Scientific Visualization, 2025, volume 17, number 4, pages 57 - 64, DOI: 10.26583/sv.17.4.06

This paper is an extended version of a contribution presented
at the Graphicon 2025 conference.

Development and Application of Machine Vision Algorithms for Workpiece Positioning in Multi-Axis Laser Processing

A.A. Molotkov[1,A], O.N. Tretyakova[2,A], D.N. Tuzhilin[3,B], A.A. Shamordin[4,B]

[A] Moscow Aviation Institute (National Research University), Moscow
[B] LLC "Laboratory of Industrial Research," Lasers and Equipment TM Group, Moscow

[1] ORCID: 0000-0002-9335-5219, karacerr@gmail.com
[2] ORCID: 0000-0003-0256-4558, tretiyakova_olga@mail.ru
[3] ORCID: 0000-0002-8570-1732, tuzhilin@laserapr.ru
[4] ORCID: 0009-0001-5092-3351, amordin@laser-app.ru

Abstract

This paper addresses the problem of positioning workpieces with curved surfaces for subsequent multi-axis laser processing. The solution is based on recognizing the position of the drawing's zero point, physically formed by surface height variations of the workpiece. The paper presents an approach to visualizing and detecting the drawing's zero point using machine vision algorithms applied to a video stream from an industrial digital camera. An algorithm for object boundary detection is described, employing a modified breadth-first search (BFS) with subsequent path reconstruction to the boundary. The developed software module is capable of detecting either the coordinate of a hole center or a workpiece boundary, relative to which multi-axis processing is carried out. In addition, the features of calculating the pixel-to-millimeter conversion coefficient for axis motion are considered, enabling precise movement according to the video channel image. This approach significantly reduces the time required for manual positioning and improves both accuracy and repeatability of the process.

Keywords: multi-axis positioning, video-based positioning, image processing, filtering pipeline, machine vision.

1. Introduction

The present work continues and develops our previous studies [1–7] aimed at creating and improving software for automating technological processes in domestic high-tech CNC laser equipment. Under modern conditions of scientific and technological progress, the use of components with complex spatial geometry, particularly with curved and spatially developed surfaces, has become increasingly important in mechanical engineering. Such elements are integral components of high-load, high-performance systems of various applications. Examples include gas and steam turbine blades, jet engine combustion chambers, centrifugal pump impellers, compressor impellers, and other components used in power engineering, aviation, transportation, and marine industries.

The application of geometrically complex components allows a substantial expansion of machine functionality, improvement of operational characteristics, and a higher level of adaptability in technological processes. Accordingly, requirements for processing accuracy and positioning of such parts are growing, which makes the problem of automated control particularly relevant.

Problems of spatial positioning using machine vision are actively studied in a number of works. For example, [8] considers the integration of machine vision into modular equipment positioning. In [9], a method of automated tool positioning for modular equipment based on visual analysis is proposed. In [10], the application of computer vision to correct control programs through boundary analysis is described. Analysis of such studies shows that existing solutions are generally oriented toward flat or reference objects and rely on template matching.

The novelty of our proposed approach lies in using natural height differences on the workpiece surface, visualized as contrast boundaries in an image, for automatic determination of the drawing's zero point. Unlike template- or marker-based methods, our system uses a modified breadth-first search (BFS) algorithm to extract object boundaries and determine either the edge coordinate or the center of a hole. The resulting information is used to calculate the conversion coefficient from image pixels to real machine coordinates. This approach enables highly accurate alignment of the control program with the actual workpiece position, with minimal time cost and without complex preparatory procedures.

2. Problem statement

The production of workpieces with curved surfaces generally includes several sequential stages, performed on different types of equipment. At each transition between stages, it is necessary to reposition the workpiece to align the control program, which contains tool paths, with the actual position of the object in the machine's working space. Failure to ensure alignment accuracy may result in defective or poor-quality products.

Traditional positioning methods typically involve the use of contact sensors that probe the workpiece surface step by step, or the use of high-precision fixtures that fix the workpiece in a strictly defined position. However, such approaches are not always applicable, especially when working with objects that have geometric deviations obtained at previous production stages. In some cases, traditional methods require considerable time for preparatory operations.

