Scientific Visualization, 2025, volume 17, number 1, pages 114 - 121, DOI: 10.26583/sv.17.1.09

Research and Application of Machine Vision Algorithms for Defect Detection in Additive Technologies

O.N. Tretyakova[1,A], D.N. Tuzhilin[2,B], A.A. Shamordin[3,B]

[A] Moscow Aviation Institute (National Research University) MAI, Moscow
[B] 2LLC "PROMIS LAB" of the group of companies "Lasers and Equipment TM", Moscow

[1] ORCID: 0000-0003-0256-4558, tretiyakova_olga@mail.ru
[2] ORCID: 0000-0002-8570-1732, tuzhilin@laserapr.ru
[3] ORCID: 0009-0001-5092-3351, ashamordin@laser-app.ru

Abstract

This paper discusses solving the problem of visualizing and recognizing defects that arise during selective laser melting using machine vision algorithms. The main goal of defect recognition is to reduce the time spent on selecting the technological parameters of the additive manufacturing equipment using automation methods of analysis of results. The paper presents an approach to visualizing and detecting defects that occur during the leveling stage of the metal powder layer. A methodology for software and hardware defect detection is considered and implemented. A general approach to image processing and analysis using a conveyor method is developed. The paper also discusses issues related to layer-by-layer photo documentation of the leveling process to simplify the analysis of the causes of defects. The developed software module can detect defects at the initial stages of production, allowing the process of printing knowingly defective products to be stopped, thereby enabling faster adjustment of the technological parameters of the equipment. This approach significantly reduces the time interval spent on selecting the technological parameters of the equipment and it reduces the cost of selective laser melting by saving metal powder on printing defective products. The advantages and disadvantages of the work done and the results obtained are presented.

Keywords: SLM, machine vision, defect recognition.

1. Introduction

This work continues and further develops our research [1-5] on the development of software and laser technological equipment for the practical implementation of the Selective Laser Melting (SLM) technology in domestic enterprises. The SLM technology is based on the process of manufacturing products by selectively melting metallic powder layers using laser radiation. In the first stage, a layer of metallic powder of a specified size is evenly applied to the working surface, and in the second stage, the laser beam locally heats and melts the material according to predefined data from the 3D model layer. The previously developed software complex [1-5], which includes the LAMachineVision software platform created for visualizing the SLM process [2], has successfully solved the multi-parameter task of selecting equipment operation parameters for selective laser melting of metallic powders [5]. In the practical industrial realization of the SLM technology, we encountered a problem related to the duration of the operation for selecting technological parameters. At each stage, due to incorrect selection of technological parameters, defects may arise. After the powder is applied, longitudinal stripes orthogonal to one of the axes of the working surface can appear during leveling, depending on the leveling direction, resulting in damage to the leveling device.

2. Architecture of the proposed defect recognition software module

To reduce the duration of selecting technological parameters while considering these factors, a defect recognition software module named FlexADD (Additive Defect Detector) was developed to visualize, detect leveling defects, and perform layer-by-layer photo-documentation of the process. The program code was written in C++ 17 using the QT 5.15 software platform. The MvCameraSDK library was used to work with the industrial Hikrobot camera, and the OpenCV library was utilized to simplify the implementation of recognition algorithms and frame processing. The built-in QT mechanisms for working with the OpenGL scene were used for visualizing the video stream from the camera and leveling defects. The FlexADD defect recognition software module supports simultaneous operation with multiple video cameras and controls physical lighting modules located in the working camera. Lighting control is achieved through communication with a specifically developed controller via the HID standard. Due to the cross-platform architecture of the technologies used, the program can run on both Windows and Linux operating systems. The created FlexADD defect recognition software module utilizes the StateMachine architectural concept (Fig. 1), which allows for the division of states and transitions between them. This approach uses to manage complex processes or algorithms. StateMachine tracks the current state of the FlexADD program and defines possible next states and transitions between them. This approach makes the code more understandable, modular, and easier to support and further develop, as each state and its behavior are described separately from others. Additionally, using StateMachine helps avoid errors in the program related to incorrect execution order of operations or improper state transitions. Text logging of program actions plays an important role in industrial development, facilitated by the nature of the StateMachine concept.

