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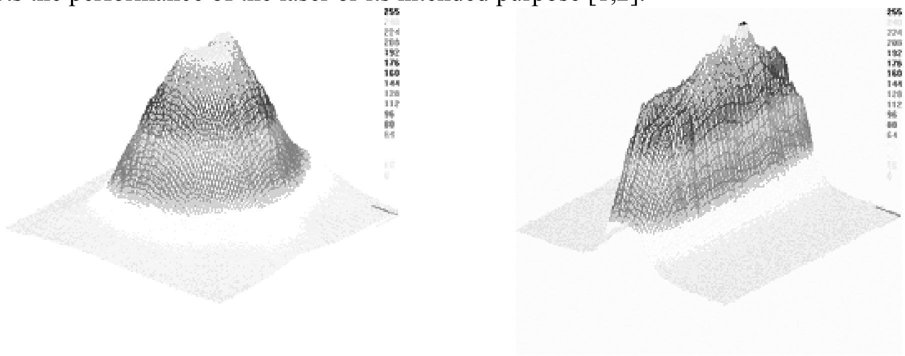
SOFTWARE SUPPORT OF ACCURATELY MEASUREMENT AND PREDICTION OF LASER BEAM PROFILE CHARACTERISTICS

Abstract. The research of conformity between deformation function and geometrical characteristics of the 2D images of laser beam profile and development of the methodological approaches for the analysis of the signal geometrical characteristics dispersion in the laser trace and their further restoration is concentrated in the given work. On the basis of the developed methods, the program realization of processing of the laser beam spot images in real time with the increased measurement accuracy of energy centres coordinates, as compound characteristics of a laser beam profile is carried out.

1. INTRODUCTION

Nowadays such fields as laser processing of materials, laser detection and ranging of objects, printing arts and other branches of technology experience urgent need of large-scale introduction of optoelectronic systems with automatic correction of formed light radiation errors. In order to provide acceptable quality of correction we need constant dynamic control of light radiation characteristics, e.g. spatial distribution of its intensity, including evaluation of above-mentioned distribution deviation from initial or reference distribution.

The significance of the beam profile is that the energy density, the concentration, and the collimation of the light are all affected by it. Also the propagation of the beam through space is significantly affected by the beam profile. Figure 1 shows a number of typical laser beam profiles illustrating the variety that can exist. Since such a variety exists in laser beam profiles, it is essential to measure the profile in any application if the energy distribution affects the performance of the laser or its intended purpose [1,2].



a) b)

Figure 1. Various laser beam profiles: a) HeNe, b) Excimer [1].

Example of ideal laser beam for different purposes is a Gaussian beam. A Gaussian beam allows the highest concentration of focused light. These idealized beam is shown in Fig.2.

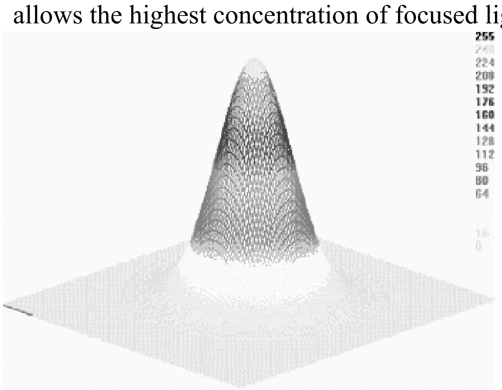


Figure 2. Ideal Gaussian beam for highest concentration of energy [1].

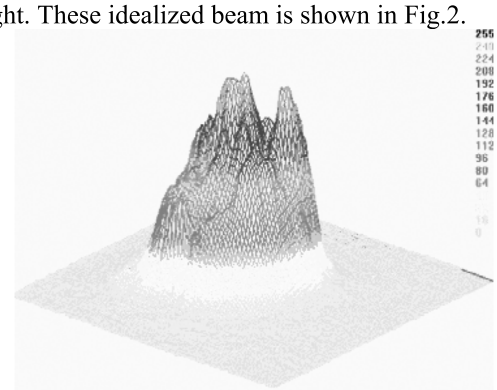


Figure 3. Highly structured would-be Gaussian beam [1].

