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TRIANGULATING LASER SYSTEM FOR MEASUREMENTS AND INSPECTION OF TURBINE BLADES

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A laser-based triangulation system for measurement and inspection of turbine blades in real time is considered. The system makes it possible to calculate and import the coordinates of points of a profile and surface.

Key words: *laser-based triangulation sensors and systems, laser-based optical measurement systems, turbine blades.*

In recent years, methods and tools for the measurement of complex profiles and surfaces of finished articles have been developed and found extensive use in different branches of industrial production. A host of scientific research institutes and instrument-building enterprises have been at work at making constant improvements and modernizing existing and recommended devices and systems used for measurements of parts with complex configurations as well as in the creation of more precise automated and computerized systems.

Besides the traditional devices used for measurement that employ contact measurement tools, modern instrument-building firms have become increasingly more focused on research associated with noncontact measurers. The use of noncontact measuring devices fits in with the innovative processes which all the leading industrial firms are involved with and makes it possible to achieve required degrees of precision and speed of measurements as well as implementation of remote measurements at sites that are not accessible to contact methods.

The question of estimating the geometric parameters of objects in the course of measurements, diagnostics, and nondestructive testing is raised quite often in the technical literature. Researchers and developers of measurement systems are usually oriented towards the three basic principles of noncontact optical recording: interference, shadow, and triangulation principles.

Optical sensors and devices whose operating principles are based on the use of interference exhitit a high level of precision, though at the same time precise positioning and the predicted form of the object’s surface (curvature, roughness) are required. Moreover, there is the problem of positioning the sensor, where a slight shift will lead to reflection of the light ray away from the detector, hence the use of laser triangulation is often the only possible approach.

There is a rather large number of new measurers among the noncontact measuring instruments that function on the basis of the method of optical triangulation. These devices combine modern technical and technological advances, universality, and flexibility and are used in measurements and inspection in many industries, moreover, they are sufficiently distinguished by the profile of the product manufactured.

All the triangulation measuring devices, systems, and complexes that now exist may be divided into the following types:

1) triangulating clearance gauges and sensors;

2) 2D/3D triangulating profilers;

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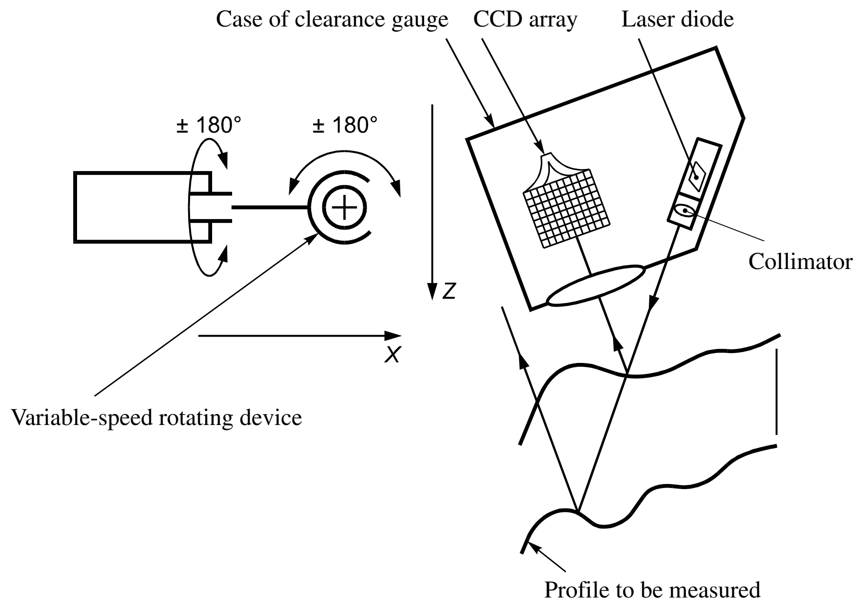

Fig. 1. Flow chart of Zeiss LTP60E laser triangulating clearance gauge.

3) 3D laser scanners; and

4) information measuring systems based on triangulating sensors.

