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An Approach to Building a Specialized CNC System for Laser Engraving Machining

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Abstract

An analysis of laser-dotted engraving technological specifics and laser-impulse machines control problems is presented. The main problem for material processing with impulse laser emission is the necessity to maintain the impulse frequency in a fixed interval. Any violation of this interval isn't allowed, because it leads to significant energy dispersion between impulses and, as a result, to uneven material processing.

The traditional control method with impulse confirmation waiting could be realized in any NC System. However, it leads to performance loss and incomplete use of machine capabilities. An approach is developed via impulse processing control based on the combination of advance NC blocks scanning method and speed profile adaptation for impulse frequency limit conditions.

Experiments show that the developed approach allows to greatly increase the processing speed compared to the method with impulse confirmation waiting. The performance increase up to 30 – 50 % is achieved; whilst the quality of processed details is maintained. The efficiency of the developed approach is supported by associated tools for the optimization and analysis of control program.

Keywords: CNC; laser engraving machining; pulsed laser processing; algorithm of machining time estimation;

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1. Introduction

Laser processing – is a technology proved by many years of experience, which is used in many fields of industry. Laser emission material processing could be performed in continuous or in impulse mode.

Impulse laser emission is used when processing material properties could be changed only with high emission density, or when impact should be focused and short-term [1,2].

One of the characteristic examples of pulse laser processing is the dotted engraving in transparent solid environments (usually optical glass is used). For the last decade the volumetric engraving has become a very popular method of creation of a wide range of souvenir and advertising products in the form of three-dimensional images, flat raster photo drawings or inscriptions. This technology is based on the phenomenon of optical breakdown – material destructions at excess of a certain threshold of volume density of emission. Laser emission passes through a layer of transparent material and makes the destroying impact only in the vicinity of a point of beam focus. To obtain the necessary power, the laser has to work in the pulse mode - to emit the necessary energy in a short period of time [3]. The size and the form of the destroyed dot area depends on many parameters, but generally for volume engraving the structure of a point can be adjusted. The material for the engraving can be almost of any kind with the condition of transparency for laser light. However, the threshold of optical breakdown is different for various environments. A combination of laser technique development and the opportunities of modern computer control systems allows processing with a frequency of thousands hertz on a laser engraving machine.

The problem of laser engraving machine control radically differs from the tasks of machines for traditional processing control (turning, milling and grinding) [4]. For laser engraving reaching the end of a NC block in the estimated time determined by laser frequency is obligatory. And it is not important, in what sequence and on what trajectory it will be

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reached. In multipurpose NC systems there is not enough attention paid to the problem of impulse processing , therefore machine tool builders are compelled to choose one of two non-optimal ways – to use the common NC system and its algorithms created for continuous processing, or to create a highly specialized control system by themselves.

Thus, in the field of engraving systems production there is a problem of creating approaches for a specialized control system of impulse processing, but on the basis of multifunctional NC system [5,6] and preserving all its advantages (control methods acquired by decades, multifunctional user interface, tools of programming) [7,8]. The features of dotted processing and process control set one more task for developers – the optimization of the control program for the sequence of points' description. Therefore, we will consider an implementation approach for pulse processing control features within traditional NC systems and the use of optimization methods for the prepared control programs for the maximum use of machine opportunities within the set limit parameters of dynamics and kinematics.

2. Laser dotted engraving technology and control problem

In production there is a wide class of equipment on the basis of lasers working in the impulse mode with impulses frequency within wide interval of 40 - 1000 Hz. There are some fields of such equipment use: pulse pulsed laser cladding [9]; pulse laser welding; marking (drawing information on a product detail); But most often, as it was already said, pulse processing, especially with a low frequency, is typical for an engraving in transparent environments.

The main feature of impulse machine control consists in the need for ensuring a strict synchronization between impulses of the laser and the movement on the processing contour. The scheme on Fig. 1 illustrates the interaction of the control system with the impulse machine during processing. On the right there is a chart of the control signals which are given out by a control system, and reciprocal signals of the laser.

