Problems of Trajectory Building During Laser CNC Processing

Yuri V. Fedosov, Maxim Ya. Afanasev
Anastasiya A. Krylova, Sergey A. Shorokhov
ITMO University
St. Petersburg, Russian Federation
yf01@yandex.ru, amax@niuitmo.ru
{ananasn94, stratumxspb}@gmail.com

Sergey V. Akimov
The Bonch-Bruevich Saint-Petersburg
State University of Telecommunications
St. Petersburg, Russian Federation
akimov-sv@yandex.ru

***Abstract*—The paper deals with the problems of trajectory building during laser computer numerical control (CNC) processing and presents a new approach to the optimization of the CNC tool trajectory during laser treatment of irregular shapes. The development of the firmware of the CNC machines encounters a number of problems, the most important of which is minimization of the processing time. Two main methods of time reduction are provided—by increasing speed of the treatment using smooth aliasing of acceleration/deceleration curves and reducing the number of auxiliary moves. The processing is represented as nodes, forming a terminating device trajectory. The CNC controller defines trajectory between the nodes, and the terminator is moved from node to node step-by-step. Decreasing the processing time is possible when the CNC tool is scanning paths to be processed and combine acceleration/deceleration curves to reach a maximum speed is considered. A genetic algorithm with crossover similar to the crossover used to solve the travelling salesman problem to reduce the number of auxiliary paths is proposed. The chromosomes formed by building blocks, each of them defining trajectory segments sequence and their orientation are compiling the used algorithm. To change the adjacent segments, heuristics is used so the path between ends of segment, hence the length of the auxiliary part, will be as short as possible.**

I. INTRODUCTION

Modern instrument-making production cannot be realized without advanced technologies. The key method is the use of technological equipment with computer numerical control (CNC). Since the late seventies of the last century such equipment has been constantly improving and now we have new, useful types of machines such as 3D-printers, 3D-scanners, automated assembly lines, laser engravers, marking systems, as well as hybrid and adaptive technological systems [1]. Research and development of the algorithms of CNC functioning is a complicated task, which includes the problem of minimizing the processing time in regards to equipment software and hardware abilities and their motor drives mechanical characteristics [2], [3]. As it can be seen in [4], [5], the trajectory optimization can be one of the main sources of problems regarding the productivity and the quality of the surface machining process.

Note, that any CNC-controlled technological equipment includes a mechanism for moving a terminating device along the specified trajectory. Certainly, its efficiency (especially the processing time) depends on the moving trajectory and speed of the mechanism. Obviously, the choice of equipment components corresponds to the principal production system efficiency criterion—production time minimizing. This creates the problem of the trajectory formation during laser CNC processing.

Generally, the trajectory building problem consists of finding a relationship between the time and path to be processed. Accordingly, the trajectory is usually expressed as a parametric function of time, which provides at each instant the corresponding desired position [6]. Obviously, after having defined this function, other aspects related to its implementation must be considered also. In the common machining process, computer-aided manufacturing (CAM) software generates tool paths. Managing the geometry of the tool path, as well as the kinematic parameters of the machine tool, are two key factors for quality and productivity improvements [7].

While most of the existing feedrate planning algorithms take velocity and acceleration into consideration as capability constraints, the introduction of higher order dynamic states, such as jerk and/or jounce, makes the feedrate planning and optimization extremely challenging, as the dimension of the planning problem is increased accordingly [8]. A key issue is to improve the machining feedrate while keeping the machining precision and satisfying the acceleration constraints of the CNC machine [4]. Trajectory planning includes velocities, accelerations, and jerks along the path. A common task is to find trajectories for a priori specified paths, which fulfill a certain criterion (e. g., minimum execution time) [3].

There are two main methods of trajectory planning: on-line and off-line. On-line trajectory planning is a real-time adaptive motion planning during program execution, off-line planning is NC-code pre-operation to find the continuous paths of the maximum length and auxiliary passes minimization.

As a solution to the problem of off-line planning, we propose the using of genetic algorithms. Genetic algorithms are widely used in the designing and optimization of the CNC software [9]. In particular, the work [10] describes the use of a genetic algorithm in order to obtain the non-dominated sorting genetic algorithm (NSGA-II) and build the Pareto front graph for the creation of a multi-objective optimization technique to optimize the cutting parameters in the turning processes: cutting depth, feed, and speed. The paper [11] is dedicated to the problems of the application of genetic algorithms in computer-aided process planning (CAPP). In other words,