However, lasers rarely exhibit the most uniform irradiance profile. Sometimes Gaussian beams are highly structured, or may be tilted in energy from one side to the other. Figure 3 illustrates some real world examples of distorted beam profiles. For example, in Figure 3 the highly structured beam would not focus nearly as well as the ideal Gaussian beam.
Thus, researches aimed at accurate measurement and prediction of laser images coordinates of laser images at random time intervals are very important for the solution of applied tasks.
The given scientific research consists from description of point of reference determining method, learning algorithm and experimental results. We shall consider the initial signals on example of sequence of laser images series in our experiments [3]. In our research certain restoring of geometry signal characterizations is exceeding other methods, be based on traditional way of approximation [4]. The present methods may be spreading on multivariate event.

2. REFERENCE POINT COORDINATE ESTIMATION

Recently, we have suggested a method of estimate of the geometry characterizations of laser beams, distorted by atmosphere. The aim of our approach may be generalized as follow. Let ***g(t)*** – original vector, and ***Y(t)=X(g(t))=g(t)–D(g(t))*** – analysed distorted vector. To make analysis, making it possible to restore of vector ***Y(t),*** the geometry signal characterizations should be claimed. A key idea include that:

1) for non-displaced distorted vector for each given signal value a optimum non-linear stable specific density is pointed out;

2) a displacement ***D***(*t*) for a displaced distorted vector by its approximation coefficients relationship is defined;

3) the errors that is depended of discretization and statistical parameters are eliminated. In this paper we show that it is a row of correspondences between ***X(g(t))*** and factors of approximating, and also fluctuations of geometric signal characterizations, which are predict by approximation functions.

By reference point coordinates *(x,y)* (further a reference point) of frame we mean the energy center coordinates of image *X(g(t))*. Components of this image have be depended on direction of laser beam stream propagation only and will be invariant to ***X(t)****.* (*x*,*y*) coordinate of energy center coordinate (*x*,*y*) with non-linear specific density *w*(*g(t)*)=(*w(f(x,y)) (t=const)*), corresponding given brightness *f*(*x*,*y*) value (further density). Its moment value is expressed as follow:

$$x=\frac{1}{M}\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} w\,(f\,(x,y))\cdot x \qquad y=\frac{1}{M}\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} w\,(f\,(x,y))\cdot y, \qquad M=\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} w\,(f\,(x,y)). \quad (1)$$

Reference point estimation learning algorithm is optimal density *w*(*f(x,y)*) determination method combined with image classification and segment partitioning by edge line approximation coefficients, which will consensus with multiple valued to be approximated defects.

For our method description, first assume that for considered image a centers of limited by various signal edges (further – partial centers) do not vary significantly. In this case, to find reference point it is necessary to find the density that corresponds to given value (brightness) of signal.

To find reference point we determine non-linear densities of regions of given brightness from equation systems:

$$\sum_{i=0}^{n-1} w_i \sum x_i^{(j)} \cong x_e;\ \sum_{i=0}^{n-1} w'_i \sum y_i^{(j)} \cong y_e; \qquad (w_i>\lambda_x;\ w_i'>\lambda_y) \qquad (2)$$

where w_i – densities to be found, corresponding to i-th given brightness (w_i – for x-parameters, w'_i – for y); $\Sigma x^{(i)}$, $\Sigma y^{(i)}$– points coordinate (x, y) sum corresponding to j-th image, x_e, y_e –etalon parameters; λ_x, λ_y – small negative edges used to numerical stability making.

Equation (2) differently expressed:

$$\sum_{i=0}^{n-1} w_i x_i^{(j)} \cong x_e. \qquad \sum_{i=0}^{n-1} w_i' y_i^{(j)} \cong y_e \qquad (w_i > \lambda_x;\ w_i' > \lambda_y) \tag{3}$$

x_i, y_i — partial centers for regions of unit non-linear weights of prescribed brightness i, respectively. At this as x_e and y_e assumpt averaged partial centers value of images which have least scatter of partial centers values.
Then, more commonly, with account of scattering of partial centers, reference point coordinates express as follow:

$$x=\frac{1}{M}\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} w(f(x,y))\cdot(x+\delta_x); \quad y=\frac{1}{M}\sum_{x=0}^{N-1}\sum_{y=0}^{N-1} w(f(x,y))\cdot(y+\delta_y). \tag{4}$$

where δ_x and δ_y – point coordinate displacements from distortion, are corresponded to given image for the signal relatively to initial.
Thus, a non-linear weights we discover from equations:

$$\sum_{i=0}^{n-1} w_i \sum (x^{(i)} + \Delta x) = x_e, \quad w_i > \lambda_x \qquad \sum_{i=0}^{n-1} w'_i \sum (y^{(i)} + \Delta y) = y_e. \quad w_i > \lambda_y \tag{5}$$