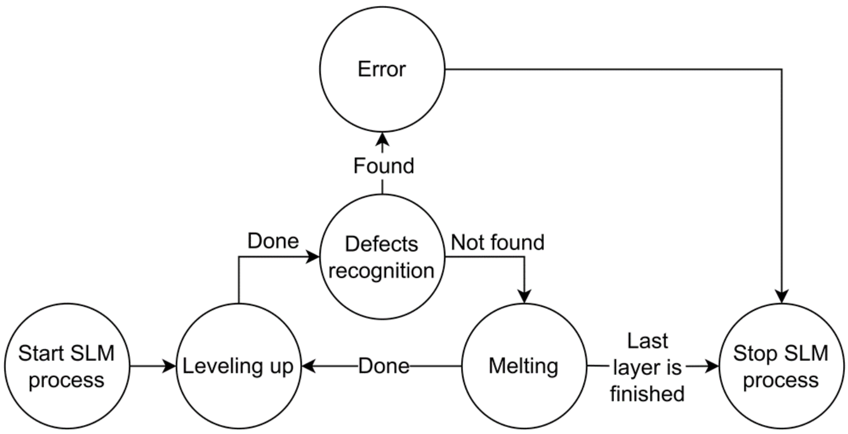

Fig 1. Visualization of the StateMachine concept using the implemented SLM process sequence as an example.

3. Controlling the lighting in the working camera

For stable defect recognition, it is not always enough to rely solely on software and mathematical tools; sometimes it is necessary to influence the intensity, color, and direction of illumination in the area of the working surface. To address this issue in the configuration for which the development was conducted, there are several lighting modules that can be controlled from the FlexADD defect recognition program. In addition to controlling the state of a specific module, brightness adjustment is also available (Fig. 2). The lighting configuration is linked to the currently selected camera, so when switching cameras, the lighting parameters also change. In the working camera, in addition to the additional lighting modules, there is also main light. Through experiments, it was found that the main light has a negative impact on the quality of recognition by causing overexposure of the working area. To eliminate the negative effects of the main light and enhance the contrast of these defects, a software control of its state was added.

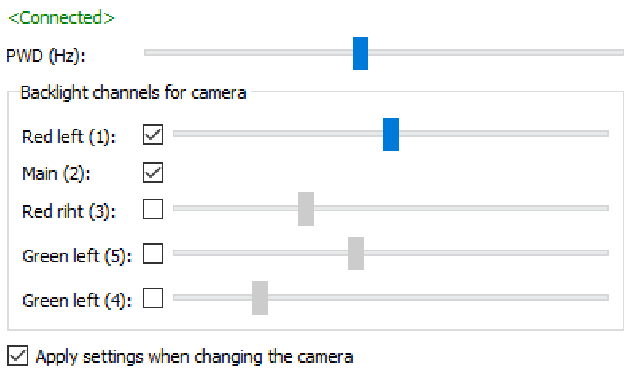

Fig. 2. Backlight control interface.

This solution provides the ability to physically influence the contrast of defects in the video stream by adjusting the angle at which light falls on the working surface, thereby increasing the effectiveness of software automation methods.

4. General methodology of defect recognition

The design of the laser setup being developed does not allow for the camera to be positioned directly above the working surface, however, such positioning is necessary for accurate determination of the coordinates of detected defects. To compensate for the non-axis positioning of the camera with the working surface, the software includes a perspective compensation function that allows the surface to be viewed from the desired angle (Fig. 3). During the calibration stage of the software, the operator must specify the height and width of the area marked in Fig. 3 in millimeters. By having the dimensions of the area in pixels and the user-entered values of the area dimensions, we determine a conversion coefficient that is then used to transform coordinates. This approach involves cropping unnecessary areas for processing, thereby further reducing the size of the analyzed image and increasing the speed of the algorithms.

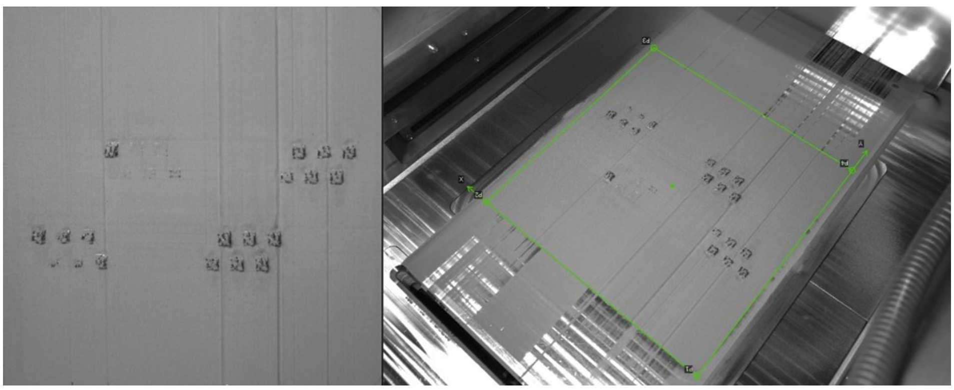
Fig. 3. Software perspective correction.

