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Hardware based analysis and process control for laser brazing applications

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Abstract

Laser brazing is widely used for joining metal sheets in industrial applications, in particular in the automotive sector, where the requirements on surface quality are extremely high. Therefore, quality control and process observation cannot be omitted. This paper presents the current works of a camera based process control system. Hardware-based algorithms for estimation of machine parameters during the process are implemented on FPGA technology. In particular the process velocity is measured in real time which makes the system suitable for controlling tasks to react instantaneously on changes of the velocity. First experimental results on a controlled laser brazing process are presented. Additionally an evaluation of the accuracy of the hardware-based velocity measurement is given.

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1. Motivation

Laser brazing is widely used for joining metal sheets in industrial applications. In particular in the automotive sector brazed seams are frequently in the visible part of the car body and therefore impose stringent requirements on surface quality Haldenwanger et al., 1999. Hence, a quality control cannot be omitted.

Today, in the majority of cases quality control is done in a post-process procedure where the surface

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quality of the seam is analysed by triangulation techniques and/or camera based analysis, see Müller-Borhanian et al., 2008. On the one hand side these inspections are time and cost intensive as they require a second step in the production line. On the other hand only the quality of the joined product can be judged. A potential defect and its emergence cannot be analysed with such post-process systems. Hence, a correlation between machine parameters and the occurrence of defects is not possible, e.g. the correlation between actual brazing velocity and/or the feed rate of the brazing wire with an increased occurrence of pores or other seam imperfections. Therefore, an on-line process control system is required that not only provides the possibility to judge the quality of the brazed seam but also measures machine parameters. The next step would be to use the measured parameters for controlling the brazing process.

This work outlines an approach of an on-line control system that supervises the brazing velocity during the brazing process by a camera-based system. Against previous works by Fecker et al., 2011 or Frank et al., 2011 or Ungers et al., 2010 or Donst et al., 2009 where the image processing is done on an industrial PC, the presented approach concentrates on hardware based image processing. The whole image processing is carried out by the Field Programmable Gate Array (FPGA) of the image acquiring frame grabber, as proposed by Franz et al., 2011 where the velocity estimation performs well on test-images without process, but does not provide sufficient results under real brazing process conditions. Contrary to Franz et al., 2011 in this work hardware based velocity estimation is successfully realised during a laser process, for the first time. Due to the nearly instantaneous analysis of the captured images first results on a controlled laser brazing process could be realised. Based on the measured brazing velocity the laser power is controlled and a constant input of energy per unit length is ensured.

2. Experimental Set-up

2.1. Process conditions and brazing set-up

For development and evaluation of the FPGA-based velocity measurement brazing experiments are done with zinc coated steel sheets and a copper-based CuSi3 brazing wire. The sheets are brazed in a flanged seam configuration. A brazed sample is shown in Fig. 1. The used parameters are summarised in Table 1.

Table 1. Brazing parameters used in the experiments

| Parameter                      | Value   |
|-------------------------------|---------|
| Brazing velocity              | 3 m/min |
| Feed rate of brazing wire     | 3 m/min |
| Laser Power                   | 3 kW    |

![Fig. 1: Flanged seam configuration of the brazed samples](image1)

![Fig. 2: Brazing set-up with ALO3](image2)
As brazing optics the *Adaptive Laser Optics* (ALO3) from the company Scansonic MI GmbH is used. In cooperation with Scansonic the ALO3 has been modified for the integration of a CMOS camera. The full brazing set-up is shown in Fig. 2.

### 2.2. Sensor integration

A CMOS Camera is coaxially integrated into the optical path of the brazing laser, as illustrated in Fig. 3(a). The frame rate of the camera is set to 100 fps which turned out to be sufficient for the controlling experiments. For the analysis of the images and for the measurement of the velocity a constant and homogeneous illumination has to be ensured. Therefore, the light of an external illumination laser with a wavelength of 808 nm is used to illuminate the process zone. With an area of interest (ROI) of 1024x512 Pixel², the incoming brazing wire, the melt pool and the re-solidifying seam can be visualised in one image; see Fig. 3 (b).

The captured images are transferred to a frame grabber via camera link standard where the image processing is accomplished on the FPGA. For the experiments the frame grabber *microEnable IV VD4-CL* from the company Silicon Software GmbH with an integrated *Xilinx Spartan XC3S4000* FPGA is used.

![Diagram of the optical set-up](image1.png)

![Image of the coaxially observed process zone.](image2.png)

**Fig. 3:** (a) Diagram of the optical set-up; (b) Image of the coaxially observed process zone.

### 3. Implementation

#### 3.1. Measuring of brazing velocity

To detect the actual process velocity small areas around one central pixel are defined, so called blocks. The intensity patterns of these blocks are relocated in the next frame. A corresponding displacement vector for each central pixel can be calculated. This approach is known as Full Search Block Matching algorithm (FSBM). The basic idea of the Full Search Block Matching (FSBM) is to find the best match of all possible displaced candidate blocks within the searching window in the next frame, see Fig 2 (a). This is done by minimisation of a dedicated metric. In this case the metric of Sum-of-Absolute-Differences (SAD) is used to evaluate the displacement candidate that matches best, as described by Liu et al., 1998. In the current frame $t$ each block is referred to by the coordinates $(x,y)$ of its upper left corner. $L_t$ denotes the intensity of the pixel with coordinates $(i,j)$, where $i$ and $j$ are relative to the block boundary. Likewise the intensity of a pixel in the previous frame is denoted by $L_{t-1}$ at the coordinates $(x+i,y+j)$ plus the relative displacement $(d_x, d_y)$. By
minimising formula (1) the displacement the values for $d_x$ and $d_y$ can be determined leading to a displacement vector for each block.

