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System development for active deviation compensation in laser-based wire micro deposition using image recognition

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Abstract

Gold plating is used to protect electrical components from corrosion and enhance functionality. A sustainable alternative is localized laser-based wire deposition: Using a laser scanning system, micro gold wires are welded into gold spots locally on the component surface. However, process and system tolerances lead to deviations between the target and actual weld positions. This paper presents a system for active deviation compensation using an on-axis camera and image recognition algorithms. Different adaptive thresholding methods and image processing algorithms are used to determine the welding target position on the part. The actual welding point of the wire on the component is calculated and transferred to the scanner as the new welding position. An approach for designing such a system for active deviation compensation and the possibility of higher-level communication with industrial controls is presented.

Keywords: Laser-based gold coating; electrical contact; micro gold wire deposition; laser-based micro deposition; accuracy improvement; image recognition; adaptive laser process

1. Introduction and state of the art

In production technology, many joining and coating tasks are covered by welding procedures, thereby quality assurance of the welding result is important. Here, inline process monitoring of classic welding technologies with current-carrying electrodes offers the possibility of drawing conclusions about the welding

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result from the current flow. However, if the weld pool or even laser welding processes are to be monitored, different methods such as image processing quality assurance must be used. Nowadays, camera and computer technology offer great opportunities for process control and optimization. Especially in welding processes, process control can be combined with the advantages of image recognition.

For this purpose, various approaches at different technology readiness levels exist in the literature. SHAO et. al. (Shao, 2011a; Shao, 2011b) investigate the deposition process of laser-enhanced gas metal arc welding, where the droplet formation on the wire is analyzed by camera and image processing algorithms.

Other approaches and applied solutions in welding automation (also with robots) are the following. On the one hand, the components to be welded can be detected and evaluated for a correct seam position by means of image recognition. On the other hand, the process can be controlled in order to achieve high weld seam quality, as shown by ASHIDA (Ashida, 2019). The system includes a camera to detect the distance from the arc center to the front end of the weld pool and the width of the weld pool to control the torch. Other methods for learning algorithms (machine learning, deep learning) are combined with image recognition.

For this paper, the focus will be on laser-based wire micro deposition on electrical contact components according to the use case. The ability to apply electrically conductive and corrosion resistant contact layers is proven to be resource efficient and sustainable compared to conventional methods such as electroplating (Beck, 2020). In the following, the example of gold spot coating of electrical contacts by laser-based wire micro deposition is used. Specifically, the development of a system that uses image recognition to detect deviations between the microwire, the component, and the laser beam position to compensate for deviations and increase overall system accuracy will be discussed.

2. Characterization of the process chain and the test rig for laser-based wire micro deposition

The Fraunhofer IPT developed a new process technology in order to coat sheet metal based components, which are stamped from different substrate materials e.g. copper, brass or stainless steel with local precious metal contact dots, see Fig. 1. These dots can be produced via the laser-based wire micro deposition. The precious metal is supplied as microwire (flat wire with 100 x 20 µm² cross-section) that is positioned relatively to the pre-stamped substrate. Subsequently, substrate and wire are irradiated with a laser source, that is deflected by a scanner. The materials melt and form a spherical contact dot with a high degree of mixing in the dot base layer for metallurgical bonding and a high degree of precious metal purity at the dot surface. However, there are system and process related tolerances and deviations. This leads to a misalignment between the component, the microwire, and the target laser focal point, resulting in poor welding results up to missing the wire with a corresponding unwelded spot. Other process errors are described in (Schmid, 2021).

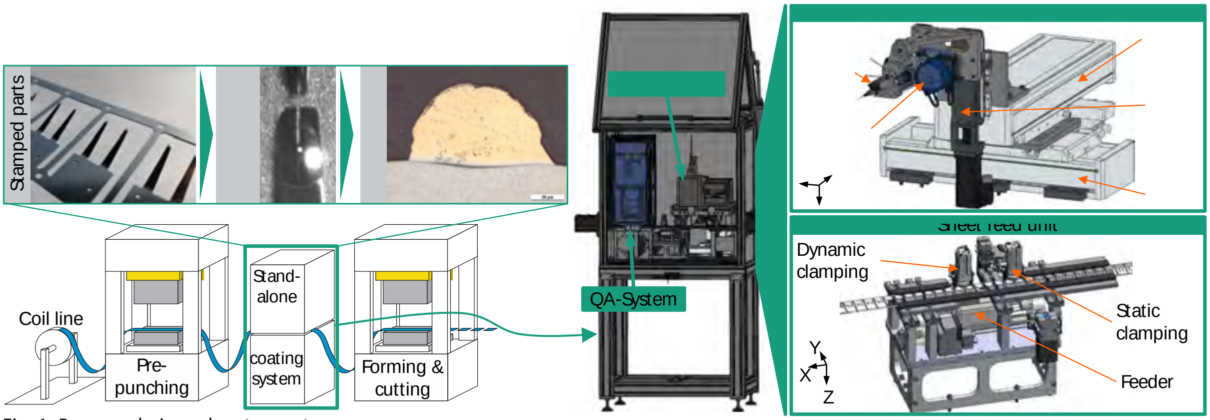

Fig. 1. Process chain and system setup.

