New CNN Based Algorithms for the Full Penetration Hole Extraction in Laser Welding Processes: Experimental Results.

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Abstract—In this paper the results obtained by the use of new CNN based visual algorithms for the control of welding processes are described. The growing number of laser welding applications from automobile production to micro mechanics requires fast systems to create closed loop control for error prevention and correction. Nowadays the image processing frame rates of conventional architectures [1] are not sufficient to control high speed laser welding processes due to the fast fluctuation of the full penetration hole [3]. This paper focuses the attention on new strategies obtained by the use of the Eye-RIS system v1.2 which includes a pixel parallel Cellular Neural Network (CNN) based architecture called Q-Eye [2]. In particular, new algorithms for the full penetration hole detection with frame rates up to 24 kHz will be presented. Finally, the results obtained performing real time control of welding processes by the use of these algorithms will be discussed.

I. INTRODUCTION

THE concept of welding could be summed up simply making reference to the joining of two pieces of material to one piece by melting and re-solidification. Several kinds of welding methods exist. In this paper the so called keyhole welding process was adopted. It belongs to the family of Laser Beam Welding (LBW) processes and employs a highly focused laser beam, making deep and slender weld seams with a minimized heat affected zone. LBW is extremely fast and allows saving energy and protecting against thermal material deformations. These characteristics make the LBW one of the most frequently used method in manufacturing processes such as the automotive industry.

As soon as the beam hits the material surface, the melt of the solid materials starts and metal vapor is created [6]. If an opportune beam power is used, due to the hydrostatic pressure of the metal vapor, all the plates of the welding setup are penetrated, creating the so called full penetration. The state of full penetration is visible in the coaxial camera image as a dark zone directly behind the laser interaction zone, the so called full penetration hole. It ensures that the two materials are properly connected over the whole cross section after re-solidification. Therefore, it represents an important quality feature which indicates the strength of the connection. Fig. 1 describes the sketch of a longitudinal section of the laser welding process and the resulting image of a coaxial camera, which shows the thermal radiation of the process, in the near infrared (NIR) range.

Thereby, the use of feedback strategies based on the full penetration hole detection could allow controlling high speed laser welding processes and improving the final result.

Today’s conventional micro processor based image processing architectures, as in [1], cannot provide the high frame rate needed for real-time closed loop control of high speed laser welding. In the last few years CNN have played an important role in real time image processing, thanks to the analogic implementation and to their key features like asynchronous parallel processing, continuous-time dynamics and global interaction of network elements, which allow performing fast parallel image elaboration [4].

Nowadays, some CNN pixel parallel architectures exist, like the family of the Eye-RIS systems developed by Anafocus [2]. Despite their state equation has not been provided, they can be programmed through the specification of templates, in order to perform fast parallel processing. The algorithms treated in this paper have been implemented to be executed on the Eye-RIS system v1.2. It is a compact and modular vision system which allows sensing and elaborating grey-scale and binarized images. It includes tools for interpreting the information contained in the image flow and for supporting decision-making based on the outcome of such interpretation. Eye-RIS system employs a novel architecture in which the image processing follows a hierarchical approach characterized by early processing and post-processing phases.

The most important characteristic of the Eye-RIS vision system is that image acquisition and early processing are simultaneously performed in all pixels of the image sensor.
This concept, which has its basis in CNN theory [4], is the transition from the Image Sensor (IS) to the Smart Image Sensor (SIS). Therefore, early processing inputs are full-resolution images and the basic tasks are meant to extract the useful information from the input image flow. Outputs of this level are reduced sets of data comprising image features such as object locations, shapes, edges, etc.

The post-processing comes just after the early processing. Consequently, it has significantly small data as input and its tasks are meant to output complex decisions and to support action-taking.

The Eye-RIS system consists essentially of an Anafocus' Q-Eye SIS, an Altera NIOS II processor and I/O ports.

The Q-Eye is a quarter CIF resolution fully-programmable smart image sensor. It consists of \(176 \times 144\) cells array and surrounding global circuitry. Each cell is interconnected in several ways with its 8 neighboring cells, allowing highly programmable and efficient real time image acquisition and spatial processing operations. In SIS, each processor is merged with an optical sensor. This means that each pixel can both sense the corresponding spatial sample of the image and process this data in close interaction and cooperation with other pixels. In fact, SIS are also called Focal-plane Processors (FPP) because they process images at the same physical layer where they are sensed.