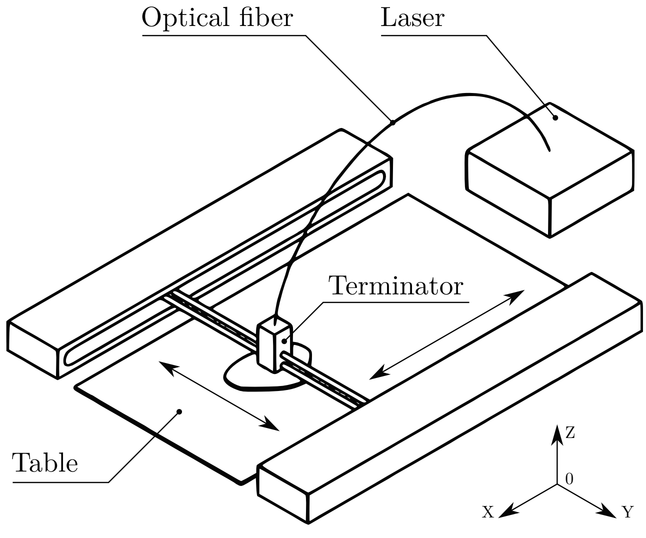


Fig. 1. Experimental device for laser processing

for the systematic determination of the machining methods (operations, machine, tool, fixture) by which a product is to be manufactured economically and competitively. Wang et al. [12] in their work investigated the issues of the application of the genetic algorithm integrated with an artificial neural network used for researching the optimal process parameters of a serial-parallel hybrid polishing machine tool. Tarokh and Zhang [13] presented a genetic algorithm approach to real-time motion tracking of redundant and non-redundant CNC manipulators.

This can be used for processing the blank materials using the complicated trajectories comprised of plenty of separated lines. For example, when producing on a 3d-printer voluminous parts with various supporting structures inside, or during cutting of large amounts of irregular parts from a metal sheet, or when producing parts with a lot of holes on the plane surface.

The rest of the paper is structured as follows. Section II contains a short description of the experimental CNC device. In order to investigate a velocity influence to the quality of laser processing, series of experiments with a photopolymer coated plate were held. The figures with the results displayed in the same section. Real-time and pre-operation optimization approaches are given in sections III and IV, respectively. Moreover, section IV represents a new approach to the pre-operation optimization based on genetic algorithm. Section V contains a conclusion and summarized results.

II. EXPERIMENTAL DEVICE FOR LASER PROCESSING

Consider the principal processing time minimizing methods exemplified by a device for selective polymer curing. Device (Fig. 1) is intended for laser processing of the surfaces of irregular shapes. It is comprised of a stationary worktable, on which an object is placed, a laser head moving in two directions is installed above the mount, and a laser beam source is optically coupled with the laser head [14–16].

A die plate coated with photopolymer is used. It was proved experimentally, that by using the emission source and moderating power (we used a solid-state laser of 405 nm wavelength and optical power of 500 mW) moving the speed of laser head has insignificantly influenced the polymer curing quality. Fig. 2 shows one of the experimental dies. This die is made of copper foil-laminated epoxy laminate sheet grade FR-4 coated with positive photoresist POSITIV20. During the experiment, after die processing it was developed in a $1\,\%$ solution of caustic soda, and then was poured with iron chloride to eliminate the copper from undeveloped areas. It should be noted, that in the speed range from 500 to 950 mm/min lines left by the laser beam have closely the same width.

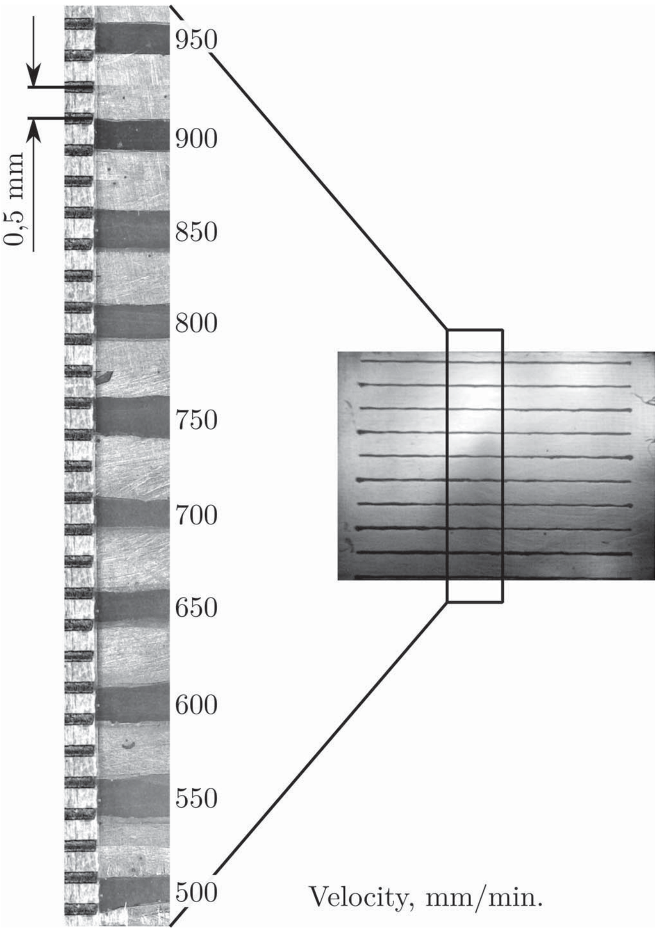


Fig. 2. Laser tracks on processed die (velocity in mm/min.)

