A new laser stripe detection algorithm for 3D scanning applications

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***Abstract*—The paper proposes a new and simple laser stripe detection algorithm for 3D scanning with surface illumination by a laser stripe. The algorithm for selecting areas of a black-and-white image containing images of a laser stripe is based on the calculation of the gradient and Laplacian of the image intensity using standard digital image processing procedures. The proposed detection algorithm is characterized by low computational cost and does not imply any a priori knowledge about the object being detected and the image, including the knowledge of the laser stripe width. The paper also describes a new algorithm for converting a laser stripe image into a broken line, suitable for use in 3D scanning with laser illumination.**

Keywords—3D scanning, image processing, machine vision)

I. Introduction

This Nowadays, new 3D scanning methods for various purposes are developed and applied around the world, including for the development of additive technologies of robotic microplasma spraying of coatings. In particular, the authors of this study used an industrial robotic arm for microplasma layer-by-layer spraying of tantalum coatings on a titanium implant, ensuring the movement of the robot along a 3D model obtained by 3D scanning the implant surface [1].

For 3D scanning and quality control methods for industrial products based on surface illumination with a laser stripe, as well as for machine vision methods that use structured light, the task of detecting a laser stripe is a key task [2], [3], [4]. These areas of application dictate a number of requirements and limitations for laser stripe detection algorithms, firstly, subpixel precision is often required, and secondly, these are restrictions on the computing power required to implement these algorithms, which makes it possible to implement detection algorithms in real-time embedded systems.

At present, a number of laser stripe detection algorithms are known and widely used [4], [5], [6], and the question of the reliability and accuracy of these algorithms has also been studied quite well. It should be noted that algorithms that provide high accuracy and reliability usually require relatively large amounts of calculations, that is, the algorithms are characterized by high computational cost and duration of the computation process. Another feature of this kind of algorithms is the need for some data about the detected object and image, for example, data about the width of the laser stripe.

The aim of this study was to develop a simple and reliable laser stripe detection algorithm as well as to develop algorithm for converting a laser stripe image into a broken line, suitable for 3D scanning with surface illumination by a laser stripe.

II. Methods

A. Formalization of the task of detecting the laser strip in the digital image.

The discrete intensity function of the black-and-white image I_{ij} can be interpreted as a discretization of a continuous function of two variables $I(x,y)$ on a rectangular grid. Such a representation makes it possible to formalize the problem of detecting a laser stripe in a digital image. The intersection of the plane of the laser beam with the surface is a continuous curve in space. The projection of this curve onto the image plane forms a continuous two-dimensional curve in the image plane. This curve is piecewise continuous, and for the points of the curve that belong to the intervals of continuity, the vector of the tangent to the curve is defined. Of course, in reality, images of laser-illuminated surface points do not form a curve, but a two-dimensional region in the image plane, called a laser stripe. Ideally, the curve is a level isoline where the maximum intensity is within the region of the laser stripe. Moreover, in such an ideal case, the isolines of the function are curves obtained by parallel transfer of the curve to the image plane. For a given point M on the curve γ, consider a line p, perpendicular to the curve, i.e., a line with a direction vector perpendicular to the tangent vector to the curve. The restriction of a function of two variables $\Phi(x,y)$

to a line with a unit direction vector $\vec{e} = (e_x, e_y)$ passing through the point $M(x_0, y_0)$ is the function defined by formula (1):

$$\varphi(s) = \Phi(x_0 + s \cdot e_x, y_0 + s \cdot e_y \tag{1}$$

The restriction of $i(x)$ of the intensity of $I(x,y)$ on the line p (in the ideal case) is called the laser strip profile. For real digital images, the restriction $i^*(x)$ $I(x,y)$ to the line p is a linear superposition of the form (2):

$$i^*(x) = i(x) + B + N(x) \tag{2}$$

Using digital filtering methods, it is possible to suppress the constant B and noise $N(x)$ components $i^*(x)$, thus highlighting the profile of the laser strip $i(x)$ [6]. The width of the laser stripe is the length of the interval where the function $i(x)$ is nonzero