Altera NIOS II processor is a FPGA-synthesizable digital microprocessor used to control the operation of the whole vision system and to analyze the information output of the SIS performing all the decision-making and actuation tasks.

The I/O ports include a variety of digital input and output ports such as SPI, UART, PWM ports, GPIOs and USB 2.0, to interface the Eye-RIS system with external devices.

II. ALGORITHMS

As shown in earlier works [3] the intensity image of the laser interaction zone is rather constant for a large range of laser power and feeding rates. Therefore, a global threshold is applicable to binarize the images acquired during the welding process. An example of binarized image is shown in Fig. 2 (a). In the following two algorithms to discriminate the full penetration hole by the execution of directional dilations are described [8]. Since they are based on basic local neighborhood operations [9], they can be implemented and efficiently run on any CNN architecture. Fig. 2 shows the result obtained executing dilations from the top – right corner to the bottom – left corner of the binarized image.

![Fig. 2: Dilations parallel to one diagonal. (a) is the source image; (b) shows the direction of the dilations; (c) is the result of the dilating operation. At the end, a logical XOR and a logical AND are applied in succession in order to keep white pixels in the dilated area only (d).](image)

The “dilation algorithm” was implemented in two different versions: the “1-side algorithm” performs dilations in one direction only, whereas the so called “2-sides algorithm” executes dilations in two different directions.

Nevertheless, the dilating operations lead to a resulting image affected with noise due to the dilation of the external edges of the interaction zone. For this reason, the application of one or more masks is necessary.

By the use of off-line built masks, the two algorithms tested over several sequences of images have provided hit percentages greater than 90%. Nevertheless, the algorithm should be independent of the interaction zone position in the image. For this reason a new strategy, called “Mask builder”, was implemented to fit the mask to the specific process. Algorithms and mask builder are based on the execution of operations which strictly depend on the direction of the interaction zone elongation. Therefore, the welding course must be kept constant during the process. In this paper, the interaction zone is assumed with his elongation towards the image bottom.

A. Mask builder

The mask builder is a tool which automatically creates one mask at the beginning of the welding process in order to make the mask independent of the specific optical set-up. The idea is to estimate the position of the interaction zone centre in order to align the mask with it. Let’s consider the example in Fig. 3.

The first step consists in creating an initial mask, which is vertically divided in two regions (black and white) of the same size, as in picture (d).

Afterwards, the source image (a) is binarized obtaining the picture (b) and the distance of the interaction zone centre from the image centre is estimated, as in (c). By this information, the initial mask is opportunely shifted in order to be overlapped to the interaction zone centre, as in picture (e). An example of masking operation is showed in (f).

![Fig. 3: Mask builder. The source image (a) is binarized (b) and the distance of the interaction zone from the image centre is estimated, as in (c). Afterwards, the initial mask (d) is shifted to be overlapped with the centre of the interaction zone, as in (e). Picture (f) shows the application of the masking operation over the source image.](image)
The 2-sides algorithm begins applying a constant threshold value to the source image and executing dilations along one diagonal from the top to the bottom. Afterwards, logical operations are applied in order to keep white pixels in the dilated area only (as in Fig. 2), and the mask is applied. Subsequently, the same procedure is executed along the other diagonal using the inverted mask, and the two results are joined together. 2-sides algorithm and the application of the masking operation lead to a single image processing time of 62 $\mu$s. Fig. 5 clarifies the 2-sides algorithm.

B. Simulation results

Both 1-side and 2-sides algorithms with the introduction of the mask builder have been tested over several image sequences. These image sequences have been acquired by the use of the Eye-RIS system during not controlled welding processes and with different operating conditions. Fig. 6 shows the results obtained over two single images, one with hole and one without hole, by the use of the 1-side algorithm. It presents also the comparison between the results obtained before and after the masking operation, using the mask created by the mask builder. The resulting noise is significantly smaller than the full penetration hole. Therefore the presence of the full penetration hole can be detected by thresholding the number of white pixels in the resulting image. The processing results have been compared to the results of a visual inspection of the image sequences and they have provided hit percentages higher than 88% as shown in Table I. Both the algorithms respect the initial request of small execution time and, therefore, they could be applied for real time control of welding processes. Furthermore, the results obtained from the two algorithms show no significant differences in the detection rate (presumably due to the symmetry of the interaction zone), but a variation of the execution time by the factor of 1.5.