This prompted the idea that further increasing the speed will decrease the processing time along with preserving an emission density capable of regular photoresist curing. In other words, selective polymer curing can be treated as high production, hence the processing trajectory must be optimized to work at maximum speed.

III. REAL-TIME TRAJECTORY OPTIMIZATION

The first optimization problem is achieving the maximum path velocity. In fact, every CNC program is represented as a sequence of commands, and most of them are describing the tool positioning. Therefore, the tool's path is a sequence of the segments. In CNC machines linear and circular interpolation is organized, therefore segments will be presented as lines and arcs. For each command (frame) the feedrate

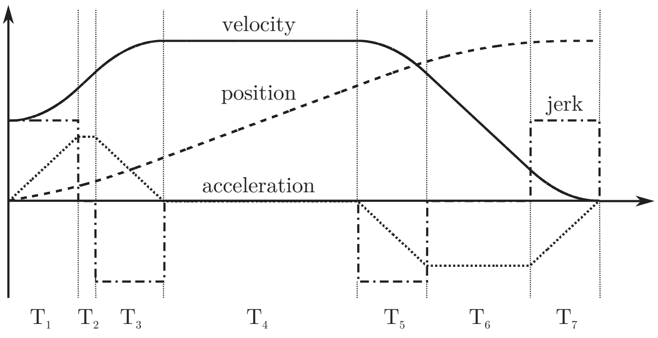


Fig. 3. Typical profiles for position, velocity, acceleration and jerk for the double S trajectory

is set, and ISO 6983-1:2009 [17] standard does not state that the machine must accelerate up to a given speed on the trajectory path described in the frame. It has been proved experimentally that an engines' mechanical characteristics do not allow the system to reach the maximum path velocity, set by the feed rate. Consequently, no engine can start at a high speed and simultaneously provide the suitable amount of torque.

For every CNC machines engines type exists, there is a correlation between the speed and time, in other words, the acceleration-deceleration graph. Generally, this graph is given by a trapezoid where, at the start, the mechanism accelerates until it reaches the necessary speed, then the mechanism moves at constant speed, and at the end, it decelerates linearly. The problem is that the feeding parameter is not tied to the frame length. Therefore, on the short trajectory segments when deceleration begins after acceleration the trapezoid graph degenerates into a triangle, and the device may not reach the necessary processing speed. It is clear that during frame-by-frame processing the trajectory composed of lots of short frames for executing the mechanism moves jerkily. This causes vibration and forces wear on the engines and other moving parts [18]. The following approach is proposed to optimize the trajectory during NC code processing:

1) *Reject the acceleration-deceleration trapezoid in favour of the double S trajectory* (Fig. 3). In view of the experimental results a conclusion was reached that such a trajectory enables optimization not only of the second coordinate derivative with time, but also of the third—the jerk. The controlled jerk provides the versatile control of acceleration and deceleration parameters in the short frames and reduces the loads on the equipments mechanical parts [19], [20].
2) *Algorithm of two-pass analysis of the NC-code.* On the first pass general trajectory characteristics will be evaluated such as the segments' lengths and their feed rates, and then the trajectory will be divided into equal blocks. On the second pass, a buffer to store blocks will be created for which acceleration-deceleration parameters must be calculated according to their combinations. The buffer size is variable and depends on the maximum speed, set in the NC-code. Consequently, the number of blocks stored in buffer will be enough to stop the moving mechanism after processing all motion parameters satisfactorily (that means without exceeding the maximum acceleration and jerk parameters). This approach will allow the moving mechanism to accelerate or decelerate slowly through several blocks to achieve its desired path velocity.

IV. OPTIMIZATION DURING NC-CODE PRE-OPERATION

Another principal task besides the real-time optimization is the processing of trajectory improvement before running it on the CNC-machine. Three approaches can be highlighted to shorten the processing time:

- a search of the longest continuous trajectory part without sharp edges, where a terminator (the laser head) can reach maximum speed, considering maximum acceleration and jerk;
- the shortening of auxiliary passes, when the head is moving while the laser is switched off;
- a combination of the first two approaches enables finding the longest trajectory without sharp edges including both manufacturing and auxiliary passes in relation to a small time for switching the laser on and off [21].

The following is proposed. At first, place the grid with certain subintervals is applied on the area to be processed. The processing trajectory is represented as nodes and many edges, and it is split into segments, which are enumerated in the list. Each segment in the list represents the trajectory direction, and their order defines the tracking sequence. The trajectory tracking time is formed by the time taken to track all the segments (when the laser is on) and the time to perform all the auxiliary passes at the maximum speed (Fig. 4).