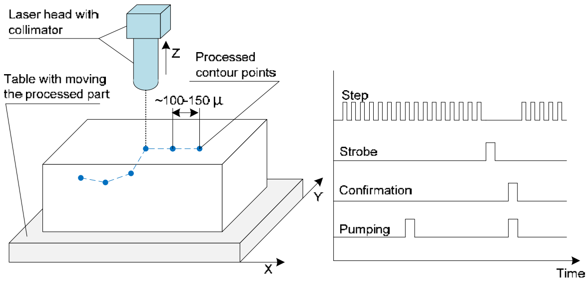

Fig. 1. Scheme of interaction control systems with pulsed laser machine.

Stages of machine elements interaction during point processing are presented on the sequence chart (Fig. 2). Signals delivery sequence is following:

System gives out signals of movement ("Step") on feeding drives up to achievement of the next point set in the operating program.

The movement stops, then the signal ("Strobe") orders the laser module to set the resonator in an active state.

The system expects a laser signal ("Confirmation") about successful point processing at the time of the next pumping impulse, then the new cycle (moving to the next point of drawing) begins.

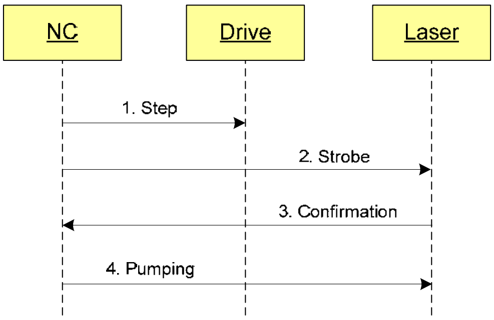

Fig. 2. Signals delivery sequence diagram of control and pilot signals delivery sequence during point processing.

The described scheme shows the main feature of impulse processing control: the system has to synchronize the movement of the beam with emission impulses. Thus the frequency of pumping impulses has to keep with a certain admissible error (otherwise, the energy and divergence of the beam will be insufficient for point processing). The absence of movement synchronization with periodical signals in NC system causes stops in the processed points [10,11]. It leads to a need to implement movements with the simplest profile of acceleration and braking with a zero speed at the beginning and in the end of a NC block as it is shown on Fig. 3.

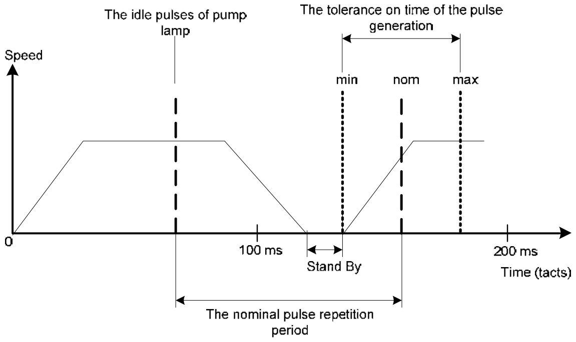

Fig. 3. Movement during standard scheme of impulse processing control.

Here *min, nom, max* - the time points defining the admission for the pumping impulses delivery. From this scheme it follows that a considerable part of processing time proceeds with a speed lower than nominal, which conducts to productivity loss. An attempt to pass the way between points without acceleration and braking will lead to dynamic loadings increase and even to the failure of the movement because of a quick stop of drives.

Thus, the problem of development a new motion control algorithm for dotted laser processing is actual [12,13].

3. Approach to motion control taking into account the synchronization with laser emission

3.1. Synchronization between motion and laser pulses

The main problem of the base algorithm of acceleration and deceleration during pulse dotted processing is the necessity to stop in the processed dots. Therefore, just finding the maximum speed between blocks is not enough and motion control algorithm should have an important feature - synchronization between motion and laser pulses to eliminate stops in processed dots. The synchronization implies that the path between the two operating points must be passed for a time determined by the nominal pulse frequency and its permissible error. In this case pulses of pump lamp are being generated by control system, not by the laser's internal clock.

Let's consider the scheme, which shows the chain of look-ahead and motion synchronization algorithms in the acceleration/deceleration module of NC system (Fig. 4).

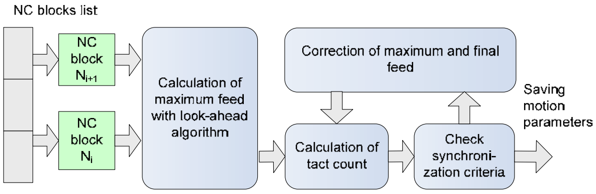

Fig. 4. Acceleration/deceleration module workflow.