The first step is to describe the system (see Fig. 1 and Fig. 2) so that all system and process related tolerances and deviations can be accurately analyzed. For detailed system component description, see also (Schmid, 2021). The contact components are fed to the machine as pre-stamped sheet metal. The sheet metal handling system consists of a guide for the sheet metal strip and a sheet feed unit that cyclically advances the (coated) components in defined feed steps. A 5-axis wire head unwinds, feeds and positions the microwire from the coating spool. The laser system is located above the process zone with the sheet substrate and the precious metal microwire. It includes a beam deflection unit containing the beam delivery of the IR fiber laser and an integrated on-axis camera. The on-axis camera allows online process monitoring at the same position where the laser beam is deflected by the scanner (Fig. 2). This allows to detect any deviations between the component, the microwire and the beam position. In addition to the process-relevant system components, the system involves a quality assurance system for the coated components and a laser safety housing.

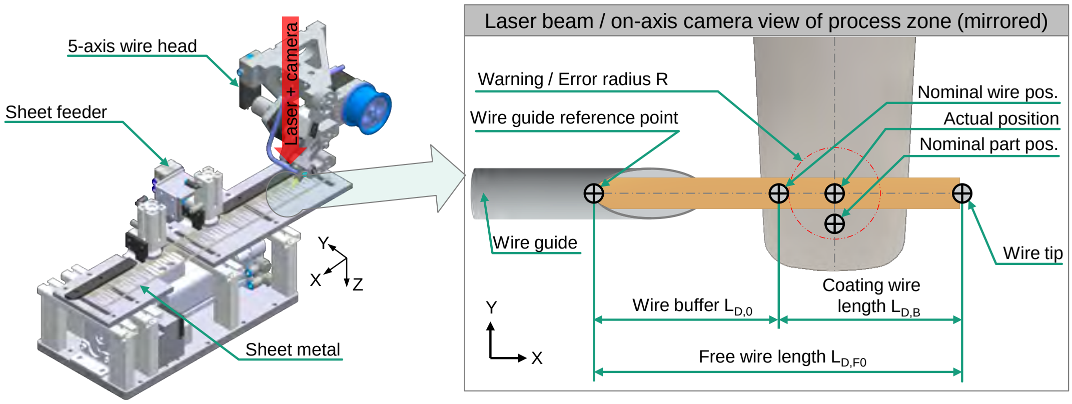

Fig. 2. Schematic representation of the initial situation for the development of the system for active deviation compensation.

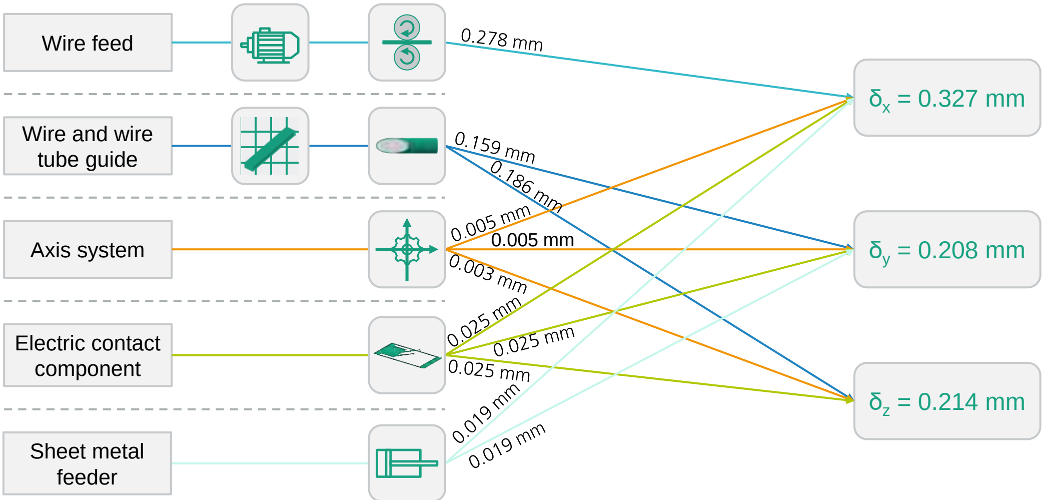

Fig. 3. Representation of the identified influence variables and their effect on the position deviation δ in millimeters.

