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Innovative measurement methods for 2D and 3D surface acquisition in additive manufacturing technology

Niloofar Kashefpour[1], Alexander Pierer[2], Holger Schlegel[1], Martin Dix[1, 2]

[1]*Institute for Machine Tools and Production Processes, Chemnitz University of Technology, Reichenhainer Str. 70, 09126 Chemnitz, Germany*
[2]*Fraunhofer Institute for Machine Tools and Forming Technology, Reichenhainer Str. 88, 09126 Chemnitz, Germany*

niloofar.kashefpour@mb.tu-chemnitz.de

Abstract

This work considers the development of a measuring system for surface quality control, which is presented for quality monitoring of the products of an already developed hybrid polymer-metal extrusion system. The extrusion system is based on wire or filament-shaped starting materials and enables 3D printing of electrical connections, insulation and mechanical protection devices that can be adapted to complex shapes, as well as the repair of conductive and insulation structures on circuit boards. A key aspect of this work is the development of a low-cost measurement system for simultaneous acquisition of 2D and 3D surface data from workpieces. This system uses two optical measurement techniques, laser triangulation for 3D surface acquisition and optical flow for 2D surface acquisition. The goal is to carry out the visual inspection automatically and in real time during production in order to avoid errors and increase the robustness of production. The publication covers the fundamentals of optical metrology, especially laser triangulation and optical flow, as well as the development of the measurement system including hardware and software. In addition, investigations are carried out to evaluate the measuring system and the measuring methods. The results show that laser triangulation is suitable for 3D surface detection, while optical flow provides good results for 2D surface detection. This work provides an insight into the development of advanced manufacturing technologies and the importance of real-time quality control in additive manufacturing.

Visual inspection, quality control, optical flow, laser triangulation, image processing, optical measurement methods, extrusion , process sustainability, defect detection

1. Introduction

Although Advanced Additive Manufacturing (AM) technologies enable flexible production of customized products and offer the possibility of integrating electronic functions into structural components as well as repairing electronic components, this requires the development and updating of appropriate quality control methods and systems.

This work considers the development of a measuring system for monitoring the surface quality of the products of an already developed hybrid polymer-metal extrusion system. The extrusion system is based on wire or thread-like starting materials. This makes it possible to 3D print permanent and stable electrical connections, insulation and mechanical protection devices such as strain reliefs that can be adapted to geometrically complex shapes, as well as repair the conductor tracks and insulation structures on circuit boards. In the first development phase, low-melting tin alloys for the conductor structures and non-polar thermoplastic polymers such as PLA and ABS were investigated. In further development steps, metals with a higher melting point (e.g. copper, aluminum, steel) should also be considered as conductive and support structures or glass as an insulator in the build-up welding process.

A key aspect of optimizing the execution of these tasks is the development of methods and systems for evaluating and quality control of processes/products in real time. This goal is achievable through two main factors, firstly through the correct selection and online correction of manufacturing parameters and secondly through accurate process control or product follow-up. The manufacturing parameters are usually selected regarding to the application to ensure the repeatability of the process and quality of the products. However, unexpected defects such as insufficient bonding or geometric dimensional deviations may occur at any time during the process. Furthermore a research study by Öberg et al. [1] shows the variation of the selected preliminary welding process specifications prepared in five welding shops for the production of the same workpiece, which also results in inconsistent quality of the workpiece and requires the existence of a human factor in the evaluation process which again affects the consistency of the assessment. However, there is a risk that some defects may be overlooked due to fatigue and limited human performance. On the other hand, there is a greater amount of time spent inspecting workpieces in this manner. The consequences are higher costs and increased energy consumption.

The idea of this work is the development of a simple and cost effective measurement system for simultaneous acquisition of 2D or 3D surface data of the workpieces. The system contains a combination of two optical measurement methods; laser triangulation for 3D surface acquisition and optical flow method for 2D surface acquisition, which enables the automation of visual inspection tasks during production in order to avoid corresponding errors and the associated additional costs, material and energy consumption and thus achieving greater robustness and sustainability of production.

The main technical simplification and cost advantage of this system lies in the use of only one industrial camera to capture the 2D image information, the 3D laser profile and the feed movement. The evaluation of the 3D-profile and the feed path as well as feed rate is done by image processing algorithms.Welded workpieces were used to perform the investigations and consider the functionality of the measurement methods for the intended application.

In the following sections, first the basics of the respective methods as well as the investigations regarding the functionality of the methods are considered and finally a short summary of results as well as a conclusion is given.

2. Optical measuring methods

Methods of optical metrology are developed on the basis of physical reflection and absorption principles. These enable non-contact, fast and full-surface measurement of workpieces. In this work, two optical measurement methods are used to acquire the 2D and 3D surface data of the workpiece. These are considered in the following sections.