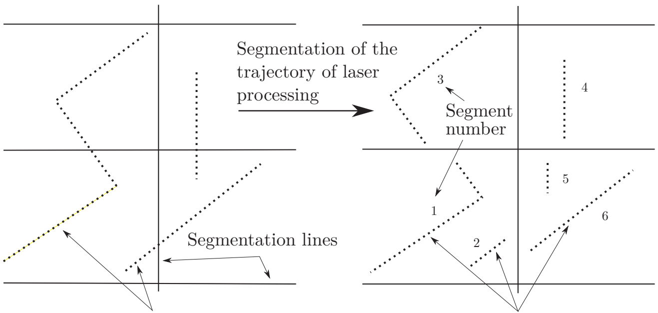
Each segment can be represented as (1):

$$S_{(j)} \overset{\text{def}}{=} \langle x_a, y_a, x_b, y_b, l, v, t, d, i \rangle \, , \tag{1}$$

where x_a, y_a, x_b, y_b are coordinates of the segment start and end points (points a and b respectively), l is segment length, v is the segment tracking trajectory speed, t is the segment tracking time, d is the segment tracking direction, and i is the segment number in processing list.

The segments list completely defines the processing trajectory (2):

$$List \overset{\text{def}}{=} \langle S_{(i,j)} \rangle, i, j \in \overline{1,n} \, , \tag{2}$$



INITIAL MAP OF THE TRAJECTORY OF LASER PROCESSING

SEGMENTED TRAJECTORIES OF LASER PROCESSING

Fig. 4. Formalizing scheme of the treatment radiation trajectory

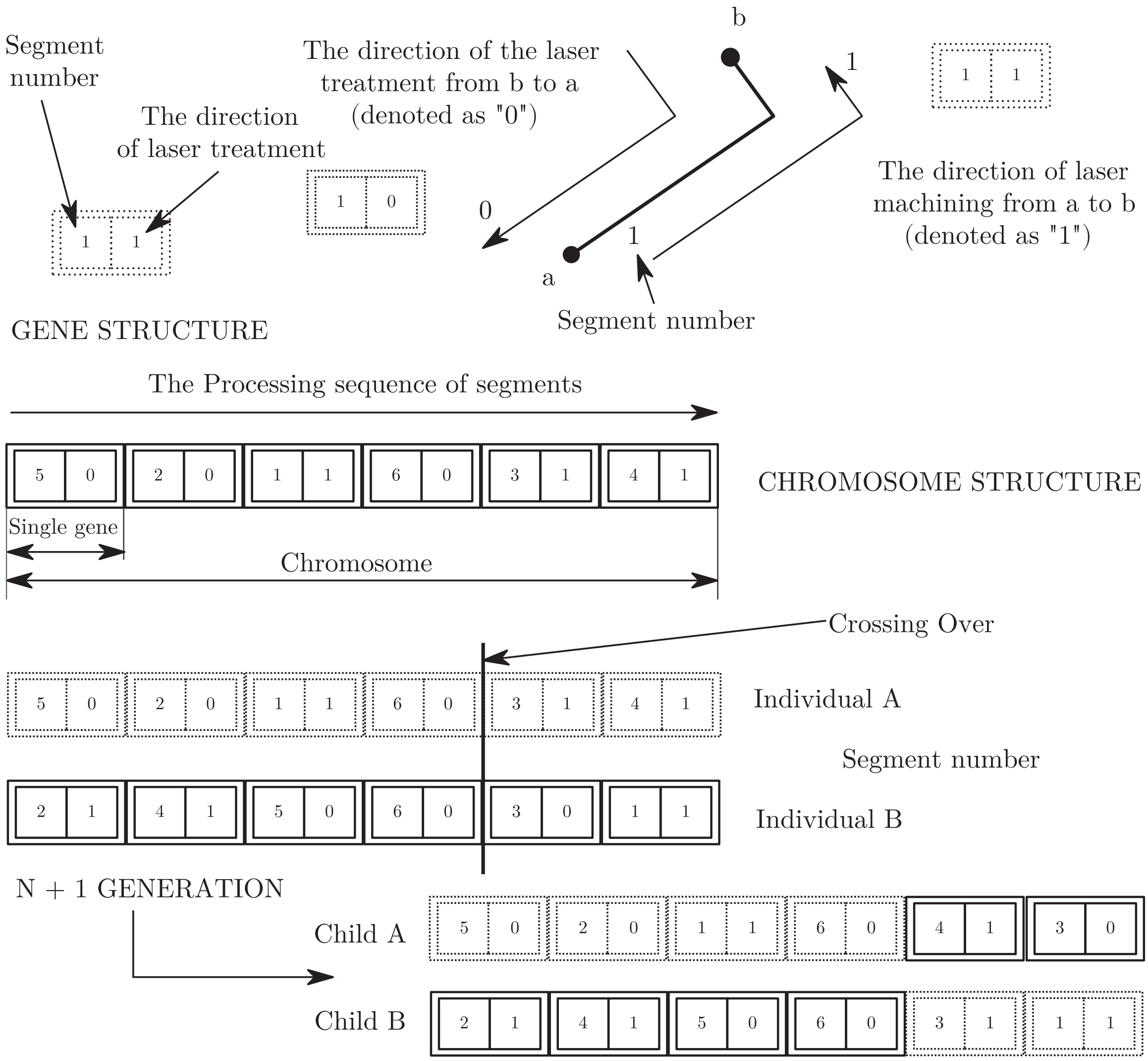


Fig. 5. Genetic modelling of the optimization of the trajectory when handling radiation