Proportional combined deviations δx, δy and δz in the spatial directions are derived from the system and process analysis. Fig. 3. presents the identified variables that influence the deviations in spatial coordinates and shows the respective analyzed values of the variables. Since the microwire is fed by a roll feed, feed errors result from the friction and contact conditions between the wire and roll, as well as from the motor encoder accuracy. Though a tube-shaped precision wire guide ensures tight guidance, the microwire deforms elastically in Y and Z directions due to its flexible properties. The axis system through which the wire head is connected, has a repeatability of ± 5 µm for X and Y-axis and ± 3 µm for Z-axis. Contact components are positioned via the punched pilot-holes, therefore deviations are resulting due to manufacturing precision (see also standard DIN 6930-2). The sheet feed has a 19 µm tolerance. When the positive and negative sum of all individual tolerance elements is considered, the maximum positioning deviation is 0.327 mm in wire feeding direction (X-axis).

The mechanical accuracy of the system for gold spot plating of electrical contacts using laser-based wire micro deposition is limited, and in extreme cases even insufficient. In particular, the deviation δy, whose effective direction is radial to the longitudinal axis of the wire, is 2.08 times the wire width. It also means that the system deviation δy can cause the wire to be missed by the laser beam, resulting in no gold spot being welded. From this, the need for a deviation compensation for the process is derived.

This paper presents a systematic approach for active deviation compensation using an on-axis process monitoring camera, which is based on image processing algorithms, see the following chapter.

3. Development of the image recognition system for active deviation compensation

3.1. Functionality and procedure

Image recognition uses the processing of pixel information to recognize objects in the present images by mathematical operations. A digital image can be defined as a function g(x) that assigns a specific color value to each pixel. For a gray scale image with one color channel, g(x) represents the gray scale value at location x. In conventional color images derived from the RGB spectrum (red, green, blue), there are three color channels (g1(x), g2(x), g3(x)) that additively define the hue at location x (Beyerer, 2016). Gray scale images are usually displayed with a color depth of 8 bits. This means that the color depth can be mapped to a total of 256 quantization levels and each pixel can assume a gray value between 0 (black) and 255 (white). Due to the three color channels of a color image, fewer quantization levels are available per pixel for an 8-bit color image. To achieve the same color depth as an 8-bit gray scale image, the number of bits must be increased. As a result, color images often have a lower resolution per color channel than gray scale images and require more data to process. Therefore, if the color information is not essential for evaluation, gray scale images are usually used for image processing. (Bredies, 2011)

Based on a gray scale image, there are two important parameters that reflect the quality of an image. These are the brightness and the contrast of the image. The brightness is equal to the mean value of all pixel values in the digital image. Contrast or dynamic range, on the other hand, reflects the range of all gray values. To locate objects within a digital image, they must differ from each other in brightness or contrast. (Werner, 2021)

According to HANDELS et al. (Handels, 2009), the operations of a vision system can be divided into six steps. The following Fig. 4 gives an overview of the sequence of the sub-steps. A detailed step-by-step description of these six image processing steps, applied to the use case of laser-based wire micro deposition for electrical contact components, is presented in Section 3.3.

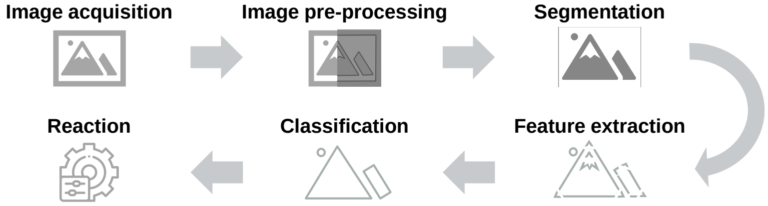

Fig. 4. Image processing procedure in six steps according to (Handels, 2009).