Before starting to move in the block, acceleration/deceleration parameters are set. After that, the counting of interpolation cycles, required for the passage of the block, is performed, and the following conditions are verified:

- Number of cycles corresponds with the nearest time tolerance window of frequency for laser pump.
- Number of cycles is more or equal to *n_nom* + *n_max_syn*. Here *n_nom* is the number of cycles corresponding to an integer count of pulse periods with nominal frequency; *n_max_syn* is the number of cycles corresponding to the period for maximum permissible frequency of the pump lamp pulse.

The second option is associated with the fact that the first pulse in the block can be made with increased frequency.

If one of these conditions is satisfied, the motion parameters are considered valid and the process of analyzing the block stops. Otherwise, a slight decrease of final block feed is performed and the verification process is repeated. If the final feed is zero, the nominal feed is reduced. With this iterative method we can determine the motion parameters of block processing, synchronized with laser pulse timing.

The initial and the final result of acceleration /deceleration profile correction is illustrated in Fig. 5.

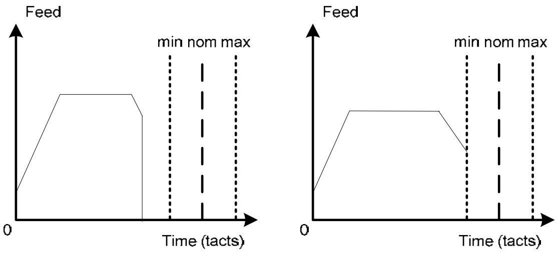

Fig. 5. Change of feed profile after synchronization.

The correction of feed profile allows reaching the working point exactly in the time window of laser pulse. Processing parameters, such as frequency of the laser, permissible error of frequency, the maximum acceleration of the axes, etc., can be customized by the system operator. It allows finding the optimum balance of performance and quality of processing experimentally.

3.2. Optimization of control program for minimal processing time

For the result of dotted engraving the set of points is more important than their order. The points in the control program can be arbitrarily interchanged to optimize program execution time. When using the simple motion control with waiting, such changes in control program do not give much effect, since stop is performed in all points. Also, control programs for engraving typically are initially optimized for the minimal total path length.

However, when using our proposed algorithm, not only the length of the path, but also the relative position of neighboring points of the sequence is important for the program execution time. The feed is limited by acceleration in the points, which depends on the relative directions of the vectors of neighboring blocks. Therefore, it is possible to achieve an increase of feed by reducing the angle between the segments of trajectory. This can be done by selecting a sequence of points with a particular algorithm. Consider Fig. 6.

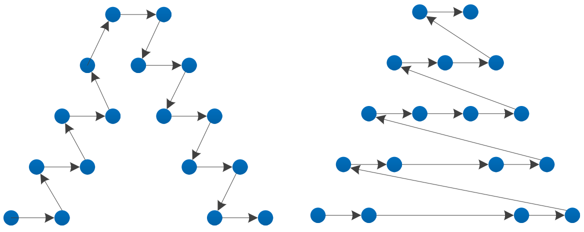

Fig. 6. Acceleration/deceleration module workflow.

The sequence of points in engraving control programs generally corresponds to the left part of Fig. 6. In this sequence the selection of the next point is determined (mainly) by the proximity to the previous. Thus, local areas are sequentially processed. However, in this case, the trajectory is the polyline with very fast changes of movement vector.

Another possible sequence is shown in the right figure - in this case the points close to a straight line are processed sequentially, if possible. The preferable search direction of neighbor points can be selected. In this example, the preferable direction is along the X axis, but can be set along any inclined axis.

It is hard to determine which sequence of points would be most effective for a particular drawing and whether it makes sense to straighten the original trajectory. To solve the optimization problem a special utility was developed. It allows generating a sequence of points in a way specified by the operator and evaluating processing time.

In the current version of this utility the simple directed random search algorithm is used. The search is performed in the individual local sequences of points. Local search allows getting a satisfactory result in a reasonable time for most drawings. The operator can select a preferred direction of search and the desired distance from points to direction lines that define the sequence.

Drawing AB15_00.srt consists of 2400 points and its processing time is about 80 seconds at a nominal frequency of 45 Hz (Fig. 7).