Thus, the main objective of the study was to reduce positioning time in multi-axis laser processing and simplify the preparatory stage. To solve it, a method was developed to detect either the coordinate of a boundary or the center of a hole (a test specimen is shown in Fig. 1) using an optical video channel, which involves recognition of height differences and calculation of their position by computing the pixel-to-millimeter conversion coefficient.

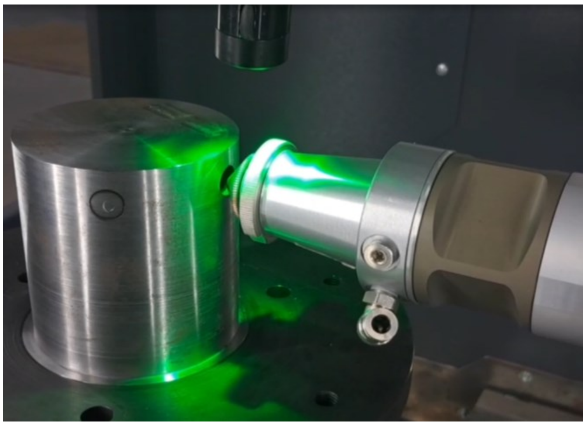

Fig. 1. Test specimen – cylinder with hole

3. Software module architecture

To solve the problem of locating the drawing's zero point, functionality was developed within the existing FlexMV software module, integrated into the control system, to recognize primitives that can be interpreted as reference points for multi-axis processing. The program code was written in C++17 with the Qt 5.15 framework. To simplify implementation of recognition algorithms and video stream processing from the industrial camera, the OpenCV library was used. Visualization of recognized objects and video display were implemented with

Qt tools supporting OpenGL. The use of cross-platform technologies enables effective operation in both Windows and Linux environments.

As noted earlier, the FlexMV module has a high degree of integration with the FlexCNC control system through TCP/IP protocol interaction. This inter-program communication allows FlexMV to initiate kinematic system actions without considering motion control details or synchronization. Such an approach made it possible to abstract from low-level device interaction and focus on implementing control algorithms.

Given the variety of laser system operating conditions and the wide range of processed materials, it is necessary to provide the operator with fine-tuning capabilities not only for detector parameters but also for filter types and their application sequence in video frame processing. To implement this functionality, a software pipeline system was integrated into FlexMV, first introduced in [4] and further developed in [5–7]. The software pipeline (Fig. 2) operates with two types of primitives:

- Detectors — algorithms for recognizing patterns in the input image.
- Filters — algorithms for pre-processing frames to improve subsequent analysis conditions.

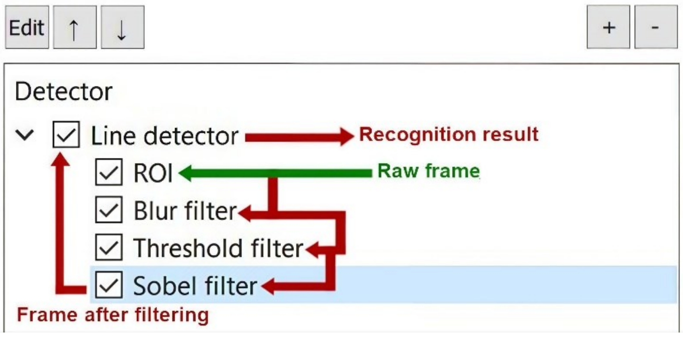

Fig. 2. Video stream processing pipeline

To understand the following discussion, it is necessary to describe a simplified structure of task execution in our control system. In addition to conventional G-code commands and tool commands, the control program may contain extended commands representing predefined sets of actions with deterministic results. These extended commands may include tool control routines, G-code sequences, or may temporarily delegate execution to other programs.

Thus, from the operator's perspective, the functionality for detecting the drawing's zero point is implemented as a call to one such extended command with parameters. When FlexCNC encounters a zero point search command, it transfers execution to FlexMV, whose result is tool positioning at the starting point of the main program execution. This approach contributes to task separation between staff: the technologist prepares and debugs the program once for a batch of parts, while the operator executes it without considering technological details or positioning features.