Defect recognition occurs at a specific moment in the process, specifically after leveling when the powder should evenly cover the working surface. The sequence of recognition (Fig. 4) is based on the StateMachine concept. Initially, the system is in a waiting state for a request to search for defects (stWait), and the connection via TCP protocol with the control program of the 3D printing setup has been established to provide information about the current printed layer. Upon receiving a command to search for defects, the defect recognition program FlexADD sequentially captures N images with N cameras (stGetCameraFrames), with consecutive processing required to switch lighting configurations. The command for defect detection also contains an array of detector names, the results of which should be provided as a response. After capturing images, the specified filters and recognition algorithms from the protocol (stAnalyzeFrames) are applied, and upon completion, the detected defects are sent to the control program (stSendResult).

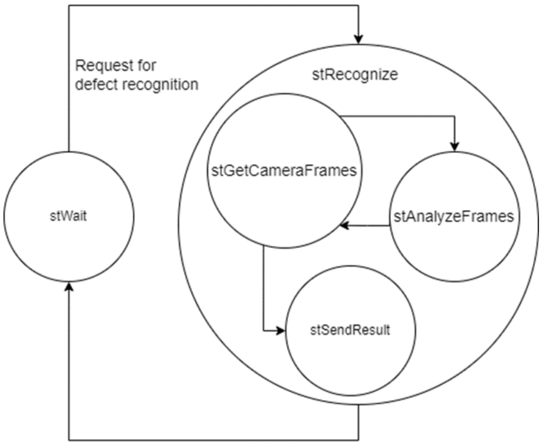

Fig. 4. Visualization of the sequence of states of the recognition state machine.

Therefore, a methodology has been developed for successful defect detection, in which the operator needs to programmatically adjust the perspective, configure the lighting, and determine the video stream processing pipeline.

5. Layered photo fixation

To simplify the analysis of the causes of defects in the FlexADD defect recognition software block, a mechanism for layered photo fixation was introduced. When a command is received to search for defects, this mechanism is activated. At the stGetCameraFrames stage (Fig. 4), in addition to obtaining images for further defect detection, these images are saved in memory. In total, with each of the N cameras, two or three images of the following types will be saved:

- Original frame obtained from the camera.
- Frame with corrected perspective.
- Frame with corrected perspective and defects visualized on it. (This option is not used if there are no defects in the frame).

Creating a detail using SLM technology can contain a large number of layers, and consequently a large number of their saved images. To systematize the photos, a file system has been created. Thus, when the SLM process is launched in the FlexADD program, a special command is received to create a directory containing the project name from the 3D printing process management program. In addition to the project name, the date and time of the process launch are added to distinguish the images made during the production of one project at different times. When the first images are saved in the previously created directory, N folders are created (based on the number of cameras used in the system), with names corresponding to the camera name in the system, set by the user during the initial personalization of the program. The images saved also contain the time of their acquisition (as it may differ from the actual time of saving), the type of image being saved, and the layer number received with the defect recognition command. After applying a structural approach to layered photo fixation, the process of analyzing the causes of defects has been significantly simplified. Progress is especially noticeable compared to the previously used video fixation, where the technician had to search for the moment of defect formation in a hours-long video. Moreover, even after identifying the necessary frame, they did not have information on which specific layer of the 3D model the defect occurred.

6. Video stream processing conveyor

The diversity of possible powder materials used in selective laser melting technology dictates the need to provide the operator with the ability to adjust not only the parameters of the detector itself, but also the types and order of image filters used in processing the input image. In order to provide the user with this capability, a function for customizable video stream processing conveyor was introduced (Fig. 5), following the methodology proposed in [6].