B. *Laser stripe detection*

Laser stripe detection is a curve reconstruction or polyline fitting process (approximation by broken line). In a number of methods of laser strip detection, the algorithm of detection reconstructs the position of individual points of the curve, and then linking the found points into the sequence, which can be interpreted as the sequence of the vertices of the broken line, which approximate curve γ. Of course, if necessary, based on the constructed sequence of points belonging to the curve, it is possible to perform an approximation more accurate than the simplest approximation by a broken line. In this study, the task of a laser stripe detection as a task of a curve reconstruction is different from the task of detecting an image area containing an image of a laser stripe. It should be noted that if during image processing it is possible to reliably detect the image area of the laser stripe, then the task of the curve reconstruction is greatly simplified. In this paper, the authors focus mainly on the task of detecting the image area corresponding to the laser stripe. In the classical work of Steger [7], when classifying methods for detector of curvilinear structures in digital images, a class of methods based on considering a curve image as an "object with edges" is singled out, for example, when recognizing a line of a handwritten image of a symbol or a riverbed in aerial photographs. The method proposed in this study uses gradient image processing specifically to highlight the "edges" of the laser strip in the image and can be attributed to this group of methods with a certain stretch. The next section provides the necessary information about the gradient processing of the images used in this study, and the advantages and features of the described algorithm are discussed.

Details of the experiment on obtaining digital images of objects with a laser stripe can be found in a previous paper [8].

III. RESULTS AND DISCUSSIONS

A. *Applying an Image Gradient for Laser Stripe Detection*

The notion of a continuous function of image intensity allows us to consider the gradient of the image function $\vec{g}(x,y)$ (3), often referred to simply as the *image gradient:*

$$\vec{g} = grad\, I = \left(\frac{\partial I}{\partial x}, \frac{\partial I}{\partial y}\right) \tag{3}$$

Of course, real digital images of discretely derivative images (functions $\frac{\partial I}{\partial x}$ and $\frac{\partial I}{\partial y}$) in the classical sense (as private derivatives of analytically given functions) are not defined. In the technique of digital image processing, methods have been developed for calculating partial derivatives and differential operators of the image intensity function, usually based on the application of the operation of convolution of the discrete function of the image intensity and the corresponding kernel of the discrete function defined in a small (in comparison with the image dimensions) rectangle of fixed sizes [6]. In the technique of image recognition, the image gradient is used to highlight the image features (the boundaries of the regions). Figuratively speaking, images containing features are characterized by high values of the gradient module function $G(x,y)$ (4) (see Fig. 1).

$$G(x,y) = \left|\vec{g}\right| = \sqrt{g_x^2 + g_y^2} \tag{4}$$

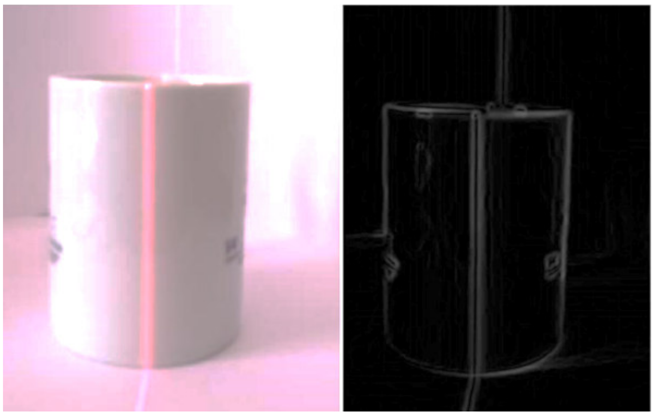

Fig. 1. Digital image of an object with laser backlight (left) and the distribution of the image gradient module (right).

The image gradient is a vector field. A two-dimensional vector field is defined by two vector fields, i.e. scalar functions of two variables $g_x(x,y)$ и $g_y(x,y)$. During software image processing, the components e_x and e_y of the gradient direction vector $\vec{e}$ were calculated by formula (5) for each image pixel and the magnitude of the image gradient modulus $G_{i,j}=G(i,j)$ at this point was calculated for each grid point (i,j)

$$\vec{e}(x,y) = \frac{1}{G(x,y)} \cdot \vec{g}(x,y) \tag{5}$$

Thus, the gradient field was set by three two - dimensional arrays. The direction of the image gradient vector at a point is perpendicular to the tangent to the isoline of the image intensity function passing through this point.