Fig. 6: Masking results. Pictures (a) and (b) are the source images with and without full penetration hole respectively. Pictures (c) and (d) are the 1-side algorithm results, while (e) and (f) show the effect of the masking operation.
### TABLE I. DILATION ALGORITHMS: SIMULATION RESULTS.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>1-side algorithm and masking operation</th>
<th>2-sides algorithm and masking operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Execution time ≈ 42 µs</td>
<td>Execution time ≈ 62 µs</td>
</tr>
<tr>
<td>1</td>
<td>≈ 99%</td>
<td>≈ 99%</td>
</tr>
<tr>
<td>2</td>
<td>≈ 93%</td>
<td>≈ 94%</td>
</tr>
<tr>
<td>3</td>
<td>≈ 92%</td>
<td>≈ 91%</td>
</tr>
<tr>
<td>4</td>
<td>≈ 90%</td>
<td>≈ 88%</td>
</tr>
</tbody>
</table>

**III. REAL TIME CONTROL OF WELDING PROCESSES**

As described above, 1-side algorithm and 2-sides algorithm allow detecting the full penetration hole with a high hit percentage and a high frame rate. Therefore, they are candidates to be applied for real time control of welding processes.

In the past, several authors have proposed closed-loop control systems by using, e.g. the laser power, the focal-point position, or other parameters as the actuator [7]. In this paper a feedback strategy by changing the laser power accordingly to the detection of full penetration hole in the acquired image is used. In the following, a description of the closed loop system and the results obtained by the real time control of several processes will be described.

#### A. Available hardware.

In order to obtain a closed loop control of the process, the Eye-RIS system must be connected to the welding machine. The available hardware, therefore, essentially consists of: the Eye-RIS system v1.2, a numerically controlled (NC) machine, the laser and the interface board.

The NC machine is responsible for safety interlocks, laser ON/OFF signals and movement. The laser is controlled by an analog voltage between 0 and 10 V which corresponds to 0-100 % of laser power. The NC machine sends the starting 24 V digital signal in order to start the laser and the algorithm flow. Consequently, the machine movement is set in action and the Eye-RIS system begins acquiring and elaborating real time images and changing the laser power accordingly to the result of the image elaboration.

The interface board was built to interface the laser and the NC machine with the Eye-RIS system. More details can be found in [5].

#### B. Experimental setup

The processes discussed in this paper have been executed in order to join a stack of two iron sheets in different operative conditions:

- Keeping material thickness, machine speed and gap between the two iron sheets constant.
- Keeping material thickness and gap constant and using variable machine feeding rates.
- Keeping gap and machine speed constant and using variable material thickness.

The welding experiments have been carried out with a 2D-laser scanner setup and a constant welding direction. The laser source is a 6 kW, 1030nm Trumpf TruDisk 6002 Yb:YAG thin disk with a 200 µm transport fibre.

The laser scanner used – a Trumpf PFO-33 – was equipped with a 450 mm focusing optic which resulted in a focal diameter of 600 µm.

The Eye-RIS system is adapted to the scanner optic through a 90° beam splitter (Fig. 7). Thus the camera perspective is coaxial to the laser beam, allowing an invariant field of view regardless of the scanner position. It is necessary to use an aligned lens system in order to achieve an appropriated region of interest (ROI) for the camera.

For the experiments a lens system consisting of three achromatic lenses was designed to achieve an optical magnification $\beta$ of about 4.6.

In combination with an optical band-pass filter, camera images with high quality can be acquired. Fig. 8, for example, shows some images acquired using the optical setup previously described, during welding processes with different feeding rates.