3.2. Image analysis and strategy

The strategy for the system to actively compensate for deviations will now be developed and the task of image analysis will be explained based on the initial situation described above. Mechanical accuracies due to the positioning of wire, relative to the component, could already be shown in Fig. 2. The concept of the active compensation system is to determine the nominal position of the part and the wire in relation to the laser or scanner position. Furthermore, the actual position (Intersection of component middle line and wire middle line) must be detected, in order to compensate the deviation from the actual position by the laser scanner. This allows for proper irradiation of the component and the wire due to the deviation compensated beam tracking. The system is required to have an accuracy of at least 10 % of the wire width, i.e. < 10 µm. In addition, the system should provide a warning if the deviation between target and actual irradiation or coating positions is R > 0.15 mm, and an error if the deviation is R > 0.25 mm.

The on-axis camera in the scanner beam path is a 1.2-megapixel monochromatic CCD-camera. It has a resolution of 1292 × 964 pixels with a pixel size in the image plane of 3.75 x 3.75 mm^2. The image scale is -0.8, which means that the image is inverted or mirrored. The wire width of 100 µm is accordingly imaged with approx. 76.8 µm on the camera sensor, from which it can be sufficiently represented with approx. 20 pixels.

Another important factor is the illumination, which must be optimized. To achieve precise and reproducible results, an illumination system is adapted to this specific application. For the present application, an illumination wavelength of 780 nm in the near infrared range is chosen due to the scanner mirror characteristics. Using an LED spot light, the light is diffusely scattered into the process zone via a reflecting surface, thus providing uniform illumination for different wire heights, geometry, as well as component positions. Reflections on the spherically stamped and embossed part have been minimized, especially in the coating area. The metallic background of the sheet feeding plane is homogenized by a translucent polymer foil. As a result, Fig. 5 shows the optimized image of the on-axis camera with the related 8-bit gray scale (GS) of the image, where GS = 0 is defined as black, GS = 255 as white. The high contrast separation of the wire (GS → 255) from the background (GS → 50 up to 100) and the component (GS → 0) is relevant for the image recognition task. The bright reflection from the spherical component surface may not affect the wire detection and must be masked by the algorithm.

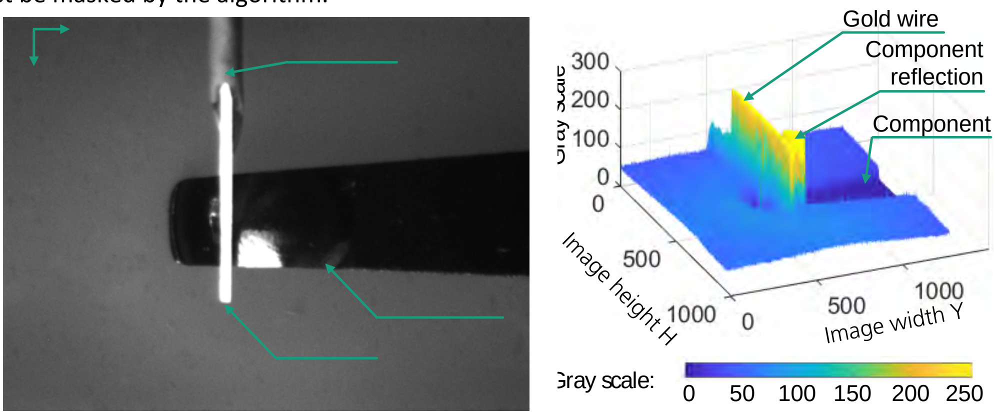

Fig. 5. Left: Image of the process zone with optimized lighting concept. Right: Associated three-dimensional gray scale profile.

The image processing program in this paper is developed using Python and the OpenCV and NumPy libraries (OpenCV team, 2022; NumPy Developers, 2022). The program structure in Python is shown and explained in the section below.

3.3. Implementation of the image recognition system for active deviation compensation

The following implementation of the system refers to the six-step procedure presented in Section 3.1 Fig. 4. The implementation of the individual steps is shown in the flowchart of Fig. 6. The sequence of the steps and their realization in the program will be discussed in detail.

As part of the **image acquisition** process, a raw image is generated using the *get_frame()* method. To be able to process the generated image, the raw image is converted to Mono8 format. Afterwards the Mono8 image can be converted into an OpenCV format with the method *as_opencv_image()*.

Image pre-processing aims to improve both the quality of image data and its information content with respect to subsequent processing steps and the representation of special image structures. For example, the goal of image preprocessing may be to reduce noise, eliminate artifacts, improve image contrast, or normalize image size. For this purpose, the image is blurred by convolving it with the OpenCV method *blur()* with a 5x5 filter kernel (Handels, 2009).