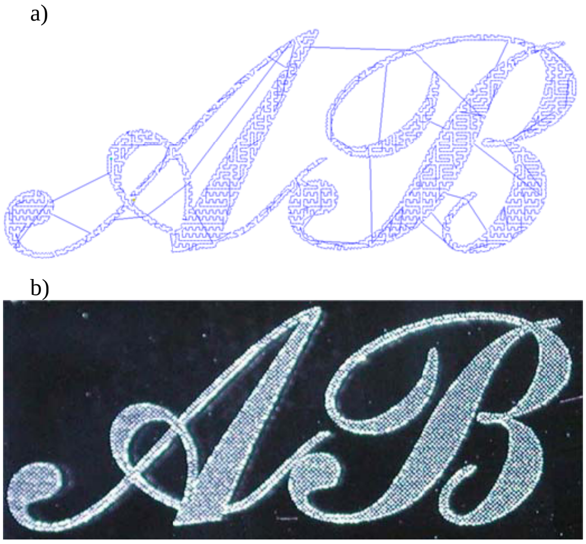

Fig. 7. (a) CAD/CAM model of file AB15_00.srt; (b) result of processing file AB15_00.srt.

After optimizing, the processing time is greatly reduced (Table 1).

Table 1. Measurement of processing time for the file AB15_00.srt.

Optimization method	Processing time, [min]	Optimization result
Default file (simple optimization for minimal path length, 2400 points)	01:19	100%
Preferable movement along the X axis	00:58	73%
Preferable movement along the Y axis	00:56	71%
Preferable movement along the inclined axis of 45 degrees	01:01	77%

The system operator can set the automatic search for the most effective processing mode. The utility iteratively selects preferable movement direction and tolerable angles between adjacent vectors, until the most effective mode is found for the given machine parameters (and taking into account the specified maximum search time). Fig. 8 shows a fragment of the file AB15_00.srt before and after optimization with preferable movement direction along X axis.

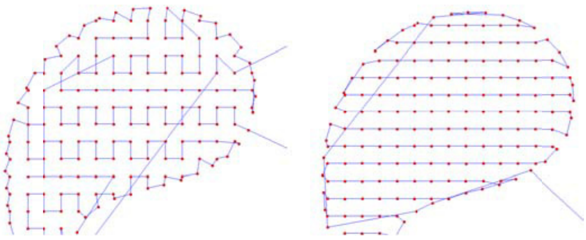

Fig. 8. Fragment of test file AB15_00.srt (default and optimized).

The utility also has the function of processing time estimation and allows the operator to quickly select the most effective mode for a specific file without multiple execution of the optimization process. Table 2 shows some estimations of the execution time of programs after an optimization of the point sequence and a comparison with the real processing time with standard machine parameters.

Table 2. Estimation of processing time.

File	Number of points	Estimation time, [min]	Processing time, [min]	Deviation
AB15_00.srt	2400	00:58	00:58	0.0%
sl6.srt	204000	80:47	82:11	-1.7%
belka_st.srt	108400	52:11	53:24	-2.3%
sp6.srt	208600	80:11	82:28	-3%

As we see, the developed algorithm in most cases gives an optimistic prognosis of processing time with error in the range of 2-3%.

4. Evaluating the effectiveness of the algorithm on an example of typical control programs

Assessing the impact of the developed algorithms on the effectiveness of pulsed low-frequency processing was carried out on the machines for laser engraving in transparent medium. Table 3 summarizes the information on the duration of processing for the 14 files of control programs (with different number of points) when using the existing algorithm of motion control and the developed algorithm of synchronizing motion with laser pulses. Comparison conducted for nominal process parameters (pulse frequency: 45 Hz, permissible acceleration: 300 mm/s^2, maximum feed rate: 1800 mm/min; the distance between processing points: 100-150 μ). Number of points rounded to hundreds.

Table 3. Results of the measurement of time of processing on the laser machine.