2.1. Laser triangulation

Laser triangulation is the most commonly used method for 3D surface measurement, and its performance has been gradually improved by accurate mechanical laser scanning control and high-resolution, high-sensitivity image sensors. There are four main components of a 3D triangulation system: a camera, a projector that is typically laser-based, a mechanism that moves the object or camera-laser system through the imaging system's field of view, and software to process the captured image and accurately convert pixel offsets into height differences [2].

The interaction between laser illumination and object surface results in a distribution of intensity values. This distribution depends on the topography of the surface and the properties of the propagating light. During acquisition, the workpiece is moved under the laser-camera-system. By capturing the intensity distribution and calculating the workpiece profile over time, a three-dimensional geometric reconstruction of the workpiece can be obtained [2,3].

In this work, the reverse arrangement of the camera-laser-system (Figure 1) is used. According to the triangulation principle, based on the known distance of the laser line to the camera axis Δx and the angle α between the projection axis of the laser and the camera axis, the height Δz of the scanned object (Figure 2) can be determined using the following formula:

$$\Delta z = \frac{\Delta x}{\tan \alpha} \tag{1}$$

This means that the system parameters Δx and α are the decisive factors for determining the sensor properties such as detection range, height or depth resolution, occlusion, and laser reflection. A trade-off between depth or height resolution and detection range is a typical problem of laser triangulation systems. Many commercial solutions have a fixed baseline, so they only work with a fixed resolution and range [4,5].

2.2. Optical flow

The motion of an object in 3D scene is projected into a 2D image by the optics of the image sensor. This is defined as a motion field that cannot be measured directly.

Optical flow is an estimation of the motion field by detecting the motion of brightness patterns using the concept of flow vectors in image sequence. Mathematically, this is referred to as the gradient of the gray values between two images and describes the gray value flow caused by the relative motion of objects and observers to each other [6]. Therefore, it contains information not only about the spatial arrangement of the observed objects, but also about their velocity change.

A detailed mathematical description of the methodology can be found in the works of Agarwal et al. [6] and Rideaux et al. [7].

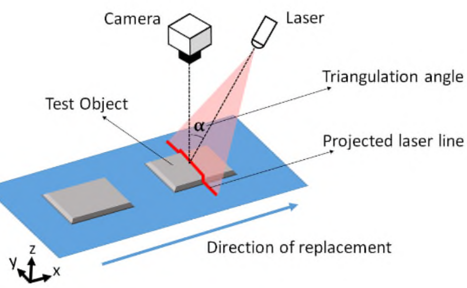

Figure 1. Configuration of laser-camera-system for laser triangulation method: reverse geometry

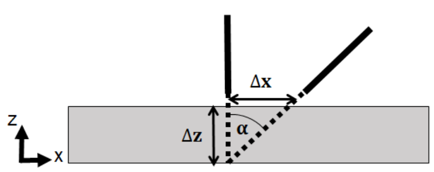

Figure 2. Parameters of the laser triangulation system

3. Development of the measuring system

3.1. Hardware of the system

Two versions of the measurement system were developed, a stationary and a portable measurement setup. The use of a color camera is a special feature of these experimental setups compared to other similar works. By using such a camera, the information concerning the color of the laser line can be acquired. The properties of different color spaces can simplify the detection or acquisition as an additional feature. The characteristic of this feature is described and implemented for example in works of Yin [8] and Breier et al. [9] for inspection as well as 3D profile detection of the printed circuit boards and in a paper of Pierer et al. [10] for inspection of the thickness of paint coating of extruded aluminum parts.

Based on these findings, a stationary measurement setup was constructed. In order to design the system as accurately as possible, the optimal triangulation configuration was calculated. Regarding the measurement system (constant distance between the camera and the laser), the parameter x can be set by adjusting the angle between the projection axis of the laser and the camera axis (α). As a consequence, α is the only free mechanical adjustment parameter that determines the sensitivity of the 3D surface measurement. The DIN 1319 defines it as *"change of value in the output quantity of a measurement device referred to the change of value of the input quantity which causes it"*. In this system, it would be defined as a relation of measured pixel shift of the camera to the height change on the workpiece. According to equation (1) and the fact that the field of view of the camera in which the laser light is visible is a boundary condition for determining the sensitivity range of the sensor, the optimal triangulation angle for 3D surface detection can be determined by looking at the image scale. This is defined by the ratio of image size and object size. The prerequisite for this is that the object lies on a plane parallel to the sensor or camera. In addition, the image scale must be recalculated in case of a change of the distance between the object and the camera.

After preliminary tests with the stationary setup, a portable measurement device with similar components was created. The mechanical components are 3D printed from PLA plastic. The portable measurement system can be moved by hand on the workpiece.