![Fig. 7: Optical setup with the laser scanner, the Eye-RIS camera and the optical imaging system.](image-url)
As explained in previous sections, the 1-side algorithm and the 2-sides algorithm can be used to detect the full penetration hole. In addition, the mask builder represents an important tool to create the mask, which can be used to cut away the noise resulting from the image elaboration. The application of the algorithms leads, as already described, to frame rates up to 24 kHz. Nevertheless, it is important to consider for the real-time control two additional phases to perform sensing and controlling operations.

Sensing and image elaboration are simultaneously performed: while the image \( i \) is being acquired, the image \( i-1 \) is elaborated. Therefore, the sensing exposure time directly depends on the elaborating time. Nevertheless, the application of the sensing functions takes an additional time of about 15 μs. Controlling operations, instead, allow changing the laser power accordingly to the processing result.

The application of these operations takes an additional time of about 15 μs. Summing the time consumptions previously listed, a single controlling step takes about 75 μs and 100 μs, for the 1-side algorithm and the 2-sides algorithm respectively. Therefore, the total controlling frequency is within the range of 10 - 13 kHz. The flow chart in Fig. 9 describes the algorithm used for real-time control of welding processes.

**C. Result of the real time control of welding processes**

1-side and 2-sides algorithms, previously discussed, have provided the same results during real-time control of welding processes. For this reason, in this paper only some experimental results obtained by the use of the 1-side algorithm will be described. Several controlled tests in different operative conditions have been executed. The experimental results point out an evident improvement of the welding quality. The first experiments were executed to join two sheets of material 0.7 mm thick with constant gap of 0.1 mm. Fig. 10 shows the result of the welding process in four different cases with feeding rates of 9 m/min, 7 m/min, 5 m/min and 3 m/min, keeping the rest of the parameter set-up constant.

![Flow chart of the real time control](image)

Fig. 9: Flow chart of the real time control. The algorithm begins as soon as the CNN-based camera system receives the starting signal from the NC machine. Afterwards, consecutive image acquisitions are performed and the mask builder is activated only if the thresholded version of the sensed image has a sufficient number of white pixels. Consecutively, sensing, image elaboration and controlling operations are performed until the stopping signal is received from the NC machine.

![Controlled full penetration weld](image)

Fig. 10: Controlled full penetration weld of zinc coated steel 2 x 0.7 mm with 0.1 mm gap in an overlap joint with constant feeding rate. Four experimental results with different feeding rates (9 m/min, 7 m/min, 5 m/min and 3 m/min from the top to the bottom) are shown.
Several tests have been also executed using bigger thicknesses as 1.0 mm and 1.5 mm with a constant gap of 0.2 mm, and thicknesses as 2.0 mm and 2.5 mm with a constant gap of 0.3 mm. Also in this cases different speeds for each thickness have been used, obtaining similar results to the previous one. Fig. 11 compares the laser response in the four treated cases. It is possible to see that the full penetration state is reached around a laser power value which increases with the welding speed.

The second test regards the joining of two sheets of material with variable thickness, keeping the machine speed and the gap constant during the process. The goal of this test is to prove that the visual control system is fast enough to avoid full penetration losses or holes by the thickness variation. In the following two experiments will be discussed. Both have been executed with constant machine speed of 4 m/min and constant gap of 0.2 mm.

The first experiment was executed using a stack of two zinc coated steel with the base material 1.0 mm thick and with the upper material whose thickness increases from 0.7 mm to 1.0 mm in the welding direction. In this case, the transition from one material sheet to a thicker one could create full penetration losses if the controlling system is not fast enough. Fig. 12 shows the result of the welding process at the top and the laser response at the bottom. The algorithm was able to recognize the absence of full penetration state by the thickness step increasing the laser power and avoiding full penetration losses in the final result.