over image sample bellow considered image line classification particularities and also close partial center displacements *(Δx, Δy)* between actual and distorted signal.
A formalization of the reference points determination is possible by performing partial differentiate system. In case of the large dimensionality using of multilevel network, proposed in [5] also possible.
Let us to return to image line classification. In the geometrical characteristics for image behaviour evaluating, we will use edge lines of image in treating photo. Theirs fragments at polar coordinate system segment will be considered. At image selecting an edge lines approximation by a method of least squares used. Was made [6], that for natural origin image at scanned edge line approximation, possible to utilize the ratio of square to cubic approximation coefficients. At that, monotonous components have a appreciable this coefficients correlation, and it being known that given ratio depends on monotonous phases.

3. VARIATION of LEARNING METHODS REALIZATION

Variation 1

We tested the performance of our model on five data sets. Let us show that xe and ye templates should be determined as respective to best in sense of coincidence of local centers to the map. From experiments was showed that those images have close c2, c3 approximation coefficients. From [7] follows, that these images have close displacement. Obviously, that in case of high displacement nonuniform distribution of energy appears, that result in dispersion of local centers coordinates.
A distribution of the cubic coefficients and the square coefficients with respect to brightness edges is showing on Fig. 4. The vertical axis denotes the cubic coefficients and the horizontal axis shows the square coefficients. In Fig. 4 global image sample observes;

the correlation between the cubic and square coefficients is approximately 35-40 %. It is more than between other coefficients. In the case of selective sample that correlation is increasing.

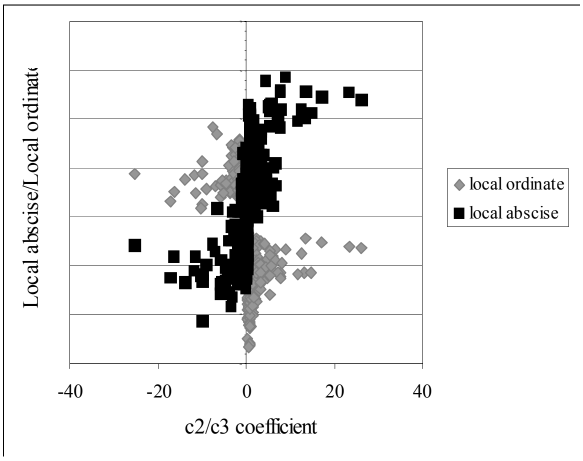


Fig. 4. Function of coordinate from c2 /c3 quotient.

The computional complexity of algorithm allows to perform processing of hundred images per second on the usual computer.
As a result of offered learning the inaccuracy of definition of reference points does not exceed 1,5 pixels. It consists of inaccuracy of definition of the determined template, inaccuracy inside ranges of displacement, not absolute correlation of square and cubical factors of approximating for fixed displacement and from inaccuracy from discretization effects and effects influence on statistical parameters.
On the Fig. 5 showed edge line of used example template image, and correspond image on Fig. 6. Fig. 4 shows a graph of the distribution of the quotient of square on qubic coefficients from local centers of determining reference point of laser paths of 140 used images (70 images used for training and the rest used for center dynamic locating).

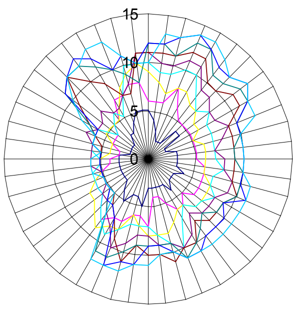


Fig. 5. Etalon image edge lines.

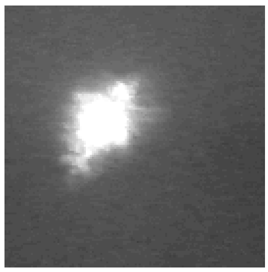


Fig. 6. Determined etalon image (128×128).