3.2. Software of the system

The algorithms required for the acquisition procedures were implemented in the XEIDANA® framework developed at Fraunhofer IWU (Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU, Chemnitz, Deutschland) [11]. This framework enables the implementation of complex data analysis tasks by modularization and parallelization of data processing algorithms and sensor fusion. In this work, the data acquired by camera is fused by means of the appropriate modules and used to determine the 3D profile of the workpiece as well as the displacement diagram of its motion.

By using the RGB camera, the bitwise combination of the hue and color saturation of the laser light is used as a strong feature to detect the laser line on the workpiece. This is achieved by converting the RGB image to the HSI color space and decomposing it into the appropriate components. Mathematical transformations between the RGB and HSI color spaces are mentioned in the work of Saravanan et al. [12]. In the process, three new images are obtained in terms of the component's hue (H-image), saturation (S-image) and intensity (I-image).

The combined HS-evaluation can also differentiate reddish, albeit relatively weakly color-saturated, rust spots from the laser line. The average of the segmented laser line (Figure 3-d) is the input image for the triangulation calculations (Figure 3-e).

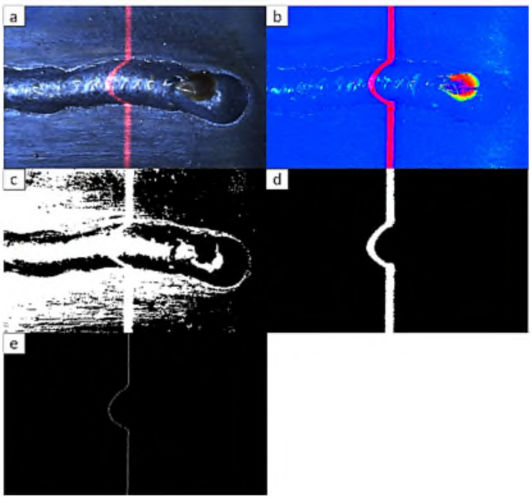

Figure 3. a) Calibrated input image, b) Hue image (H-image), c) Color saturation image (S-image), d) Segmented laser line, e) Average value of segmented laser line.

The 2D surface acquisition module receives two consecutive calibrated RGB images from the camera in the input and calculates the flow vectors of the pixels between these two images. The feed motion results from the conversion of flow vector with the image scale. Whereby the determination of the exposure time of the camera plays an important role in the interference-free acquisition.

3.3. Investigations for evaluation of the system

For the experimental evaluation, investigations were carried out both according to the measurement methods (laser triangulation and optical flow) and measurement systems (stationary and portable measurement systems).

The accuracy and linearity of the measurements of laser triangulation method were considered by means of the measurement of test standards (gauge blocks) with a size of 0.5 to 6 mm.

The investigations according to the application of optical flow for 2D surface measurement were carried out with regard to the repeatability as well as the linearity of the measurement results and depending on the feed path, feed speed, feed direction as well as surface design of the sample object.

Having established the good functionality of the optical flow method, especially for longer feed paths, the authors compared it with the image registration method. This method evaluates the similarity of two images and calculates a transformation between them. A very robust and well-established image registration method in industrial image processing uses the so-called Enhanced Correlation Coefficient (ECC) [13].

To evaluate the developed measuring system, it was used for surface detection of welded workpieces. During the tests with the stationary measuring system, the workpiece was moved under the laser-camera-system at a speed of 100 mm/min. (Figure 4) Two nuts were placed next to the weld as reference points for the beginning and end of the detection. The smooth, shiny as well as weakly textured surface of the nut resulted in its noisy image on some parts (measurement deviations).

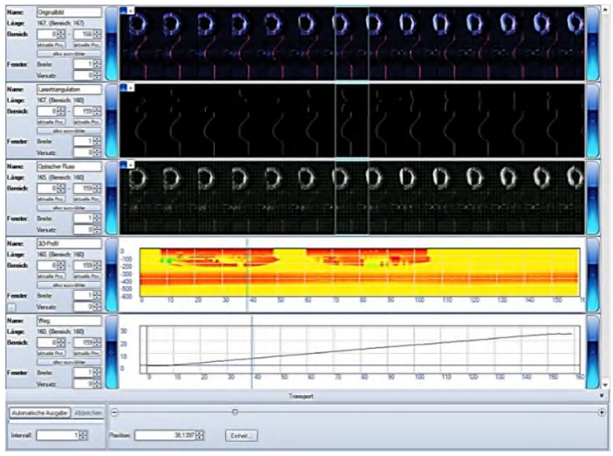

Figure 4. Measurement results of the stationary measurement system (the rows contain respectively: the color image sequence captured by the camera, the segmented images to extract the laser line, the RGB image with the directions of movement measured from the optical flow, the 3D profile of the workpiece, the displacement diagram of the motion)