The second experiment is similar to the previous one, but the thickness of the upper material changes from 1.0 mm to 0.7 mm in the welding direction. In this case, since the welding process passes from one material sheet to a thinner one, the critical state of variable thickness could produce holes and cuttings if the controlling system is not fast enough decreasing the laser power by the thickness changing. Fig. 13 shows that the control system can recognize the presence of the full penetration hole by the thickness variation and decrease the laser power until a new full penetration state is reached.
The next test described in this paper regards the welding of two material sheets 0.7 mm thick with a gap of 0.1 mm in condition of variable feeding rates. In the following two experiments will be discussed: the first one executed with a speed variation from 3 m/min to 9 m/min through 5 m/min and 7 m/min; the second one, instead, executed reversing the speed variation from 9 m/min to 3 m/min, through 7 m/min and 5 m/min. As in the previous experiments, the goal is to prove that the controlling system is able to change the laser power accordingly to the feeding rate variation in order to avoid full penetration losses in case of process accelerations and holes or cuttings in case of process decelerations. Fig. 14 and Fig. 15 show the results of controlling; in both cases the control system was able to opportunely increase and decrease the laser power with the occurrence of speed changes.

D. Controlled versus uncontrolled

The conventional way to achieve a proper full penetration weld without controlling mechanisms is to regulate laser power or feeding rate until full penetration is reached and add 10% laser power as a safety factor. Such a conventional uncontrolled full penetration weld is shown in Fig. 16. Typical for this process is the significant contamination of the bottom side of the joining partners with smoke residue and spatters. Furthermore, there are usually significant craters or even holes present especially at the end of the weld seam due to the deceleration of the machine axis by the end of the welding process.

With the controlled full penetration welding process one can see a completely different behavior (Fig. 17). Notable is the almost complete absence of smoke residue on the bottom side of the joining partners and the reduced spatter traces.

It is also visible that the intervention of the control system reduces the laser power automatically at the end of the weld seam when the feeding rate decreases to a halt. This reduces the formation of craters and holes at weld termination.

Fig. 14: Controlled full penetration weld of zinc coated steel 2 x 0.7 mm with 0.1 mm gap in an overlap joint and variable feeding rate from 3 m/min to 9 m/min. The image at the top shows the welding result, while the image at the bottom shows the controlled laser power response.

Fig. 15: Controlled full penetration weld of zinc coated steel 2 x 0.7 mm with 0.1 mm gap in an overlap joint and variable feeding rate from 9 m/min to 3 m/min. The image at the top shows the welding result, while the image at the bottom shows the controlled laser power response.

Fig. 16: Uncontrolled full penetration weld with 10% factor of safety. Parameters are v = 9 m/min, P = 5.5 kW, zinc coated steel 2 x 0.7mm with 0.1 mm gap in an overlap joint. Smoke residue and craters are visible on the bottom side of the joining partners.
Fig. 17: Controlled full penetration weld of zinc coated steel 2 x 0.7 mm with 0.1 mm gap at a feeding rate of $v = 9$ m/min. The image at the top shows the welding result, while the image at the bottom shows the controlled laser power response.

**IV. CONCLUSIONS**

This paper proposed new strategies for the extraction of the full penetration hole from the interaction zone in order to control laser welding processes. They were implemented on a CNN based camera system. Compared to conventional FPGA based systems, the frame rate was increased by an order of magnitude. A high frame rate is necessary to improve the robustness of the welding process against external influences.

For the full penetration hole feature, the processing time for the full frame area image is about 42 $\mu$s for the 1-side algorithm and 62 $\mu$s for the 2-sides algorithm with similar detection rates. Therefore, the former was used to build up a real time closed loop system for the laser power with controlling frequencies up to 13 kHz.

The proposed closed loop system can also handle particular kinds of welding processes, characterized by variable feeding rate or joining partners with variable thickness.

The quality of the controlled weld seam is better than the uncontrolled one. In fact, the visual control leads to a significant reduction of smoke residue and spatters on the bottom side of the material. In addition, the laser power is quickly changed when particular situations occur, as the presence of thickness and feeding rate variations, preventing the formation of craters, holes and full penetration losses. Therefore, the CNN based control system proved its ability to meet the requirements for real time high speed camera based process control in laser welding.

The execution of the algorithms discussed in this paper presupposes that the welding course is constant during the process, since it is based on dilating operations along specific directions.

Further studies regard the implementation of new CNN based algorithms in order to make the control system independent of the welding direction.

**ACKNOWLEDGMENT**

The results were obtained in the project “Analoge Bildverarbeitung mit zellularen neuronalen Netzen (CNN) zur Regelung laserbasierten Schweißprozesse (ACES)”. This project is funded by the „Landesstiftung Baden-Württemberg“.

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