The triangulation method of measurement is a promising and widely used approach to the solution of a wide range of measurement problems. It is used mainly in geodesy and cartography and only in recent times has it begun to be applied in the area of linear and angular measurements and inspection of precision parts with complex configurations. This is chiefly because of the fact that the electronic components that are required for the creation of precision instruments based on the triangulation method did not satisfy the requirements imposed on them and were not suitable for introduction in industry in terms of their price/quality ratio.

Triangulating sensors are generally provided with a case that contains its basic components, but for scientific and research purposes these components may be kept separate.

The principal structural elements of a triangulating sensor are presented in Fig. 1. The figure depicts a diagram of the Zeiss LTP60E triangulating laser clearance gauge, which is in fact a triangulating sensor, but used as the noncontact sensor of a coordinate measuring tool. It is mounted on the manipulators of these tools and used together with two variable-speed, rotating devices that are able to rotate by ±180°. The triangulating clearance gauge is mounted together with traditional contact clearance gauges. Thus, a noncontact method that will not damage the objects that are being measured is realized; the fact that no damage is produced in the object is an especially important feature when working with brittle and easily deformed parts. A triangulating sensor comprises the following components:

• source of coherent or partially coherent optical radiation (laser or laser diode) with optical system;

• photodetector (gage or array of photocells) with optical system on which the reflected beam is focused; and

• electronic and mechanical components (case and attachments of the sensor, built-in and connected interfaces, etc.).

The laser radiation photodetector is an important electronic component of a triangulating sensor and influences its precision. The contemporary electronics industry produces a vast quantity of these devices. But in view of the experience of manufacturers of triangulating sensors, at present among the entire range of devices three types of photodetectors which conform to the three technologies used in their manufacture may be distinguished: CCD, CMOS, and PSD devices [1].

The basic measurement problem that may be solved by means of triangulating sensors is that of noncontact determination of the distance to an object, though the sphere in which they may be used is quite broad. This is chiefly because of the flexibility of this type of sensor and the fact that it may be adapted to solve a host of measurement problems. Information measurement systems and systems for inspection and diagnose of different objects and recognition may be realized on the basis of one or more triangulating laser sensors. Several types of automated systems that are capable of performing the following functions may be constructed:

- noncontact determination of the presence and(or) absence of an object;
- determination of the distance to the surface of an object;
- measurement and inspection of the profile of the surface of articles with complex configuration;
- measurement of geometric parameters (thickness, length, width, nonrectilinearity, inner and outer diameters, planarity, rippling);
- determination of the position of an object;
- recognition of manufactured objects;
- measurement and inspection of the levels of liquids and friable bodies;
- classification of objects; and
- measurement and inspection of positioning precision.

The use of pointwise laser scanning in which a laser probe spot is projected onto the surface of an object which is to be measured is the most common use for triangulating sensors. Such a rather simple and reliable technique is used in the overwhelming majority of such sensors.

As a consequence of the difficulties associated with their introduction, conceptual schemes of the triangulation method of measurement are not as widely used as is the classical point method. The most well-known of such approaches is that of scanning with projection of a line or of points arranged in a line (linear method) and of arrays of points that make it possible to develop and improve the classical approach referred to earlier. With the use of such approaches, it is possible to substantially increase the rate of measurement, which is of critical importance for improving high-technology industries.

In the linear triangulating method, instead of a laser spot on the surface of the object that is to be measured, a laser line is projected. The laser line is created by means of special optical components which expand the light spot and a diaphragm. The line may be either continuous or consist of separate discrete points (spots) situated at some distance. Scanning with respect to a laser line makes it possible to measure a profile all at once or, if the line is sufficiently prolonged, in several measurement steps. The linear triangulating method is realized in the optical sensors of such coordination measurement tools as the the Eagle Eye Navigator from the firm of Carl Zeiss and the scanCONTROL 2800/2810 2D/3D laser roughness indicators from the firm of Micro-Epsilon.