where n is the number of segments, i is the segment identifier, and j is the segment number in the list determining the processing list. Then the processing time is (3):

$$T = T_p + T_{idle}, \tag{3}$$

where T_p is the time to pass the processing trajectory (working parts), T_{idle} is the total time spent to move the laser head from one segment to another in addition to the time necessary to move from the base point to the first segment and from the last segment to the base (starting point). In other words, the time for auxiliary passes.

Hence, the optimization problem can be formulated as finding the sequence of treatment segments and their orientation (beginning and end of the treatment) at which time, T will be minimal. As the time spent on the laser treatment of the segments is independent of the sequence of the processing segments, the interest is to minimize only the time T_{idle}.

Considering the fact that the engines moving the laser head in two coordinates can work independently, the free run time between two active modes will be proportional to the maximum increment for each axis (4):

$$T_{idle(i)} = k \max(|x_a - x_b|, |y_a - y_b|) \tag{4}$$

Total time of auxiliary passes will be (5):

$$T_{idle} = \sum_i T_{idle(i)}, i \in \overline{1,n} \tag{5}$$

This problem can be solved using genetic algorithms (Fig. 5). We propose the following solution. A chromosome will be composed of genes, describing the segments tracking sequence and their orientation and defining processing direction (Fig. 5). Each individual gene contains information about a segment number and the direction of processing for determining the movement of the laser head along the segment. In the case when the laser head moves in the direction from a to b, it is denoted as a “0” and in the case of movement in the opposite direction it is “1”. The sequence of genes in the chromosome determines the sequence of laser processing of individual segments, and thus, the chromosome uniquely