As can be seen from Fig. 1, the laser strip on the visualization of the distribution of the gradient module corresponds to a specific pattern, namely two parallel stripes corresponding to the high values of the image gradient module. The first impulse of the authors of this study was to apply a line scan of the gradient modulus function to detect this pattern. Scanning along the lines of one or another function of the $N \times M$ dimension, the nodes of which correspond to the image pixels will be called the process of the repeated application of the sequence processing procedure. $\{F_{i,1}, F_{i,2}, \ldots, F_{i,M}\}$ for all lines of the image, i.e., for all index values $j=1,2,\ldots,N$. Scanning along columns and diagonals is defined similarly. However, experiments quickly showed the low reliability of this approach to the problem of the laser stripe region detection. The problem was the presence of a large number of high-level gradient modulus regions occurring on image features other than the edges of the laser stripe. This led to an unacceptably high number of false positives of the detector. However, the authors managed to develop a reliable algorithm of the laser stripe area detection, which was also based on the recognition of a certain pattern during progressive scanning, using the calculation of another scalar field - the Laplacian field of the image.

B. *Algorithm of the laser stripe area detection in a digital image.*

The first stage of the laser stripe detection method proposed here is the pre-processing of the image with a Gaussian Blurring Filter. After such processing, the profile of the laser strip with a sufficiently high accuracy is described by the Gaussian type (6):

$$f(x)=A \cdot e^{-\frac{x^2}{2\cdot\sigma^2}} \tag{6}$$

The first and second derivatives of the function f are given by formulas (7) and (8), respectively:

$$\frac{df}{dx} = -\frac{A}{\sigma^2} \cdot x \cdot e^{-\frac{x^2}{2\cdot\sigma^2}} \tag{7}$$

$$\frac{d^2 f}{dx^2} = \frac{A}{\sigma^2} \cdot \left(\frac{x^2}{\sigma^2} - 1\right) \cdot e^{-\frac{x^2}{2\cdot\sigma^2}} \tag{8}$$

Gradient and Laplacian operators are invariant to coordinate system rotations. Let us consider a Cartesian coordinate system on the image plane, the origin of which is located at point O of the curve γ, the Y axis is tangent to the curve γ at the point O, and the X axis is perpendicular to γ. Then the limitation of the gradient modulus function on the X axis will look like (9):

$$g_x(x) = \frac{A}{\sigma^2} \cdot |x| \cdot e^{-\frac{x^2}{2\cdot\sigma^2}} \tag{9}$$

Laplacian image L is determined at the arbitrary point of the plane of image M as (10):

$$\mathrm{L(M)} = \left(\left.\frac{\partial^2 I}{\partial x^2}\right|_M + \left.\frac{\partial^2 I}{\partial y^2}\right|_M \right) \tag{10}$$

In the selected coordinate system $\frac{\partial^2 I}{\partial y^2} = 0$ and the Laplacian limitation l_x on the X axis will have the form (11):

$$l_x(x) = \frac{d^2 f}{dx^2} = \frac{A}{\sigma^2} \cdot \left(\frac{x^2}{\sigma^2} - 1\right) \cdot e^{-\frac{x^2}{2\cdot\sigma^2}} \tag{11}$$

Graphs of the distribution functions of the gradient modulus and Laplacian in the cross section of the laser strip are shown in Fig.2.

Let's introduce two threshold levels: $G_m \succ 0$ for the values of the modulus of the gradient in the image pixel and $L_m \prec 0$ for the magnitude of the image Laplacian in the image pixel. Let's define three predicates (12), (13), (14) for testing image pixels:

$$P(M) = \begin{cases} True, if\, L_m \prec 0 \\ False, \quad otherwise \end{cases} \tag{12}$$

$$Q(M(= \begin{cases} True, if\, G(M) \succ G_m and L(M)=False \\ False, \quad otherwise \end{cases} \tag{13}$$

$$N(M)=\overline{P}\,(M) and \overline{Q}\,(M) \tag{14}$$

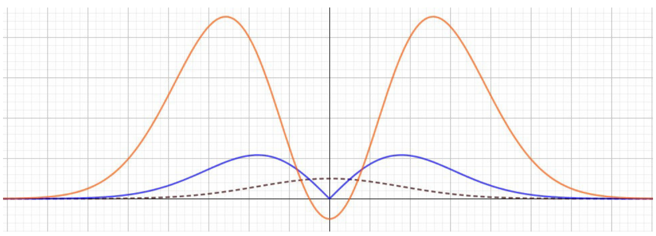

Fig. 2. Graphs of the distribution functions of the modulus of the gradient (blue) and Laplacian (red) in the cross section of the laser strip, the intensity of which is given by the Gaussian function (black dashed line)