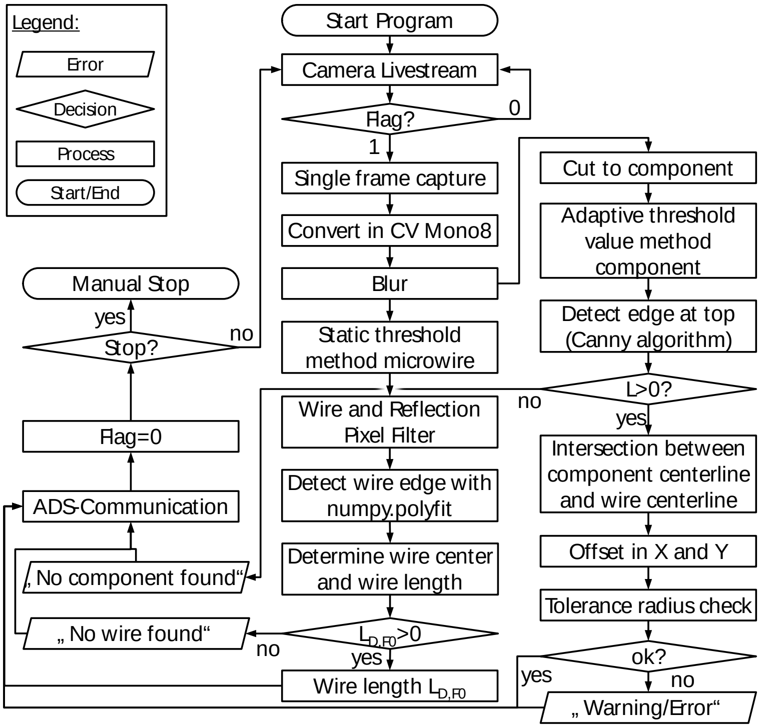

Fig. 6. Program flow diagram of the system for active deviation compensation.

Segmentation divides the image into pre-defined areas (segments) containing specific target objects. For the implementation of the image processing system, the method of binary segmentation *threshold()* will be discussed in the following. Starting from a gray scale image with 256 brightness levels, it is determined which brightness ranges of the image are mapped to the binary states. For this purpose, a binary threshold is defined. Since both the component and the wire need to be detected, the segmentation must be applied twice in order to derive each of the target objects, see Fig. 7.

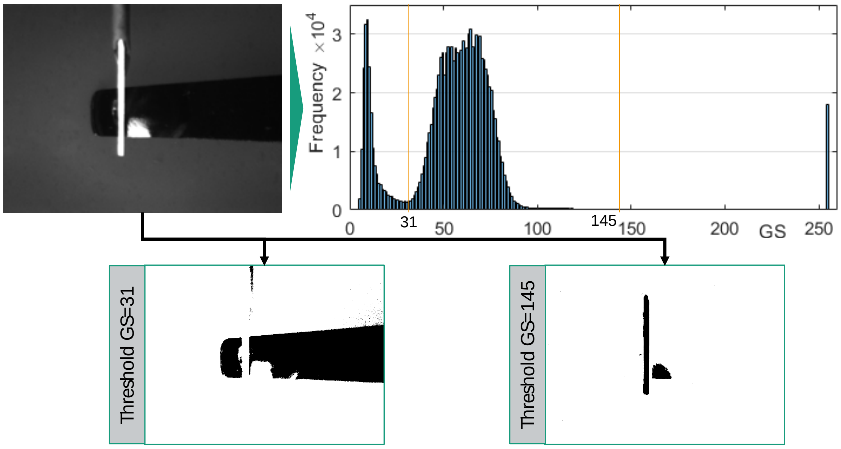

Fig. 7. Image, gray scale histogram and derived dual segmentation based on two thresholds GS=31 and GS=145.

Feature extraction is the definition of features in each segment by edges and lines. First, the reflection from the spherical component must be filtered. Then, edge detectors are applied to the resulting gradient magnitude image. A commonly used edge detector is the Canny Algorithm. The *canny()* command suppresses pixels that do not have a maximum along the gradient direction. The remaining edges are then subjected to a line tracing method with hysteresis. The result is an image that contains only the edges of the original image. Accordingly, the wire and component edge can be detected (Bredies, 2011; Nischwitz, 2020).

Goal of the **classification** is to recognize an object based on the features extracted in the previous step. The program therefore is divided into three main parts. The first part of the program works on the calculation of the wire center and the component center (both described as a linear polynomial fit). Second, according to the brightness gradient along the wire center, the guide reference point and the wire tip can be calculated and thus the wire length $L_{D,F0}$ can be attained. The third part of the program calculates the intersection of the wire centerline and the part centerline and derives the offset between the actual position and the nominal position in X and Y direction, see Fig. 2 and Fig. 8. The result is shown in the figure below.