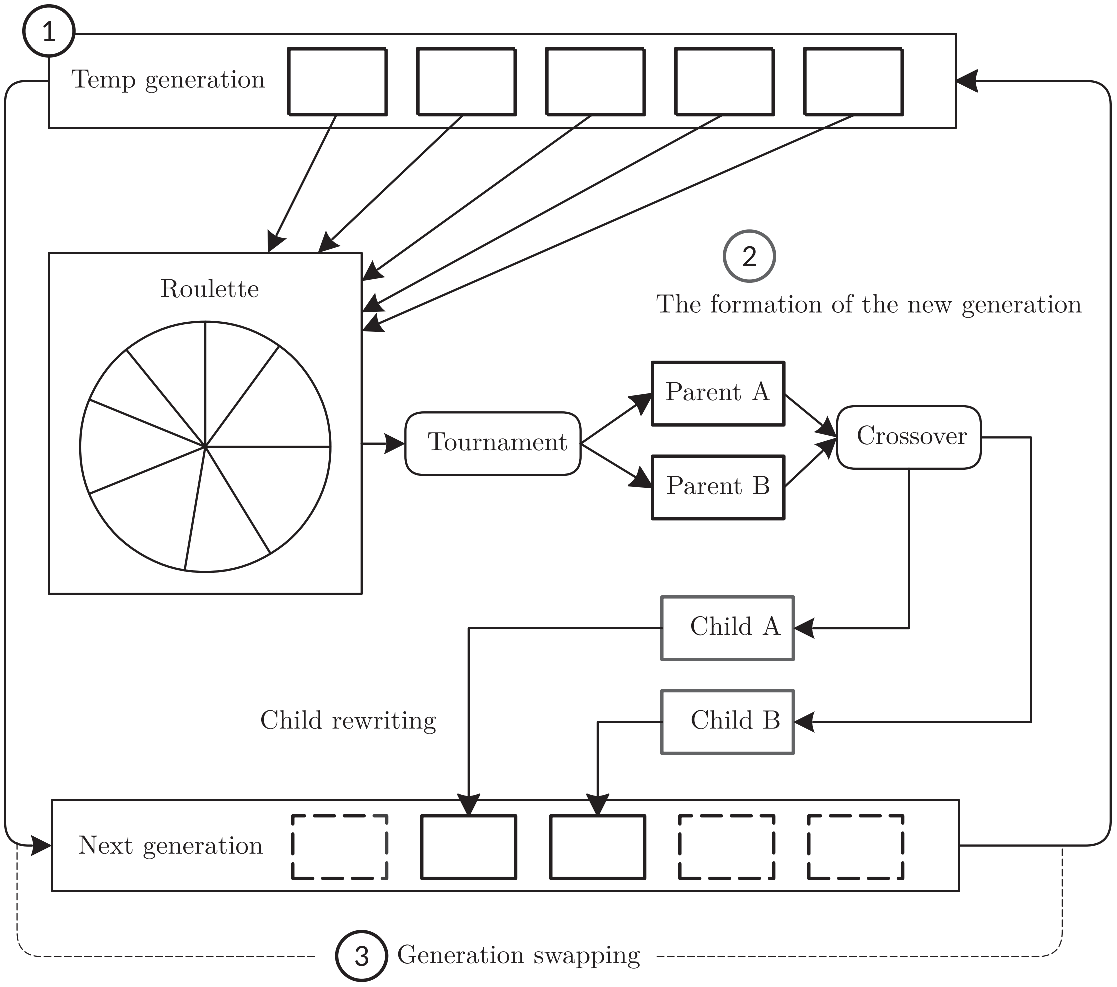


Fig. 6. The scheme of functioning of the program

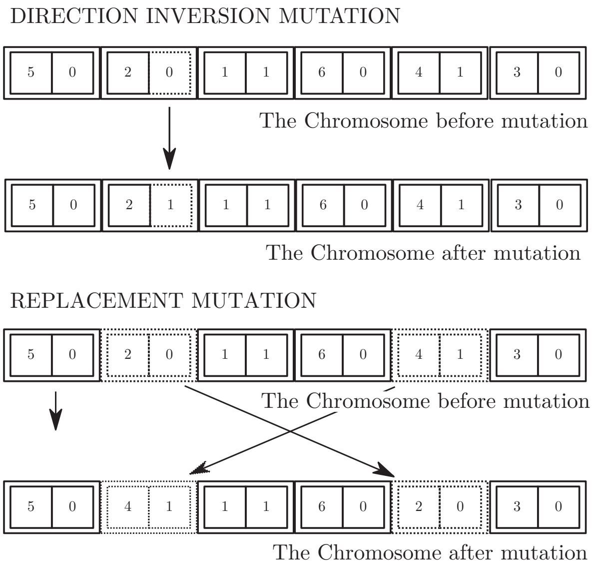


Fig. 7. Mutation types

encodes the trajectory of the laser head in the machining process of the product.

Given the feature task, one must use the crossing-over, keeping all the genes included in the parent chromosomes. If it will not execute this condition, a portion of the segments to be processed will not be processed and some segments are processed twice. This type of crossing-over was studied and applied to solving problems of the travelling salesman by genetic algorithms. The simplest form of the crossing-over operator is shown in Fig. 6. The mutation operator may be in the direction of the processing segment and in the rearrangement of individual segments (Fig. 7).

The genetic algorithm's crossing-over will be similar to the crossing-over used to solve the travelling salesman problem (two parts of the first parent are copied and the rest between is taken in the same order as in the second parent), with the exception of adding of the direction of passage of the d-segment [22], [23].

As genetic algorithms have shown their effectiveness in solving the travelling salesman problem, there is every reason to believe that they will be effective for the problem