In the array triangulation method an array of laser points (spots) is projected onto the surface of the object that is being scanned. The array is produced through enlargement of the laser beam by means of optical components and by guiding the beam through a diffraction grating. Scanning with projection of the array of points makes it possible to encompass the surface entirely or of an segment of the surface of given magnitude. As far as I know, there is no information in the literature on this topic relating to triangulating measurers that employ this method, so that it may be concluded that it is only rarely employed, though this says nothing as to whether it is techncally feasible.

Practical realization of the theoretical foundations and principles of the triangulation method of measurement have led to the creation of information measurement systems that are based on the UIM-21 computer-controlled universal measurement microscope. Turbine blades and other parts that have surfaces with complex configurations are used as the scanned objects. Such a triangulation laser-based information measurement system is intended for noncontact measurements of the coordinates of the points of an object and for the subsequent construction and display of profiles and surfaces. The UIM-21 microscope is equipped with two scanning photoelectric linear sensors that provide digital indication of the current coordinates of the object that is being measured and the capability to input coordinate information through a computer serial port as well as a CCD camera to which it is connected by means of a USB interface for the purpose of obtaining video images of the measurement zone. In order to perform laser-based triangulation measurements, the microscope is additionally equipped with a laser diode with optical beam focusing system, power pack, and a sectional centering bracket. With this type of information measurement system it is possible to scan an object that is being measured in real time by a laser beam according to a given algorithm.

Two types of design of a laser-based triangulation information measurement system are possible. In the first design the CCD array and the laser diode are made fixed while the object being measured is allowed to travel relative to the array and the diode, while in the second design the components of the sensor are able to travel relative to a fixed object. The first design has been constructed.

The process of generating the coordinates of the points of a particular object in triangulating measurements is in many ways analogous to a measurement process using a microscope. In the course of scanning, the laser beam reaches the surface of the object in the course of propagation and forms a probe spot on the surface. Once it has been reflected from the surface, the beam reaches the gage or array of photocells in the form of a pulse that generates a digital photograph of the laser spot on the object's surface. The digital photograph constitutes an array of intensities of the optical radiation recorded by the photodetector. Prior to measurement the part must be placed on the microscope stage in such a way that the laser spot is situated at the initial point of the selected profile. A digital photograph of the laser spot is created by the CCD video camera and the coordinates of the center of the spot in the coordinate system of the CCD camera are determined from the laser spot. Next, the required scanning step is selected and the object is moved a distance equal to this step with respect to one of the coordinates. The step is measured by the microscope scanning photoelectric sensors and information on the step is transmitted to the computer. A new digital photograph of the laser spot is created for each new position of the measurement object. The position of the laser spot in the photograph changes if the distance to the measured zone of the object's profile changes. If the measured profile is a straight line, the position of the laser spot will not change, since the distance to the surface then remains constant. All the actions or measurement steps that have been enumerated here must be performed repeatedly until the end point of the profile is attained. Measurement information on the scanning step and the coordinates of the center of the laser spot in the coordinate system of the CCD array that is accumulated in the computer memory in the course of scanning is used to calculate the coordinates of the points of the profile and makes it possible to construct and display the profile. Calculation and display of the measured surface of an object may be realized as a result of scanning of profiles in selected sections of a part according to a special computer program.

The operating principle of laser-based triangulating sensors and systems is based on the determination of the position of the center of the pulse formed by projection of the reflection of a laser beam by the controlled object on a linear or array photocell consisting of N or $N \times N$ cells, respectively. The pulse travels along the photodetector, thus determining by means of its own location the measure parameter, i.e., the distance to the object at each point. The selection of the method used to find the center of the pulse is dictated by a compromise between the admissible errors and the required speed of the measurement system. Different methods were compared in terms of precision and computational costs. The results were obtained in a modeled stochastic sequence s of length N in the form of isolated pulses x with additive Gaussian noise n in which $s = x + n$.

The different methods used to search for the center of a pulse may be divided into two basic groups, depending on the presence or absence of a requirement for preliminary threshold processing. For example, approximation by means of the method of least squares belongs to the latter group. It makes it possible to obtain estimators of the highest quality that are close to the potential estimators. An obvious drawback of the method lies in its considerable computational costs for implementation, due to the need to transform a matrix of dimension $m \times m$, where m is the order of the approximating polynomial, and the use of a procedure for finding the location of the global maximum.