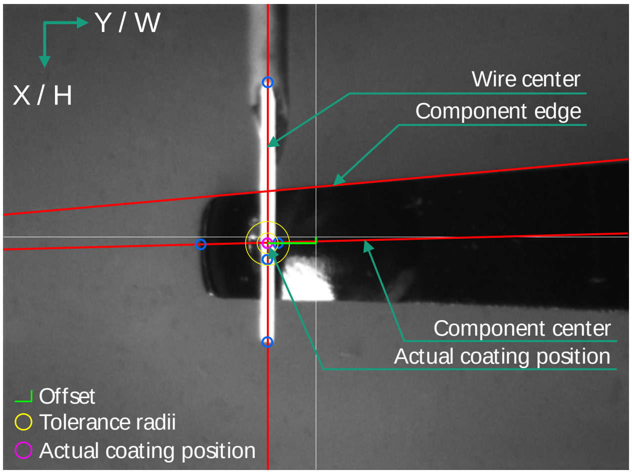

Fig. 8. Result image of the implemented image processing.

After the image processing has been carried out, the determined parameters are transferred to the Beckhoff PLC of the machine for causing a **reaction**. For this purpose, Beckhoff PLCs provide the fieldbus and device-independent ADS interface. With ADS, devices can send messages to other ADS devices via the TwinCAT router. The unique identification between the ADS devices is carried out via the NetId identifiers and the port (Beckhoff, 2022). To enable communication between the PLC and the computer, a bidirectional connection must first be established between the communication participants. For this purpose, the ADS program library from Beckhoff is available. It can be called using the Python wrapper *pyads*. In addition to the offset values in X and Y direction, the wire length and coded error messages are transferred according to the action plan.

4. Validation and system accuracy evaluation

To be able to make a statement about the functional stability and the accuracy of the system for active deviation compensation, two test criteria must be fulfilled. First, various limit states are to be tested based on extreme value images. Second, an absolute system accuracy is to be determined using manually labeled control images. The following states are defined as critical (limit states):

1. Microwire with local molten gold ball at the wire tip
2. The microwire has been cut. The cut piece is in the process zone
3. The component is twisted
4. Microwire is out of image plane
5. The microwire is positioned above the reflection of the component surface
6. The microwire is bent

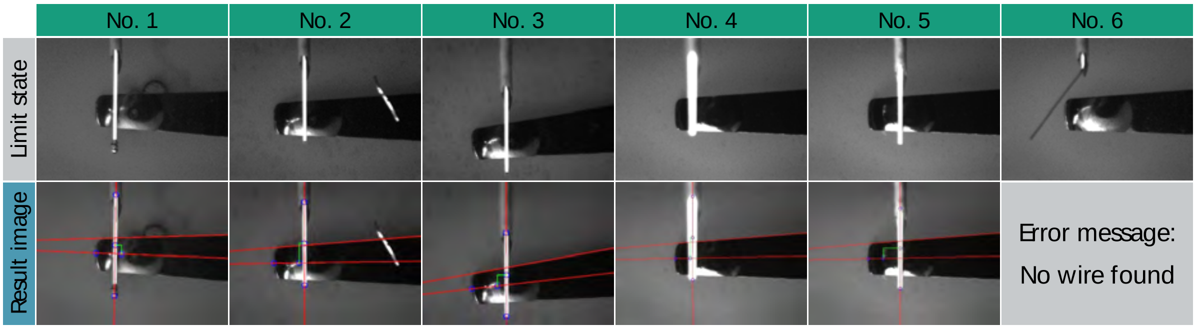

Fig. 9. System stability analysis of different limit states.

The analysis in Fig. 9 shows that the system operates in a stable manner over wide ranges of the above limit states. Only in case of strongly bent or buckled microwires, due to the non-existent reflection and the associated low gray value, the microwire is incorrectly segmented in the threshold method and thus cannot be distinguished from the background. The system detects the error and reports "No wire found".