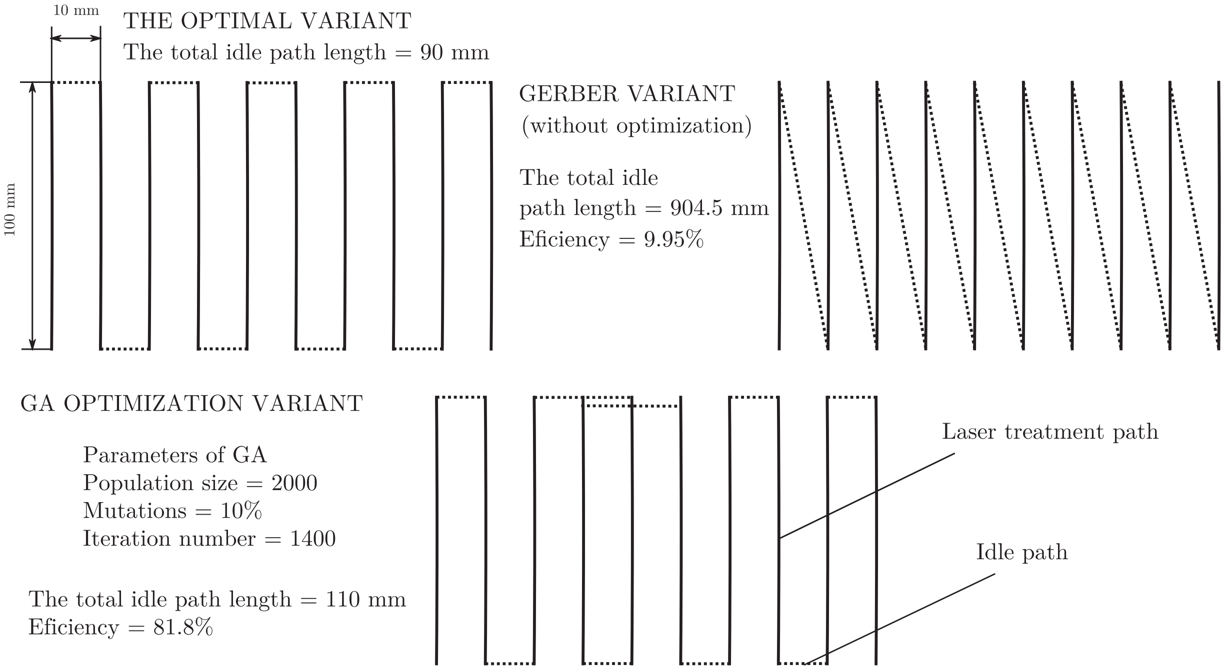


Fig. 8. Trajectories comparison

of optimizing the trajectory of the treatment by laser radiation [24–26]. However, the use of genetic algorithms has a number of disadvantages, such as premature convergence, less effective local optimization, slow convergence to global optimal solution, etc. In recent years many researchers try to improve a genetic algorithms, coding schemes, and genetic design of the operator. That is why in this work the adaptive genetic algorithm is presented. To improve algorithm efficiency heuristics such as changing adjacent segments is proposed. So that the path between endings of the segment, hence the length of auxiliary pass, will be as short as possible.

Applying the heuristic method of prototype continual improvement [27], combined with the global adaptive irregular search method proposed by professor of Mathematics and Mechanics Faculty, St. Petersburg State University Sushkov Y. A. [28] is also possible. This method is used in the following way. To start, the number of solutions are generated randomly, and the optimal solutions are selected as finite many n. It should be noted that this approach has not previously been used to optimize the trajectory in the CNC systems.

Next, modify these solutions using the permutations. Then a new finite many n composes from optimal modified solutions, and from step to step the metric (Hamming distance) decreases. After completing the given iterations the number for each solution runs the prototype modifying process. Results of computing the experiment are presented in Fig. 8.

In figure the number of examples of the PCB topology is shown. The PCBs designing is performed using various E-CAD systems. But when PCB comes into production, the output Gerber-RX format is used. The Gerber-RX file is presented as textual description of the commands, each of them is presented to draw a specific topology element (contact pads, vias, lines, arcs, circles, etc.) using the plotter. Comparative analysis has been performed on automatically generated trajectory and trajectory that have been optimized using proposed genetic algorithm. Initial non-optimized trajectory generated by E-CAD Altium Designer has an efficiency of 9.95 % in comparison to optimal (drawn manually). For genetic algorithm experimentally the following optimization parameters were defined: population size is 2000, mutation of 10 %, iteration number is 1400. These parameters allowed to reach the efficiency of 81.8 % in comparison to optimal trajectory that can be considered as a acceptable solution for this class of problems.

V. CONCLUSION

Approaches to building optimal trajectories for a moving mechanism during laser processing were studied. Time metrics were used as the main optimization criterion. Two principal approaches to minimize time are proposed: increasing processing speed by the smooth merging of acceleration-deceleration curves and decreasing the number of auxiliary passes. Testing runs showed that a significant time decrease is possible when the CNC controller performs acceleration or deceleration along the consequent paths previously selected and stored in the buffer.

To reduce the number of auxiliary passes, a genetic algorithm with modified heuristics was developed, which is similar to an algorithm used to solve the travelling salesman problem. The proposed methods for optimizing the moving mechanism trajectory during laser processing will decrease processing time and increase the efficiency of technological equipment. At present, a testing stand has been constructed and a universal software library created, which consolidates the described algorithms and allows the calculation of the optimization parameters.

REFERENCES

[1] M. Y. Afanasev and A. A. Gribovskiy, “Kontseptsiya adaptivnoy platformy tekhnologicheskogo oborudovaniya [An adaptive platform of technological equipment concept, in Russian],” *Isvestiya vusov. Priborostroenye*, vol. 58, no. 4, pp. 268–272, 2015.

[2] Q. Zhang and S.-R. Li, “Efficient computation of smooth minimum time trajectory for cnc machining,” *The International Journal of Advanced Manufacturing Technology*, vol. 68, no. 1, pp. 683–692, 2013.

[3] T. Kröger, *Literature Survey: Trajectory Generation in and Control of Robotic Systems*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 11–31.

[4] L. Zhang, R. Sun, X. Gao, and H. Li, “High speed interpolation for micro-line trajectory and adaptive real-time look-ahead scheme in cnc machining,” *Science China Technological Sciences*, vol. 54, no. 6, pp. 1481–1495, 2011.

[5] C. Yuan, K. Zhang, and W. Fan, “Time-optimal interpolation for cnc machining along curved tool pathes with confined chord error,” *Journal of Systems Science and Complexity*, vol. 26, no. 5, pp. 836–870, 2013.