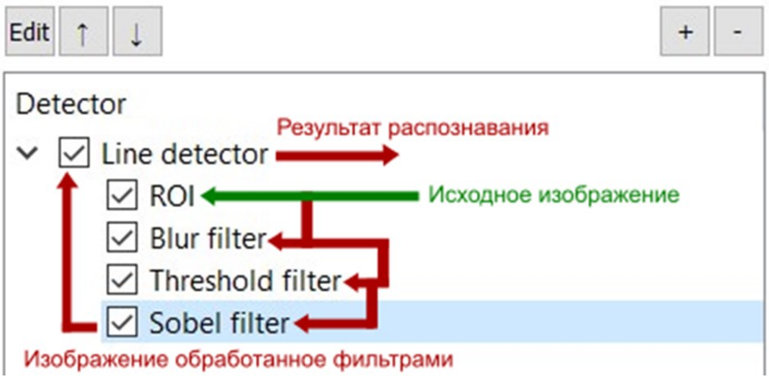

Fig. 5. Video stream processing pipeline.

This mechanism operates with two types of primitives. The first type is detectors, implementing algorithms for defect detection on the incoming frame. The second type is filters, performing preprocessing of the frame before sending it to the detector. The FlexADD defect recognition program implements flexible customization of filters and detectors, allowing interactive visualization of the impact of parameter changes on the frame state (Fig. 6). The arrangement order of filters in the conveyor plays an important role in tuning, as each filter receives an image processed by the previous filter (see Fig. 5).

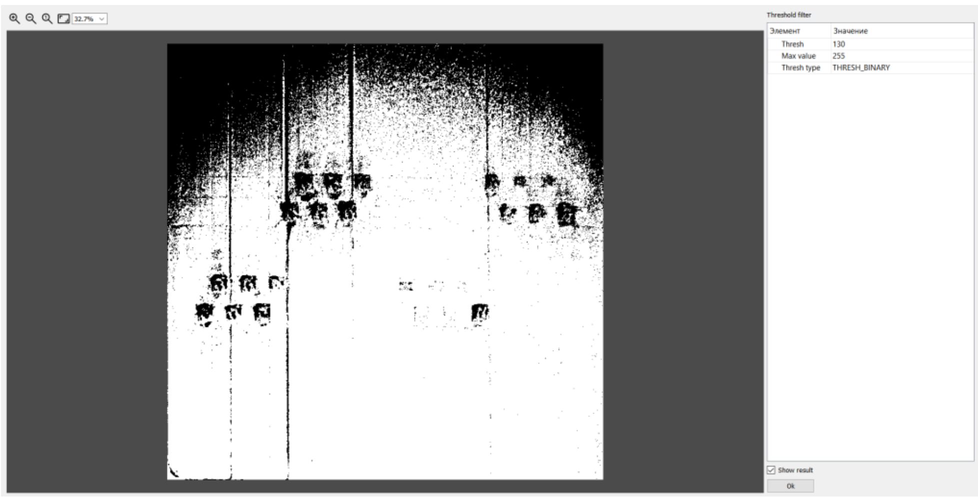

Fig. 6. An example of setting a threshold filter.

Through such processing of the input frame, it is possible to neutralize the difference in physical properties of the powder affecting its display on the camera.

7. Stripe recognition

As already mentioned, stripes can appear as a result of a damaged leveling tool passing over the working surface. To detect the lines left by the leveling tool, a popular method based on Hough transformations [6–8] was applied, let's delve a bit deeper into the principles of its operation with primitives like "straight lines".

A straight line in the image space can be expressed with two variables. For example, in the Cartesian coordinate system parameters: (m, b), or in the polar coordinate system parameters: (r, θ).

For Hough transformations, the linear equation of a line in polar coordinates can be written as:

$$y = \left(\frac{-cos(\theta)}{sin(\theta)}\right)x + \left(\frac{r}{sin(\theta)}\right)$$

For each point (x0, y0), we can determine a family of lines passing through this point as follows:

$$r\theta = x0 \cdot cos(\theta) + y0 \cdot sin(\theta)$$

This means that each pair (rθ, θ) represents each line passing through (x0, y0). If we build a family of lines passing through a given point (x0, y0), we obtain a sinusoid. If we perform the same operation for all image points and find that curves from two different points intersect in the (θ,r) plane (Fig. 7), it means that both points belong to the same line.

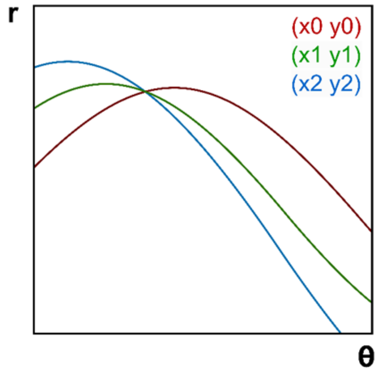

Fig. 7. Three points belonging to the same line.

After traversing the image with this algorithm, the output is the equation of the line in polar coordinates, thanks to which the visualization of the defect on the camera frame is implemented (Fig. 8).