There is a special interest represented by the problem of a forehead laser spot position prediction on the basis of the already known part of the path. Considering the fact that the trajectory of power centre of a laser spot is represented given next parametric a curve

$$\begin{cases} x = x(t) \\ y = y(t) \end{cases},$$

where *x*, *y* are coordinates of centre, *t* is time. Given problem represents a task of extrapolation of a function, given discrete values (x_i, y_i) in discrete time series t_i, $(i = 1,2,...,n)$. Because of the actual physical nature of this function it is possible to suppose presence its continuity and smoothness. It allows to fulfil extrapolation using formulas of numerical differentiation. Considering, $\Delta t = 1$, first and second coordinate derivatives are computed using time points of already known piece of the path.

$$x'(t_n) = x(t_n) - x(t_{n-1})$$

$$y'(t_n) = y(t_n) - y(t_{n-1})$$

$$x''(t_n) = x(t_n) - 2x(t_{n-1}) + x(t_{n-2})$$

$$y''(t_n) = y(t_n) - 2y(t_{n-1}) + y(t_{n-2})$$

Then the coordinates of centre of a spot at time point are evaluated under the formulas.

$$x(t_{n+1}) = x(t_n) + 2\frac{x(t_n) - x(t_{n-1})}{t_n - t_{n-1}}\Delta t + \left(\frac{x(t_n) - x(t_{n-1})}{t_n - t_{n-1}} - \frac{x(t_{n-1}) - x(t_{n-2})}{t_{n-1} - t_{n-2}}\right)\Delta t^2$$

$$y(t_{n+1}) = y(t_n) + 2\frac{y(t_n) - y(t_{n-1})}{t_n - t_{n-1}}\Delta t + \left(\frac{y(t_n) - y(t_{n-1})}{t_n - t_{n-1}} - \frac{y(t_{n-1}) - y(t_{n-2})}{t_{n-1} - t_{n-2}}\right)\Delta t^2$$

$$x(t_{n+2}) = x(t_{n+1}) + 2\frac{x(t_{n+1}) - x(t_n)}{t_{n+1} - t_n}\Delta t + \left(\frac{x(t_{n+1}) - x(t_n)}{t_{n+1} - t_n} - \frac{x(t_n) - x(t_{n-1})}{t_n - t_{n-1}}\right)\Delta t^2$$

$$y(t_{n+2}) = y(t_{n+1}) + 2\frac{y(t_{n+1}) - y(t_n)}{t_{n+1} - t_n}\Delta t + \left(\frac{y(t_{n+1}) - y(t_n)}{t_{n+1} - t_n} - \frac{y(t_n) - y(t_{n-1})}{t_n - t_{n-1}}\right)\Delta t^2$$

Due to a laser path discretization and errors of power centre definition, the evaluation of values of derivatives has major number of errors, that does not allow to receive satisfying extrapolation of a path more than on one step forward (i.e. at a moment $t_{n+1} = t_n + \Delta t$).

The preliminary cubic spline-interpolation of an available trajectory of power centre with consequent extrapolation under the formulas was applied to improve the quality of extrapolation

$$x(t) = x_n + \left(\frac{(t_n - t_{n-1})m_{n-1}}{6} + \frac{x_n - x_{n-1}}{t_n - t_{n-1}} \right)(t - t_n)$$

$$y(t) = y_n + \left(\frac{(t_n - t_{n-1})m_{n-1}}{6} + \frac{y_n - y_{n-1}}{t_n - t_{n-1}} \right)(t - t_n) ,$$

where x_n, y_n is the final point of the path, *t* is a time point, for which prediction is made, *m* is a coefficient of a normal cubic spline.

The approach based on spline - interpolation gives essentially better quality of extrapolation, however does not allow to extrapolate a path more than for three steps forward. The reason for that, apparently is, that the "dot" approach to a laser path as to a trajectory of spot power centre, coordinates of which heavily fluctuating, is ill conditioned from an extrapolation problem point of view. For this purpose, possible perspective approach can be to use "area" performances of the parameters of a spot or its preparats, which are free from fluctuations. Besides that, the opportunity of extrapolation of paths with the help of a self-learning neural network is researched.

Variation 2

Application of method for the rise of exactness of foresight for the points of realization is considered, that after the led signs get in the digit of extrapolation. A question of realization of prognoses for the sentinel rows for the case of short-term prognoses is considered possibly to use single-step methods of prognostication. For implementation of prognoses of middle and large duration a known method of "sentinel windows" is used, but a task is substantially complicated for the cases of polyvalent prognostication, when estimation of future values of parameters for a few interconnection processes is carried out. In this case it is necessary not only to sort out all possible parameters, that determine essence of process, but also optimum sizes of entrance and initial sentinel windows, that swims out from necessity to take into account the different sentinel delays (time after action) of influence of one parameters on other. As a result the necessary sizes of sentinel windows can turn out enough large, and measurable of neural networks, that are used for prognoses - considerable. In such situation of application of neural networks on the basis of model "Functional on the great number of tabular functions - FTF", that secure high speed of teaching for the tasks of large measurable, turns out more effective [8].