Obviously, an image pixel can satisfy either one of these three predicates and not satisfy the other two, or not satisfy any of these predicates. Consequently, the set of image pixels D is divided into three pairwise disjoint sets $S_1=\{M \in D \mid P(M)=True\}$, $S_2=\{M \in D \mid Q(M)=True\}$, $S_3=\{M \in D \mid N(M)=True\}$ moreover, an arbitrary image pixel belongs to one of these sets $(S_1 \cup S_2 \cup S_3=D)$. Let us construct a discrete function $F(M)$ (15) given on the pixels of the image:

$$F(M) = \begin{cases} 0, N(M)=True \\ 1, Q(M)=True \\ 2, P(M)=True \end{cases} \tag{15}$$

The laser strip corresponds to a characteristic pattern - a band within which $F=2$ (the value of the Laplacian is less than the threshold value), framed by areas in which $F=1$ (the value of the gradient modulus is greater than the threshold value and the Laplacian value is greater than the level of the negative threshold L_m) (see Fig. 3).

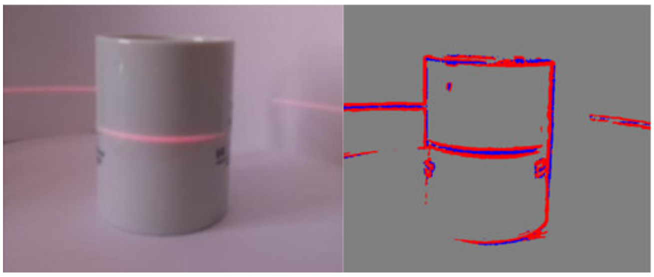

Fig. 3. Image of the scanned object (left). Visualization of the distribution of the F function (right). Regions of the image in which the modulus of the image gradient is higher than the specified threshold G_m are highlighted in red. Regions of the image in which the value of the Laplacian of the image is less than the level of the negative threshold L_m are highlighted in blue

To detect a laser stripe, the proposed method uses scanning of a discrete function in one of the directions (in rows, columns, or diagonals). The scanning direction is selected either according to the previously known orientation of the laser strip on the image, or scanning is carried out in three directions, followed by the procedure for selecting the scanning results.

The scanning procedure was implemented using a Finite State Machine (FSM), the alphabet of input symbols of which was the set of values of the function F, and the set of states of which corresponded to the stages of the pattern $(F=0) \to (F=1) \to (F=2) \to (F=1) \to (F=0)$. The strip boundaries were determined during the transition from the interval $F=0$ to the interval $F=1$ and the reverse transition from the interval $F=1$ to the interval $F=0$. In addition, during the scanning process, intervals with a high level of the modulus gradient value $(F=1)$ were determined, on which the direction of the gradient vector was subsequently calculated.

C. Laser Line Detection Algorithm.

As noted above, preliminary detection of the laser stripe region in the image greatly simplifies the procedure for approximating the curve γ . The following is a brief description of the detection method, which is only one of the possible methods for detecting a laser stripe. Since the laser stripe image area detection algorithm allows estimation of the stripe width and its position, it becomes possible, in particular, to apply the methods described by Sun et al. in paper [4]. So, in the case of a positive result of scanning the line, in the region of a high value of the gradient modulus, the point $P(x_p, y_p)$ was chosen, which is the middle of the corresponding interval. Based on the scanning results, the interval $[a,b]$ was selected on the straight line l, passing through the point P along the direction vector of the gradient (e_{xp}, e_{yp}), calculated for the point P. The constraint $f(x)$ of the gradient intensity function I on the straight line l on the segment $[a,b]$ was constructed by the method of linear interpolation.