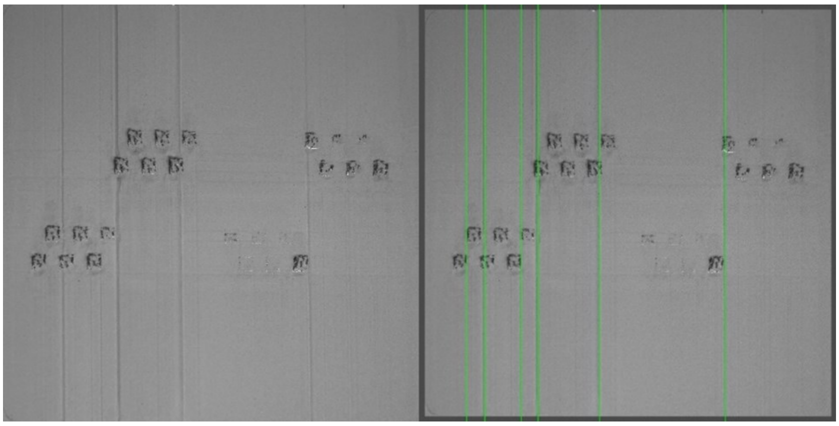

Fig. 8. Detected defects.

8. Conclusion

Additive SLM technology is primarily used to create products with complex geometry, which are either much more difficult or impossible to produce using traditional machining methods. To achieve the required mechanical parameters of the final product, it is necessary to fine-tune the 3D printing process by adjusting the parameters of the technological process [5], which requires significant time investment.

The introduction of our developed defect recognition software module, FlexADD, into the existing structure of the software complex for implementing SLM technology has significantly reduced the time required for adjusting equipment parameters during the 3D printing process. This was achieved by identifying defects at any stage of 3D printing, allowing the immediate termination of the lengthy technological process of creating a defective product. Early defect detection and process stoppage enabled savings on metal powder, thus reducing the production costs of parts.

The application of the FlexADD defect recognition software module in practice resulted in a more complex equipment setup for 3D printing, as the operator of the laser technological system needs to adjust a number of parameters: filters, detectors, as well as lighting configuration and perspective. However, it is worth noting that the configuration of our software module is not tailored to specific products but to the metal powder used in printing, which is convenient for serial production.

The implementation of the FlexADD defect recognition software module has led to a reduction in the overall time spent on adjusting technological parameters of SLM technology and a reduction in the production costs of this process through metal powder savings by halting the process in the event of defects. The analysis of the reasons for defects has been simplified by integrating layer-by-layer photofixation into the software complex, indicating the time and layer number of the saved image.

Acknowledgments

The authors express their gratitude to the management of the "Lasers and Equipment TM" group of companies for their assistance in providing material and technical support for conducting experimental research and modeling the considered process.

References

1. Molotkov A.A., Tretiyakova O.N. On possible approaches to visualizing the process of selective laser melting // Scientific Visualization. 2019. Vol 11. № 4. PP. 1-12.
2. Molotkov A.A., Tretiyakova O.N., Tuzhilin D. N. About development and application of a software platform for machine vision for various laser technologies // Scientific Visualization 2022. №5. P.P.108-118.
3. Molotkov A.A., Tretiyakova O.N. Application of machine vision and mathematical modeling methods for the development of electronic device creation technologies // Instruments. 2022. № 4. P.55-58.
4. Molotkov A. A., Saprykin D.L., Tretiyakova O. N., Tuzhilin D. N. Development of a complex of programs for the creation of industrial laser technological equipment // Instruments. 2022. № 5. P.15-22.
5. Molotkov A.A., Tretiyakova O.N. Work out of technological modes in the creation of SLM technology. // Instruments. 2023. № 8. P. 44-47.
6. Kudrina M.A. The use of Hough transformation for detecting straight lines and circles in an image // Proceedings of the Samara Scientific Center of the Russian Academy of Sciences, 2014.
7. Kudrina M.A., Kiryakov S.A., Kudrin K.A., Degtyareva O.A. Vectorization of raster images using Hough transformation // "Reliability and Quality". 2013. №1. P. 337-340.
8. I. A. Matveev, V. I. Tsurkov, N. N. Chinaev, "Forming the pupil circle using the Hough transformation for the boundaries of connected components", Autom. Remote Control. 2015, № 11, 104–117; Autom. Remote Control, 76:11 (2015), 1988–1999.