3.4. Results

For the measurement system, the influencing factors regarding the measurement accuracy can be classified according to its components as follows:

- Camera: reprojection errors, lens aberrations
- Laser: spot size, linearity of the laser line
- Object: speckle noise, occlusion, tilt angle, color anomalies such as rust spots or glossy spots on the workpiece
- Conveyor: vibrations
- Environment: ambient light noise

The measurements of the test standards using laser triangulation resulted in a maximum measurement deviation of 0.11 mm, which is sufficient for fulfilling the requirements of DIN EN ISO 5817 level C ("medium") for permissible dimensions of weld irregularities. This is also suitable for the evaluation of 3D extruded parts, whereby the layer thickness varies between 1 to 3 mm depending on the technology and requirements of the component and an extrusion thickness accuracy of 0.5 mm should be maintained.

It is worth noting that the less fluctuations the segmented line has, the more accurately the profile can be measured. In the system the combination of saturation and hue serves as features for segmenting the laser line so that in the presence of a suitable additional light source, the variations caused by ambient lighting and/or nature or manufacture of the test object etc. (e.g. rust stain) can be avoided. During the dynamic tests, a correlation between the speed of the conveyor and the measurement resolution was found, whereby the measurement reliability increased as the feed speed of the object on the conveyor decreased. Here, a compromise between the feed speed, the measurement resolution, as well as the acquisition time should be determined. It was also demonstrated that the segmented laser line could be used to monitor or inspect the weld regarding the external/surface anomalies.

When implementing 2D surface detection using the optical flow method, a dependence of the measurement accuracy on the feed motion as well as the motion speed was found, whereby with an increased path and/or feed speed, the measurement deviation and standard deviation of the measured values also increased. In addition, a dependence on the nature of the sample was found, whereby for objects with recognizable textures qualitative good results for the detection of the feed motion are provided. Moreover, the influence of exposure time on the quality of motion detection by method of optical flow is remarkable. The comparison of the measurement results with the results of the ECC method (Figure 5) showed that an increase in the feed path causes a greater reduction in measurement accuracy with the ECC method than with the optical flow. Additionally, the optical flow has shorter calculation times compared to the optical flow.

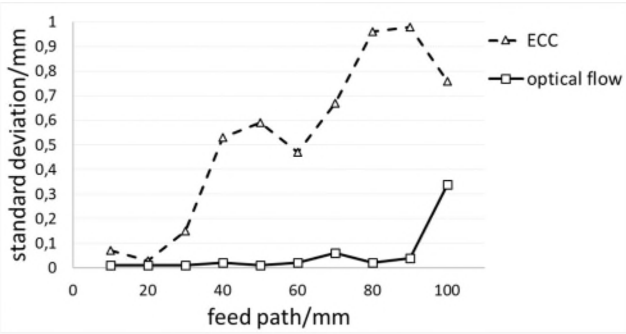

Figure 5. Standard deviation of feed path measurement by optical flow and ECC with a feed rate of 500 $\frac{mm}{min}$

In the measurements using the portable measurement system (static object and moving camera-laser-system), the 3D profile of the object has a lower resolution. This can be justified by the variable speed of movement and the inevitably uneven hand guidance of the device.

4. Conclusions

The investigations have impressively shown that the combination of laser triangulation and feed detection by means of optical flow is an extremely promising method, especially in the context of the novel additive manufacturing process that uses hybrid metal and plastic extrusion. This process enables layer-by-layer creation of complex components, using both metals and plastics in a single process. According to the results when the object to be measured has recognizable textures, the optical flow provides high-quality results for the detection of the feed motion. This precision is essential to ensure that the layers are correctly matched during the additive manufacturing process and that high-quality end products can be produced.

Fine-tuning of lighting and camera parameters, including adjustment of lighting color composition, irradiance and optimal choice of camera exposure time, plays a crucial role in optimizing this process for hybrid metal and plastic extrusion. These parameters make it possible to precisely detect the materials and ensure the quality of the printed layers. In addition, it has been shown that the quality of segmentation of the laser line, especially with respect to the nature of the sample surface, has a significant influence on the measurement accuracy of laser triangulation processes. A low variation in the segmented line is essential to accurately perform offset measurements and thus generate accurate profiles for hybrid metal and plastic extrusion.

The results of this work thus lay the foundation for the development of an ergonomically optimized device for the manual inspection of components as a part of the additive manufacturing process. Moreover, they can be integrated directly into automated test systems to support the monitoring and quality assurance of this innovative manufacturing method.

These results are instrumental in increasing the efficiency and quality of hybrid metal and plastic extrusion in the manufacturing industry, and open up exciting possibilities for the wider application of this revolutionary manufacturing process across multiple industries.

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