[6] L. Biagiotti and C. Melchiorri, *Trajectory Planning for Automatic Machines and Robots*. Springer Berlin Heidelberg, 2008.

[7] X. Beudaert, S. Lavernhe, and C. Tournier, “Direct trajectory interpolation on the surface using an open cnc,” *The International Journal of Advanced Manufacturing Technology*, vol. 75, no. 1, pp. 535–546, 2014.

[8] A. Bharathi and J. Dong, “Feedrate optimization for smooth minimum-time trajectory generation with higher order constraints,” *The International Journal of Advanced Manufacturing Technology*, vol. 82, no. 5, pp. 1029–1040, 2016.

[9] L. A. Gladkov, V. V. Kureichik, and V. M. Kureichik, *Bioinspirirovannye metody v optimizacii: monografija [Bioinspired optimization methods: the monograph, in Russian]*. Moscow: Fizmatlit, 2009.

[10] H. Ganesan and G. Mohankumar, “Optimization of machining techniques in cnc turning centre using genetic algorithm,” *Arabian Journal for Science and Engineering*, vol. 38, no. 6, pp. 1529–1538, 2013.

[11] G. Ma and Fu, *Genetic Algorithms for Manufacturing Process Planning*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 205–244.

[12] G. Wang, Y. Wang, J. Zhao, and G. Chen, “Process optimization of the serial-parallel hybrid polishing machine tool based on artificial neural network and genetic algorithm,” *Journal of Intelligent Manufacturing*, vol. 23, no. 3, pp. 365–374, 2012.

[13] M. Tarokh and X. Zhang, “Real-time motion tracking of robot manipulators using adaptive genetic algorithms,” *Journal of Intelligent & Robotic Systems*, vol. 74, no. 3, pp. 697–708, 2014.

[14] M. Y. Afanasev, Y. V. Fedosov, and A. A. Nemkova, “Designing features of power optical units for technological equipment,” *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, vol. 16, no. 2, pp. 244–250, 2016.

[15] M. Y. Afanasev and Y. V. Fedosov, “Device for laser processing of the surface of random shape,” Patent RU 161 667, 04 27, 2016.

[16] M. Y. Afanasev and Y. V. Fedosov, “Optomechanical system,” Patent RU 2 583 163, 05 10, 2016.

[17] *ISO 6983-1:2009 (en): Automation systems and integration—Numerical control of machines—Program format and definitions of address words—Part 1: Data format for positioning, line motion and contouring control systems*, ISO ISO 6983-1:2009 (en).

[18] L. Wang and J. Cao, “A look-ahead and adaptive speed control algorithm for high-speed cnc equipment,” *The International Journal of Advanced Manufacturing Technology*, vol. 63, no. 5, pp. 705–717, 2012.

[19] L. Wang, J. F. Cao, and Y. Q. Li, “Speed optimization control method of smooth motion for high-speed cnc machine tools,” *The International Journal of Advanced Manufacturing Technology*, vol. 49, no. 1, pp. 313–325, 2010.

[20] S. Sun, H. Lin, L. Zheng, J. Yu, and Y. Hu, “A real-time and look-ahead interpolation methodology with dynamic b-spline transition scheme for cnc machining of short line segments,” *The International Journal of Advanced Manufacturing Technology*, vol. 84, no. 5, pp. 1359–1370, 2016.

[21] J. Jahanpour and B. M. Imani, “Real-time p-h curve cnc interpolators for high speed cornering,” *The International Journal of Advanced Manufacturing Technology*, vol. 39, no. 3, pp. 302–316, 2008.

[22] B. Korte and J. Vygen, *The Traveling Salesman Problem*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 557–592.

[23] G. Sun, C. Li, J. Zhu, Y. Li, and W. Liu, *An Efficient Genetic Algorithm for the Traveling Salesman Problem*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 108–116.

[24] F. Baesler and C. Palma, “Multiobjective parallel machine scheduling in the sawmill industry using memetic algorithms,” *The International Journal of Advanced Manufacturing Technology*, vol. 74, no. 5, pp. 757–768, 2014.

[25] R. Dewil, P. Vansteenwegen, and D. Cattrysse, “A review of cutting path algorithms for laser cutters,” *The International Journal of Advanced Manufacturing Technology*, pp. 1–20, 2016.

[26] T.-M. Lo and J.-S. Young, “Improvements of productivity for pcb drilling by laser driller machine,” *International Journal of Precision Engineering and Manufacturing*, vol. 15, no. 8, pp. 1575–1581, 2014.

[27] G. L. Pappa and A. A. Freitas, *Evolutionary Algorithms*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 47–84.

[28] V. V. Emelyanov, V. V. Kureichik, and V. M. Kureichik, *Teorija i praktika jevoljucionnogo modelirovanija [Theory and practice of evolution modeling, in Russian]*. Moscow: Fizmatlit, 2003.