The most commonly employed of the methods that require threshold processing are the center of gravity and median methods, since these two methods may be implemented in real time. Their common drawback derives from the need for threshold processing, since adaption of the threshold level to a signal s is an ill-posed problem that always leads to an increase in computational costs.

The energy center M of a pulse x determined by the center of gravity method is interpreted as the coordinate of the mean of the geometric sequence s:

$$M = \sum_{g=0}^{N-1} g\, s[g] \Bigg/ \sum_{g=0}^{N-1} s[g], \tag{1}$$

where $s[g]$ are readings of the analyzing sequence s.

The estimator M possesses a high sub-pixel precision , though it is characterized by significant variance and bias to the value $N/2$ with nonzero constant component. Elimination of the bias is achieved by threshold processing. Since in (1) the

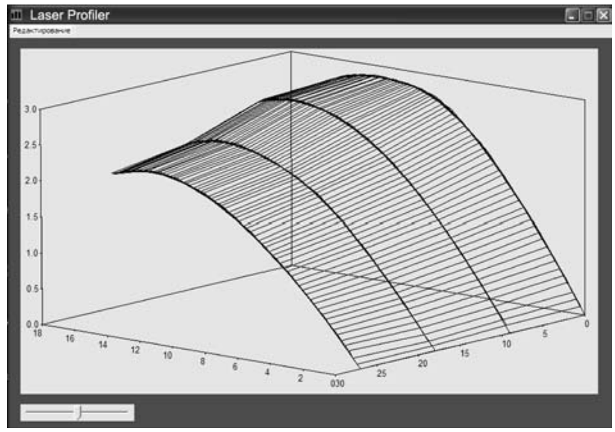

Fig. 2. Interface of window of module for graphical display of surfaces.

denominator serves for normalization of s, only the numerator is significant for the precision of the algorithm; the numerator may be understood as a cyclic convolution of the sequences g and s of length N for a zero shift shift index.

The median method is based on a search for the median of the pulse, i.e., the ordinal number of a reading g to the left and right of which the two areas of the pulse are equal. A median estimator ensures a precision to 0.5 pixel. Note that the bias of the estimator that is found in the median method is slightly lower than that found in the center of gravity method, though in the case of a symmetric pulse and with threshold processing the two methods yield results that are close in value.

In the case of a fixed form and fixed area of the pulse as well as with constant intensity of the noise, the bias may be compensated at the stage of calibration of the optical measuring device by decreasing the resolution of the measurement system. This type of calibration eliminates the need for threshold processing. Thus, the computational costs for implementation of the particular method and the attained variance or standard deviation of the estimator may be taken to be the principal quantitative characteristics of these methods. A review of these characteristics of well-known methods shows that, in practice, only the extreme possibilities are realized, i.e., high speed and simplicity of implementation with low quality of the estimator, and conversely.

Specialized computer software is needed to implement triangulating methods of measurement in order to determine the coordinates of the center of the laser spot. This is achieved based on an analysis of the digital photographs, calculation of the coordinates of the points of the profiles of the objects that are being measured, and the construction and display of the profiles and surfaces.

The Laser Profiler [Lazernyi Profilomer] complex consists of intelligent software intended for analysis of measurement data and the solution of problems that arise with the use of triangulating methods of measurement. The following functions are provided in the complex:

1) ability to import data files in *.cvs format from the software of the UIM-21 computer-based microscope;

2) adjustment of the program in accordance with the particular measurement problem which is to be solved;

3) determination and calculation of the coordinates of the center of the laser spot;

4) construction of the profiles of a surface on the basis of an analysis of obtained data;

5) calculation of the coefficients of a polynomial of degree n from the coordinates of the profile for the purpose of obtaining a compact mathematical description of a measured profile; and

6) construction of the surfaces of a measurement object.