File number	Number of points	Old algorithm processing time, [min]	New algorithm processing time, [min]	Reduction of processing time
1	34800	30:11	18:15	40%
2	12100	10:29	7:01	33%
3	23200	20:19	14:08	30%
4	108400	92:08	48:16	48%
5	65200	55:36	31:14	44%
6	30900	26:12	16:01	39%
7	38600	33:19	24:02	28%
8	8600	7:52	4:58	37%
9	26700	23:28	13:36	42%
10	52000	44:26	28:13	36%
11	31200	26:51	17:54	33%
12	28000	23:49	14:28	39%
13	35200	30:43	19:45	36%
14	21100	18:17	10:11	44%

In the present sample of files the reduction of processing time is 28-48%, although the values less than 30% are fairly rare.

The results show that the developed algorithm of synchronization of the movement and of laser pulses enables reducing the processing time for manufacturing the pulsed laser machine by 30 - 50% compared with a standard positional control scheme with stops at the end points of NC blocks.

The measurements carried out on an experimental machine running at rated speed of 1000 Hz and faster drives showed similar results in the difference at runtime (the difference in these parameters can reach for some programs 80-100%), which shows the effectiveness of the algorithm in a wide range of operating frequencies and speeds of movement.

Improved performance is due to reducing the deceleration time, which leads to the fact that the execution time of a block fits with high probability into a smaller number of periods of the laser radiations (Fig. 9).

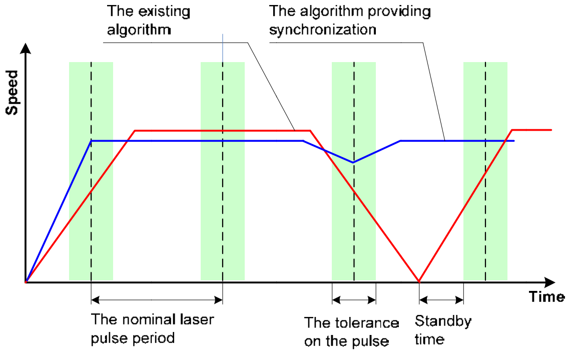

Fig. 9. Profiles of speed of in passing joints of NC blocks.

5. The construction of process chain for performing the dotted laser engraving

The developed control algorithm and the methods of optimization of sequences of points allow generating the typical approach to the preparation of control programs to improve the efficiency of the production process. Such an approach can be organized as follows (Fig. 10). The top row shows the main stages of the design process of dotted engraving, below are the tasks to solve at these stages to optimize the process of technological preparation and production.

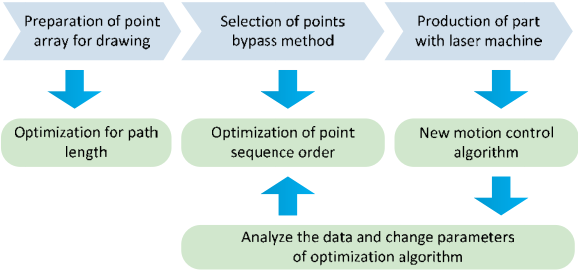

Fig. 10. Process chain for performing the dotted laser engraving.

During the technological preparation of production of parts produced using laser engraving the following are performed: the optimization of the trajectory for the length of the path; the optimization of a sequence of points for the projected processing time; the application of control algorithm with synchronization and previewing (look-ahead) of NC blocks. According to the results of manufacturing each part, the operator can perform the analysis of the quality products and make a comparison of predicted and actual processing time. The data obtained can be used to make changes to the process of optimizing a sequence of points and selecting a new processing strategy for the next product, which allows gaining experience and improving process efficiency for a wide range of products.

Fig. 11. Products obtained on the laser Engraving machine ARTI.

The proposed method is successfully applied on the machine of volumetric laser engraving ARTI, which has a relatively moderate index of limiting pulse frequency (65-70 Hz), but the minimum cost and operating cost through the use of low-power laser and simple step-dir drives. However, using the developed control algorithms and control programs optimizes machine exhibits with high efficiency in production of small-scale and single products (Fig. 11).

6. Conclusion

Algorithms of previewing trajectory and motion control on the parametric curves for pulsed laser machines are developed, which allows minimizing stopping at processed points and achieving a constant contouring speed. The application of the developed algorithms leads to a reduction in processing time by 30-50% as compared to using algorithms which do not take into account the synchronization of motion with laser pulses. The efficiency of the look-ahead algorithm for NC blocks is significantly increased when connecting the method of adaptation to the conditions of the velocity profile restrictions on the frequency of the pulses [14].

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