To determine the coordinate of the point of intersection $Q(x_q, y_q)$ of the straight line l with the curve γ, the position of the center of mass x_c of a flat figure bounded by the graph $f(x)$ was calculated using formula (16):

$$x_c = \frac{\int_a^b x \cdot f(x)dx}{\int_a^b f(x)dx} \tag{16}$$

After that, the coordinates of the point $Q(x_q, y_q)$, were calculated using formulas (17) and (18):

$$x_q = x_p + x_c \cdot e_{xp} \tag{17}$$

$$y_q = y_p + y_c \cdot e_{yp} \tag{18}$$

Thus, for each laser stripe interval detected during scanning of the line, the position of the corresponding point of the imaginary "ideal" curve γ, that is, the image of the line of intersection of the laser beam plane with the surface was calculated. Further, the constructed points of the curve were connected into a sequence of vertices of a broken line approximating the curve γ.

D. Software implementation of the algorithm and discussion of the results

The algorithm was implemented and tested as software [9] written in C# for detecting a laser stripe on the image of a scanned object and representing an elongated area of the laser stripe as a broken line without self-intersections (Fig. 4).

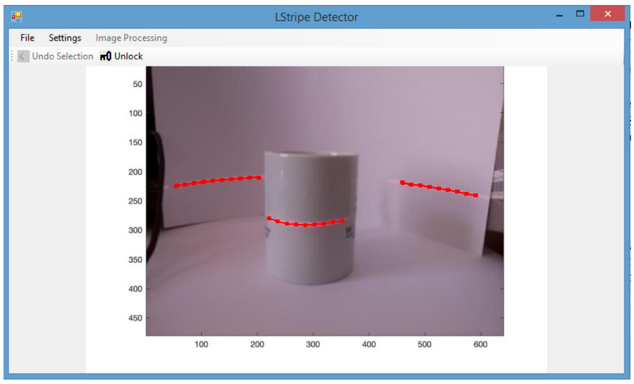

Fig. 4. View of the main window of the software [9] after performing the laser stripe detection procedure. The constructed broken lines are highlighted in red in the image

When a color image was input to a computer program, it was first converted into a black and white image using a standard algorithm. As emphasized above, the described general detection algorithm consists of two sequentially applied algorithms: the detection algorithm for the laser stripe area in the image, and the detection algorithm itself, which reconstructs the image of the intersection curve of the laser beam plane and the surface. To assess the impact of the parameters of the detection procedure on its quality, the graphical interface of the software [9] allows to visualize the map of the distribution of the values of the Laplacian of the image and the modulus of the image gradient, as shown in Fig.5.

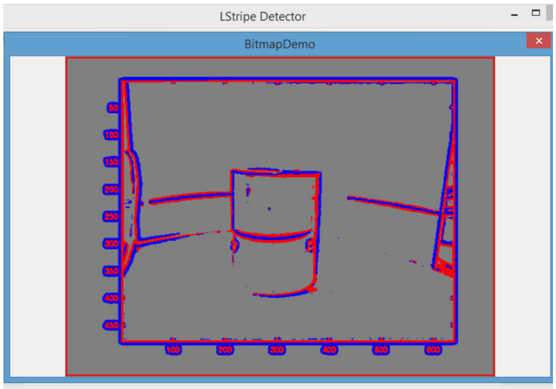

Fig. 5. Pop-up window of the computer program [9] with a map of the distribution of the values of the Laplacian of the image and the module of the image gradient

When testing, the reliability of the original algorithm for detecting the laser strip in the image was important primarily. Testing on the images at the disposal of the authors showed the high reliability of the proposed algorithm with the expected high speed. Since a set of images corresponding to such different initial conditions as various lasers used, different types of scanned surfaces, various types of video cameras used in testing was very limited, this work can be considered as an announcement of the method, designed to draw attention to the proposed detection method for assessment of its capabilities and restrictions.

IV. Conclusions

A simple algorithm for extracting areas of a black-and-white image containing images of a laser stripe is developed. The algorithm is based on the calculation of the gradient and Laplacian of the image intensity using standard digital image processing procedures. The proposed algorithm is characterized by low computational cost and does not imply any a priori knowledge about the detected object and image, in particular, no knowledge of the strip width is required.

Preliminary application of the described algorithm to the image, in order to subsequently apply one of the known methods for detecting a laser stripe in the regions of stripe localization already detected at the previous stage, can significantly increase the overall performance and reliability of the detection algorithm

A new algorithm for converting a laser stripe image into a broken line is developed, suitable for use in 3D scanning tasks using laser illumination.

The results of the research are of significance for a wide range of researchers developing image processing algorithms for 3D scanning with laser stripe illumination and machine vision methods using structured light.

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