Modern algorithms for digital processing of discrete signals based on theoretical and procedural studies in the area of the design of triangulation sensors and systems are implementd in the Laser Profiler software product. The software product described earlier was developed in the Visual Basic programming language with the use of components written in C++. These programming languages and the corresponding development environments were suggested by considerations of hardware and software compatibility with most modern personal computers and operating systems. A programming mode with the use of general-purpose control tools and specialized graphical components (to realize 3D display) was selected in order to simplify the processing functions. In combination with standard control elements, these components have made it possible to realize the required functionality of the software product [2].

The microscope software makes it possible to preserve images obtained from the CCD camera in either *.bmp or *.cvs format. A file in *.cvs format constitutes measurement data structured and written in the form of an array of intensities. The Laser Profiler software product functions with digital photographs in *.cvs format that have been imported from the microscope program.

Following launching of the basic module all the measurement problems that may be solved by the program – specifically, determination of the coordinates of the center of the laser spot and construction of profiles of the surface being measured and of the surfaces of the measurement object – become accessible. Following selection of one of the measurment problems in the basic module, depression of the corresponding key causes a new program window representing the module of the problem which is to be solved opens. If the coordinates of the center of the laser spot are determined, the parameters of the preliminary adaption (prior to downloading of the data) will include selection of one of six methods of discriminating boundaries (Roberts or Laplace method, median filtration method, Sobel method, or a statistical method) [3]. Downloading of the data is performed automatically once a step has been selected from the program menu and the data file has been opened. The program outputs a corresponding report upon conclusion of the data analysis. The coordinates of the center of the laser spot (expressed in terms of the coordinate system of the CCD array) that have been determined are presented in the same downloaded program window.

Once the profiles of the measured surface have been constructed, the active working window of the profile construction module enables the following preliminary setups: selection of one of six methods of discriminating boundaries; specification of the measured part that has been selected in the course of measurements of the shift step; selection of the direction of the given shift; and specification of the triangulation angle to be used.

Batch downloading of a group of files containing the measurement data related to a single measured profile is performed following implementation of the setups. For this purpose, it is necessary to indicate which of the group of profile files is the first, with the other files being downloaded automatically. Downloading of the data is performed automatically once a step has been selected from the program menu and the first file containing data from the group of files of the measured profile has been opened. The newly constructed profile of the surface appears in the window that represents the module for graphical display of profiles. In this window, it is possible not only to scan the profiles of the surface, but to also import their images into any convenient graphics editor. Thus, the profile graphical display module enables scanning and importation of the calculated coordinates of points of the profile as well as analysis of the resulting profiles of the surface. The software package incorporates calculation of the coefficients of a polynomials of degree n on the basis of regression analysis and any other additional algorithms that have become necessary in the course of operation of the information measurement system. The coefficients of a polynomial of degree n are calculated on the basis of the calculated coordinates of points of the measured profile. The level of approximation of the measured profile that is achieved by means of this polynomial depends on the selected degree of the polynomial in accordance with visual estimation of the complexity of the profile of the measured surface.

In constructing the surfaces of a measurement object, the active working window of the construction module activates the same preliminary adjustments as in the construction of profiles of the measured surface. Batch downloading of the group of files containing measurement data related to one of the measured profiles is similarly downloaded. The constructed surface of the measurement object appears in the window that displays the module for graphical display of the surfaces (Fig. 2). Graphical construction of the surfaces of the back edge of a turbine blade after it has been scanned in the four selected sections of the laser-based triangulation measurement system is shown in the same window.

The ability to rotate the spatial module within the interval of angles from –180 to 180° is provided as a way of assuring completeness of the visual representation of the 3D surface. Through the use of the Flipper Graph Control graphical 3D component in the Laser Profiler program it becomes possible to implement the necessary demonstration functions for representation of the three-dimensional surfaces.

Tests of the triangulation laser information measurement system has shown that it is highly reliable and fast and is also simple to operate. Similar systems may be applied for measurement and inspection of turbine blades and other objects possessing profiles and surfaces with a complex form.

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