1
3	43.8625	44.4	45.3077	46.2	89.1702	90.6
4	43.4447	43.0	45.5232	46.7	88.9678	89.7

Table 2. List of the results obtained with the inspection system on window frame 2.

#	Welding Angle [°]				Squareness [°]	
	Alpha		Beta			
	Inspected	Real	Inspected	Real	Inspected	Real
1	46.2312	46.1	43.4441	43.2	89.6753	89.3
2	46.3731	46.5	42.8427	44.3	89.2158	90.8
3	43.9552	44.8	43.9019	45.6	87.8571	90.4
4	44.6374	45.1	44.0496	44.6	88.6870	89.7

Based on these results, the performance of the inspection algorithm can be statistically analyzed. Table 3 shows the performance analysis per frame and Figure 6 shows a comparison angle by angle of the results obtained versus the measurements performed. As noted, the average accuracy is over 98%, with an error (mean ± standard deviation) of

0.7645°±0.4195° and 0.6894°±0.6010° for panels 1 and 2, respectively.

Table 3. Performance statistics of the inspection algorithm.

	Frame 1	Frame 2	Overall Performance
Average Error [°]	0.7645	0.6894	0.7269
Standard Deviation [°]	0.4195	0.6010	0.5022
Accuracy [%]	98.30	98.46	98.38

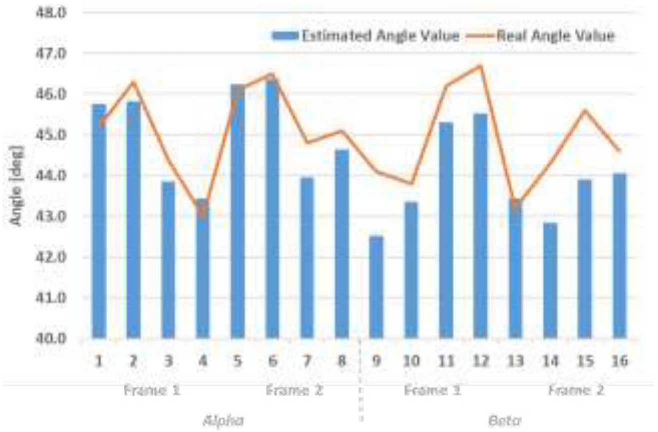

Figure 6. Inspection results vs. angle measurements for the test window frames.

3.3. Discussion and limitations

The proposed automated online vision-based inspection system is capable of accurately measuring the weld angles and squareness of a window frame after the welding process is finished. Accuracy of the weld angles is vital in terms of avoiding potential manufacturing, assembly, or installation problems later on. That said, it is worth noting that the research presented in this paper is an initial work that will be extended in the near future. The same setup will be used to detect possible surface defects, such as blackened areas due to an excessively high temperature of the hot plates.

To apply the described inspection system in a continuous production line, the inspection has to be carried out at the same speed or faster than the production is occurring to avoid introducing unnecessary delays. Table 4 presents the algorithm's time performance. The presented results are obtained using an Intel Core i7-6700 CPU with 16 GB RAM.

Table 4. Time performance for the inspection algorithm.

	Inspection
Time Performance (mean ± std. dev. of 7 runs, 100 loops each)	0.87 s ± 24.4 ms

As the inspection system averages approximately one second per corner of the welded frame, the whole window frame is fully inspected in less than five seconds. As the cooling period of the window frame after the hot plate welding is around 50 seconds for common thermoplastics used in window manufacturing (PVC), the inspection system can be considered fast enough to be integrated without delaying the manufacturing process.

The integration and, consequently, the continuous generation of quality-oriented data in hot plate welding of thermoplastics will enable the introduction of machine learning and data mining techniques. These techniques have been proven to enable and facilitate knowledge discovery in manufacturing, from description of events, association, and classification to prediction, clustering, and evolution analysis [18], [19]. As such, an in-depth statistical analysis of the welding process as a whole and of the effect certain measurable parameters have on the final quality and performance of the window frame can be performed.

4. Conclusions

Hot plate welding is considered one of the simplest and most commonly used welding techniques for mass production. In window manufacturing, this approach is currently used to weld PVC window frames. In regards to quality, current practice relies on operator's experience and visual inspection, as well as optimized machine parameters, to obtain conforming frames. This study proposes a vision-based automatic inspection system for thermoplastic welded parts, using window frames as a case study. Through the application of the novel image processing techniques, such as edge detectors and the Hough transform, a novel algorithm is presented that can extract features of the welded components, then analyze and the assess in real-time the quality of the welding process. In this study, the quality of the window frame is determined based on the weld angles and the squareness of the final frame. Two real scenarios are used to validate the proposed algorithms, resulting in an overall measurement accuracy of over 98%, with less than one degree of average error. The proposed system will be installed in a continuous production line to generate quality-oriented data and will be expanded to detect potential surface defects. Once large amounts of data can be analyzed from a quality perspective, a deeper understanding of thermoplastic welding processes will be pursued.

Acknowledgements

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