The example of method realization on the basis of FTF model for forecasting location of the power centres of laser beam images is shown in Fig. 7.

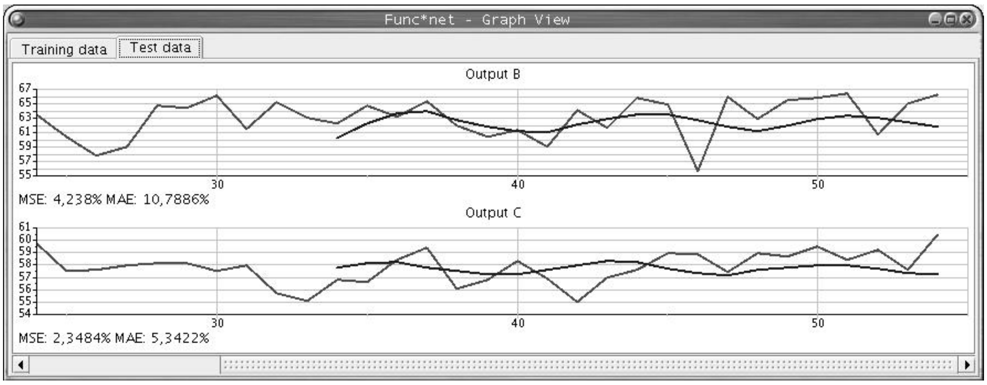


Fig. 7. The example of method realization on the basis of FTF model [8].

4. SOFTWARE SUPPORT of EXTENDED-PRECISION MEASUREMENT and PREDICTION of ENERGY CENTER COORDINATES of EXTENDED LASER PATHS IMAGES

The software support of proposed accurately measurement methods and prediction of energy center coordinates of extended laser paths images are development [9]. Figure 8 illustrated interface of image processing program.

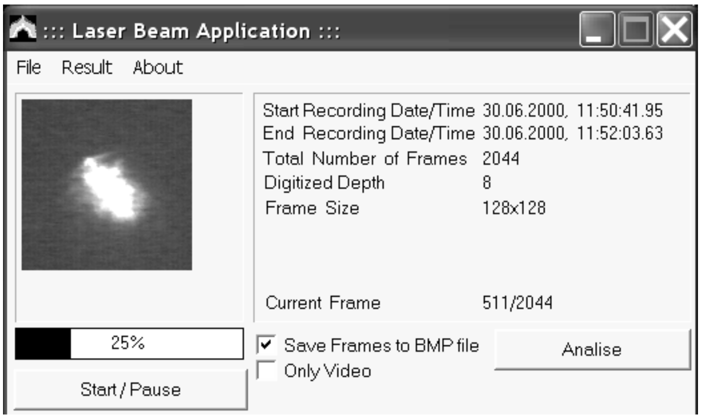


Figure 8.Main menu of image processing program.

In case of activated menu „Analise" in new window on the screen is presented processing results of the energy center coordinates of extended laser paths images. The minimal, maximum and middle values of the maximal light radiation for even image and classification of processing images.

Figure 9 illustrated option window "Detailed view". The user can load needed image and calculated all edge line of used example template image and its centers with graphical viewed on the screen by 6 brightness level.

Figure 9. Options "Detailed view".

Conclusion

In given scientific research used a nonstationary signal analysis method on the example of research of laser lines. This method disclosed relationship between signal approximation coefficients and geometry signal characterizations (for instance, energy center, moment of inertia). The example, which is demonstrating an application of this method for exact coordinate determination problem in laser line at displacement compensation in laser imaging are present.

The elaborated method reveals the interaction between approximation coefficients of the signal and geometric characteristics of the signal (e.g. energy center, moment of inertia). Numerous examples demonstrating the necessity of application of such method for accurate determination of coordinates in case of compensation of image displacement in laser route are investigated in different researches. The given work suggests teaching algorithm intended for determination of the coordinates of the reference point in laser image. Computational complexity of suggested operations permits real-time processing (20-40 ms) with rather simple hardware.

Various extrapolation approaches of laser beam location in real time are considered. The results of emulation provide maximum errors in reference point determination 1,5 pixel, it is approximately 1,5 times less than applying conventional approximation methods.

The necessary software has been developed, sufficient number of laser routes, their length being 1000 images has been investigated.

Preliminary results regarding the elaboration of the method and software intended for prediction of laser routes image coordinates at random intervals of time with approximately same accuracy parameters of their measurement have been obtained.

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