For the second test criterion, the actual position output of the system for active deviation compensation ξ_{SaDC} is compared with manually determined actual reference position ξ_{Ref}, see Fig. 10. The absolute system accuracy SGA is calculated from the average deviation of $n = 27$ control images (Fig. 10) according to eq. (1).

$$SGA = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left(\xi i_{X_{SaDC}} - \xi i_{X_{Ref}}\right)^2 + \left(\xi i_{Y_{SaDC}} - \xi i_{Y_{Ref}}\right)^2} \quad in\ [\mu m] \tag{1}$$

Furthermore, the deviation in wire length detection DLG is analyzed for the same control images, where $L_{D,F0}$ is the automatically measured wire length, $L_{D,ref}$ is the reference wire length, see eq. (2).

$$DLG = \frac{1}{n}\sum_{i=1}^{n}\left|L_{D,F0} - L_{D,ref}\right| \quad in\ [\mu m] \tag{2}$$

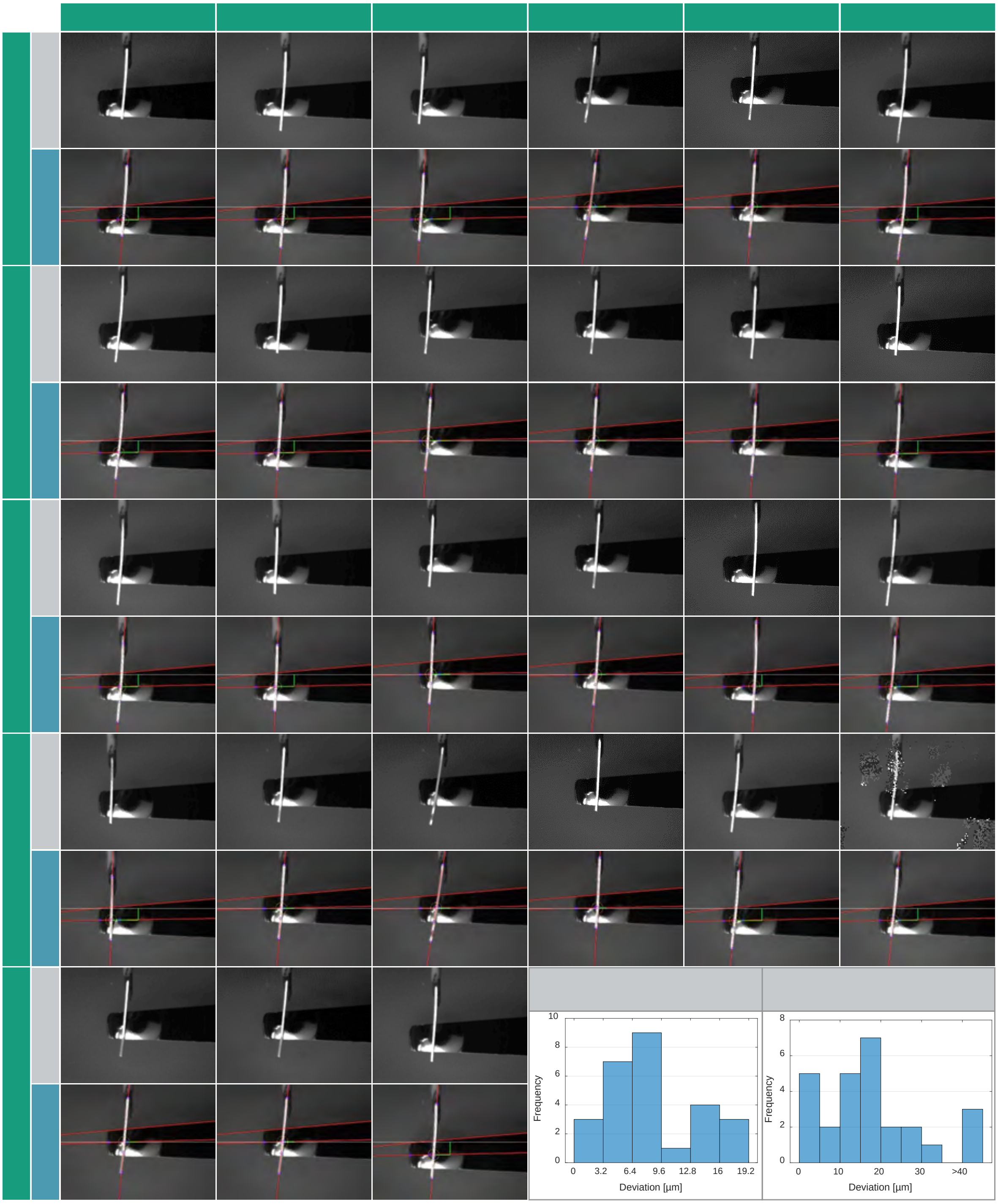

Fig. 10. System accuracy evaluation and clustered control images with their corresponding result images.