4. Zero point detection

When FlexMV receives an assignment to search for a zero point formed by height differences, the program activates the finite state machine FindEdgeSequence, a simplified scheme shown in Fig. 3.

At the first stage, preliminary edge recognition is carried out. Parameters of detectors and filters (stSearchConnect) are loaded into the video stream pipeline, and when the detector reports activation, movement (stSearchMovement) begins in the direction of the expected workpiece edge. To define the direction of motion and correct position calculations, the extended command specifies the motion axis (X, Y, Z, A, B) and the frame direction (vertical, horizontal). The motion axis is required to properly generate the search trajectory. The frame direction parameter arises because in multi-axis tasks, the axis movement direction cannot be uniquely tied to the object movement direction in the 2D image. Automatic determination of the frame direction is possible by analyzing frame shifts during positive and negative axis movement, but this process takes extra time and requires bidirectional motion from the initial position, which may be inadmissible due to workpiece geometry. During motion, the detector operates asynchronously, implementing recognition via the modified BFS algorithm (described in the next section). When a boundary is detected, the detector sends an objects detected signal, initiating the transition of the finite state machine to stStopMovement. In this state, FlexMV halts motion and, after receiving feedback from FlexCNC (PC based CNC software) confirming the stop (movement stopped), transitions to stCheckBorder, where it checks whether the boundary remains within the field of view. This is necessary because kinematics cannot stop instantly, and high initial speed may result in overshooting beyond the field of view. If after stopping the boundary is still confidently recognized, FindEdgeSequence calculates the image coordinate. In stSetFirstPos, the current motion axis coordinate (firstPosMm) and boundary position (firstPosPx) are stored. Then in stSetROI, a region of interest is set at the opposite end of the field of view, where the recognized boundary must be moved. Motion is repeated in stSearchMovement in the same direction but at reduced speed. Upon detection in the new ROI, motion halts in stStopMovement and the positions secondPosMm and secondPosPx are stored in stSetSecondPos. Then in stCalcBorderPosition the conversion coefficient is calculated:

$$pxToMm = \frac{secondPosMm - firstPosMm}{secondPosPx - firstPosPx}$$

This coefficient converts image pixels to millimeters of axis motion. Finally, in stMoveToEdgeCoordinate the tool is moved to the detected boundary coordinate, recalculated in millimeters using pxToMm. FlexMV then returns control to FlexCNC, which assigns the current position as the coordinate system origin and executes the remaining program.

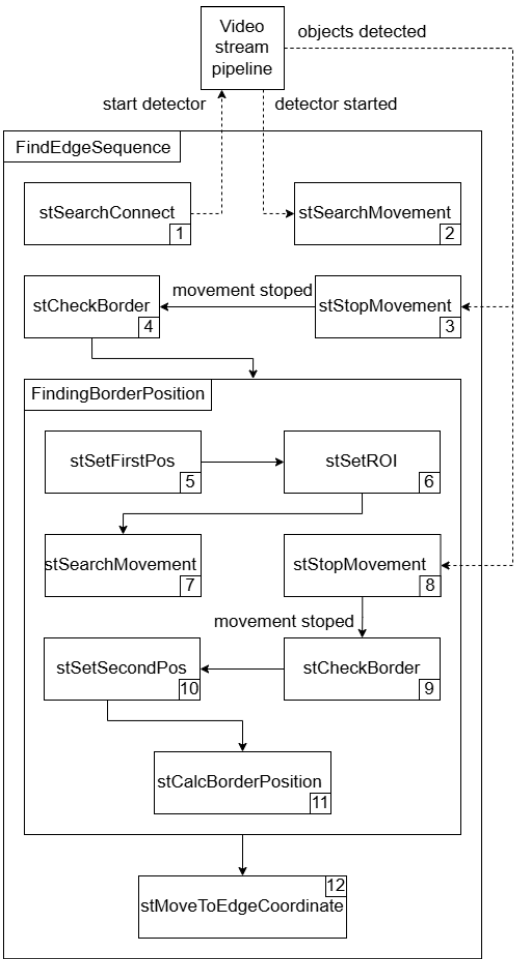

Fig. 3. Finite state machine for zero point detection

5. Boundary Recognition

As noted earlier, boundary detection is based on recognizing surface height differences, which in a 2D image appear as contrast edges: the darker part corresponds to a surface located further from the focal plane of the camera lens than the lighter part. A modified breadth-first search (BFS) algorithm is used. The algorithm (Fig. 4) proceeds step by step:

1. Input image binarization using an inverse threshold, resulting in a clear separation into depth zones: lighter pixels are treated as 1, darker as 0.
2. Matrix initialization with values of -1, equal in size to the input image, followed by subtraction of the binary matrix, yielding values of -1 and -2.
3. Distance map construction: each pixel is assigned a value corresponding to its distance from the starting point, excluding pixels with -2.
4. Reverse traversal of the distance map: the algorithm sequentially moves to neighboring pixels with lower depth values, while evaluating invalid values (-2) in the neighborhood, forming a trajectory back to the starting point. Coordinates of intermediate nodes are stored in an array for later visualization and boundary calculation.
5. Boundary coordinate calculation: the pixel coordinate of the boundary is computed as the arithmetic mean of all boundary node coordinates.

To improve stability, edge pixels of the image are checked first, enabling quick detection of contours crossing the frame. Pre-exclusion of light pixels reduces the search area and noise influence.

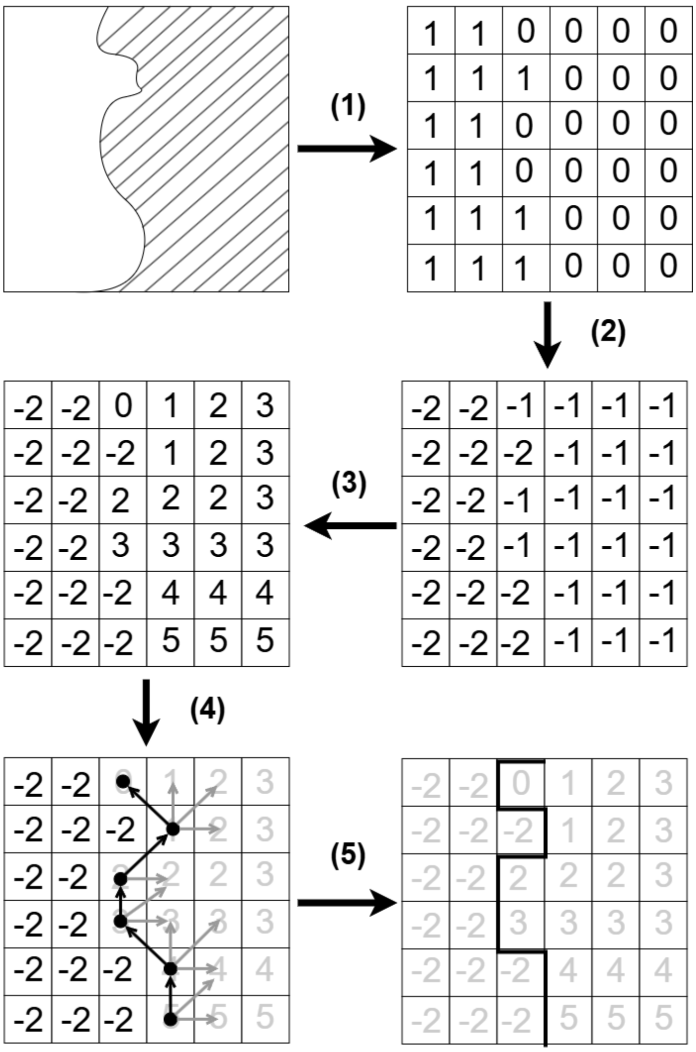

Fig. 4. Boundary recognition algorithm

After applying this algorithm, the output is an array of boundary points in pixel coordinates, enabling visualization on the input image (Fig. 5) and calculation of the boundary position.