$$SAD(d_x, d_y) = \sum_{j=0}^{B_y} \sum_{i=0}^{B_x} |L_t(x+i, y+j) - L_{t-1}(x+d_x+i, y+d_y+j)|$$

(1)

To make the measurement more stable the FSBM is carried out multiple times on different positions in the image, see Fig 2 (b). The resulting displacement vectors are then filtered to determine the main vector that represents the actual brazing velocity. The filter consists of one histogram per vector component. The main vector is composed of the maxima of the histograms in x- and y-direction, respectively.

To ensure a measurement under real-time conditions of an image stream that has been captured with 100 frames per second, the use of resources of the FPGA has been optimized. Therefore, block size, search window and number of determined vectors are adapted. With the current implementation a bandwidth of 125 MPixel/s is achieved by the used FPGA, which is sufficient to calculate the SAD of 16 $\times$ 256$\times$256 $\times$ 100 displaced candidate blocks per second, leading to 16 vector positions with a search window of 256$\times$256 Pixel$^2$ each at a frame rate of 100 frames per second. The block size is set to 8$\times$8 pixels in this case. Fig. 4 (b) shows the positions of the 16 vectors and the corresponding search windows that are used to determine the main vector.

3.2. Controlled brazing process

In order to ensure constant energy input per unit length and constant wire feed rate, laser power and wire velocity are adjusted proportionally to the measured brazing velocity. The relationship between these three parameters can be specified in two Look Up Tables (LUT) within the FPGA. Corresponding control voltage for the laser and control voltage for the wire feeder are generated by separate Digital Analog Converters (DAC). Fig. 5 illustrates the principle of the control circuit.
4. Results and Discussion

4.1. Velocity controlled brazing process

Fig. 4 shows the results of a brazing process which is carried out with a variation of the brazing speed for different control setups. In particular, the brazing speed of the handling system is several times reduced from 50 mm/s – standard brazing condition – down to about 12 mm/s. The first seam is brazed with constant laser power $P_L$ and wire speed $v_{Wire}$. A seam raising and broadening in the areas of lower brazing speed can be observed. The control of only one parameter also leads to insufficient seam quality. Only the combined control of laser power $P_L$ and wire speed $v_{Wire}$ leads to a homogenous seam surface, as demonstrated with sample 250.
4.2. Accuracy of velocity measurement

According to formula (2), the accuracy of the implemented Block Matching Algorithm is limited by three factors: whole-pixel accurate measurement, limited frame rate stability and measurement errors when determining the reproduction scale.

\[ v = \text{Pixel displacement per frame} \times \frac{\text{frame rate}}{\text{reproduction scale}} \]  \hspace{1cm} (2)

The relative total error has been calculated as \( \frac{\Delta v}{v} = 1.1 \) to 3.3 %, depending on the actual velocity. The results of the BMA are compared to a reference algorithm with a relative accuracy of 0.01%, which has been developed at the Fraunhofer ILT, described by Franz and Abels, 2010. This software-based algorithm analyses recorded image sequences on an industrial PC. Against the here presented hardware-based algorithm the software-based algorithm uses 400 vectors to estimate the velocity. As Fig. 7 shows, the FSBM performs well within the calculated errors and is capable of measuring the unstable robot movement. In this case a constant robot movement of 50 mm/s has been programmed. But both algorithms show that the movement of the robot is not at constant speed. It oscillates around the programmed speed of 50 mm/s.

![Graph showing accuracy comparison](image)

Fig. 7: Accuracy of the implemented Full Search Block Matching Algorithm, compared to a software-based reference algorithm

5. Conclusion

For the application of laser brazing hardware-based algorithms for measuring the brazing velocity could be successfully implemented, tested and evaluated. The presented results showed that the hardware-based analysis is suitable for controlling the laser power and the speed of the brazing wire according to the actual measured brazing velocity. This opens up the possibility to braze with a constant energy input per unit length which is very important in the application of joining the boot lid where the laser head needs to be realigned.
during the brazing process due to the geometry of the work piece. It also will give increased assistance during the teach-in procedure and the robot programming, because laser power and wire speed is automatically adapted to the seam geometry and the corresponding speed of the handling system; even though when the speed of the handling system is not as constant as is supposed to be.

Especially the coaxial integration of the sensor system ensures the measurement of the real velocity at the tool center point of the processing laser optics. As the presented approach is camera-based it also has the potential to not only supervise machine parameters, e. g. the brazing velocity, but also to judge the quality of the brazed product with the same system. In the long term view, with the implementation of the image processing in FPGA-technology a first step is done to fully integrate the process control into the processing optics.

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