The evaluation of the control images in Fig. 10 shows that the absolute system accuracy of the position determination can be resolved to $SGA = 8.79\ \mu m$. Single image analyses show that higher deviation is caused by slightly bent wires or in combination with high wire lengths (Examples in Fig. 10: Images A2, A4, A5, A6, B1, C6, D2, D3). Since the wire centerline was described by a straight line (linear polynomial), the intersection with the component center also deviates from the reference position. This is the main reason for the deviations. However, the absolute accuracy of < 10 µm can be considered excellent and is a significant reduction of the tolerance-related deviations of 208 µm in Y-axis and up to 327 µm in X-axis (chap. 2).

With respect to the wire length, a measurement accuracy of $DLG = 32\ \mu m$ can be determined. This value is mainly specified by a few outliers, where the microwire at the guide reference point or at the wire tip is no longer contrasted from the background due to reduced reflection and a correspondingly low gray value gradient (Examples in Fig. 10: Images A6, C1). With respect to the average wire length of all control images, $\overline{L_{d,F0}} = 2.933\ mm$, the measurement inaccuracy is about 1.1 %. Considering the operation of the laser-based wire micro deposition process, this value is sufficient.

5. Conclusion & Outlook

Image recognition in laser-based wire micro deposition for gold spot coating of electrical contacts shows clear advantages. In the initial system state, tolerance-related deviations in the system and process show insufficient accuracy. The developed camera-based solution of a system for active compensation of these deviations via image processing algorithms proves the potential for increasing the accuracy of the overall system. It has been successfully demonstrated that the system provides repeatable stable image recognition and increased accuracy in the process and laser-based wire micro deposition technology. The achieved accuracy is now < 9 µm for the weld position, which is many times lower than the initial system and process related deviations of up to 327 µm. The next step will be the combined validation within the welding process. Here, the accuracy of the compensation system is to be tested in relation to the achievable coating accuracy.

References

Ashida, T.; Okamoto, A.; Ozaki, K.; Hida, M.; Yamashita, T.: Development of Image Sensing Technology for Automatic Welding (Image Recognition by Deep Learning). In: Kobelco Technology Review, no. 37, April 2019.

Beck, U.; Marto, A.; Uhrlaß, A.; Janssen, H.; Steffens, O.: Substitution umweltbelastender galvanischer Beschichtungsverfahren durch ressourceneffizientes laserunterstütztes Auftragschweißen zur Herstellung elektrischer Kontakte (GreenCoating). Aachen, 2020.

Beckhoff Automation GmbH & Co. KG: Beckhoff Information System. Einführung ADS. URL: https://infosys.beckhoff.com/index.php?content=./content/1031/tcadscommon/html/tcadscommon_introads.htm&id= [Accessed: 16.02.2022].

Beyerer, J.; Puente León, F.; Frese, C.; Meyer, J.: Automatische Sichtprüfung. Grundlagen, Methoden und Praxis der Bildgewinnung und Bildauswertung. Zweite Aufl. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016.

Bredies, K.: Mathematische Bildverarbeitung. Einführung in Grundlagen und mo-derne Theorie. Erste Aufl. Wiesbaden: Vieweg, 2011.

Handels, H.: Medizinische Bildverarbeitung. Bildanalyse, Mustererkennung und Visualisierung für die computergestützte ärztliche Diagnostik und Therapie. 2., überarbeitete und erweiterte Aufl. Wiesbaden: Vieweg+Teubner, 2009.

Nischwitz, A.; Fischer, M.; Haberäcker, P.; Socher, G.: Bildverarbeitung. 4 Aufl. Wiesbaden: Springer Fachmedien Wiesbaden, 2020.

NumPy Developers: NumPy documentation. URL: https://numpy.org/doc/stable/ [Accessed: 10.07.2022].

OpenCV team: About OpenCV. URL: https://opencv.org/about/ [Accessed: 08.06.2022].

Schmid, T., Janssen, H., Brecher, C.: System and process development for functionalization of electrical components by laser-based gold micro deposition. Lasers in Manufacturing Conference 2021, Munich, 2021.

Shao, Y.; Wang, Z.; Zhang, Y.: Droplet measurement in laser enhanced GMAW. In: Proceedings of 2011 International Conference on Modelling, Identification and Control, p. 22–27. China, 2011a.

Shao, Y.; Wang, Z.; Zhang, Y.: Monitoring of liquid droplets in laser-enhanced GMAW. Int J Adv Manuf Technol 57, p. 203–214, 2011b.

Standard DIN 6930-2 (2011): Stanzteile aus Stahl - Teil 2: Allgemeintoleranzen.

Werner, M.: Digitale Bildverarbeitung. Aufl. Wiesbaden: Springer Fachmedien Wiesbaden, 2021.