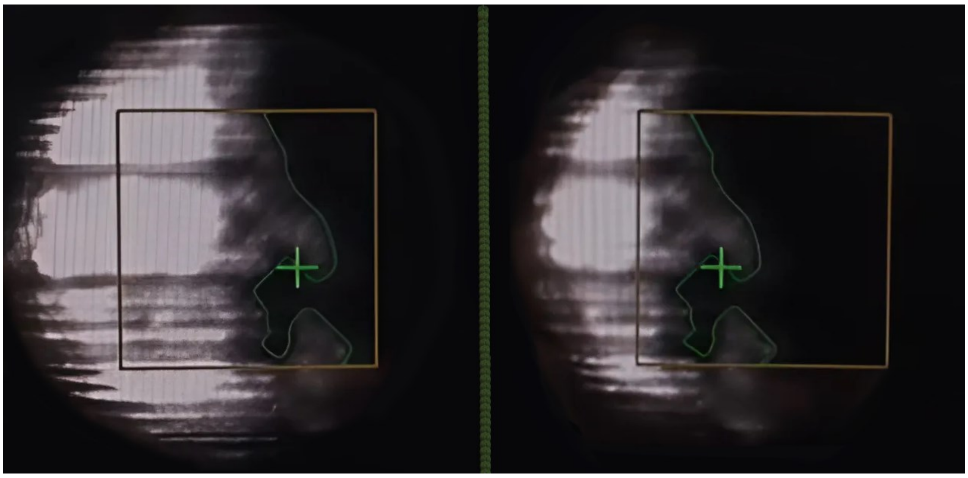

Fig. 5. Boundary recognition on the test specimen

Conclusion

The developed method for detecting the drawing's zero point using an optical video channel and the FlexMV software module solved the problem of positioning workpieces with curved surfaces in multi-axis CNC laser systems. Unlike traditional contact-based methods and expensive fixtures, the proposed approach identifies surface height differences by interpreting their image boundaries, thereby ensuring precise alignment of the control program with the actual workpiece position.

Practical application required configuration of filter, detector, and lighting parameters at the initial integration stage. However, these settings are determined not for a specific part but for equipment and material characteristics, simplifying transitions between production batches and minimizing reconfiguration time.

As a result of implementing the new functionality into the control system, workpiece positioning time was reduced, the influence of the human factor was decreased, and process repeatability and reliability in serial production were improved.

Acknowledgments

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

References

1. Molotkov A.A., Tretiyakova O.N. On possible approaches to visualizing the process of selective laser melting // Scientific Visualization. 2019. Vol. 11. No. 4. Pp. 1–12.

2. Molotkov A.A., Tretiyakova O.N. Application of machine vision in laser technologies // Electronic Journal "Proceedings of MAI." No. 127. 2022.

3. 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. No. 5. Pp. 108–118.

4. Molotkov A.A., Tretiyakova O.N. Application of machine vision methods and mathematical modeling for developing technologies of electronic device fabrication // Instruments. 2022. No. 4. Pp. 55–58.

5. Molotkov A.A., Saprykin D.L., Tretiyakova O.N., Tuzhilin D.N. Development of a software suite for creating industrial laser technological equipment // Instruments. 2022. No. 5. Pp. 15–22.
6. Molotkov A.A., Tretiyakova O.N. Testing technological regimes in the development of SLM technology // Instruments. 2023. No. 8. Pp. 44–47.
7. Tretyakova O.N., Tuzhilin D.N., Shamordin A.A. Research and Application of Machine Vision Algorithms for Defect Detection in Additive Technologies // Scientific Visualization. 2025. Vol. 17. No. 1. Pp. 114–121.
8. Afanasyev M.Ya., Fedosov Yu.V., Krylova A.A., Shorokhov S.A. Application of machine vision in problems of automatic tool positioning in modular equipment // Izvestiya Vysshikh Uchebnykh Zavedeniy. Instrument Engineering. 2020. Vol. 63. No. 9. Pp. 830–839.
9. Peshkova A.M., Kuts M.S., Petrukhin V.Yu. Application of computer vision in workpiece positioning on CNC machines // Young Scientist. 2020. No. 52. Pp. 174–177.
10. Mozhaev R.K. et al. Application of machine vision technology to improve accuracy of focused laser action on microelectronic structures in research and micromachining processes // Information Technology Security. 2023. Vol. 30. No. 4. Pp. 150–161.