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Environmental and structural health monitoring by optoelectronic scanner

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Important objects of natural environment, ecologic landscapes, as well as big engineering constructions, require geometrical monitoring to predict its structural health during their lifetime. That monitoring by geodetic devices, wireless networks or GPS technology is not always optimal; sometimes it is impossible as shown. The method based on geodetic measurements automation applying local optical scanners for monitoring in natural environment is proposed. It is based on the novel method of plane spatial angles precise measurement. It consider robust invariant AD-conversion angle-to-code for instant dynamic angle, signal energetic center search method, initial reference scale adjustment, and uncertainty decrease by mediant fractions formalism for result approximation. It is described system parts interaction for spatial angle encoding with beforehand set accuracy. Method is appropriable for uncertainty reduction limited only by reasonable ratio "uncertainty/operation velocity". The operation range, accuracy, scanners operation velocity, and its adoptions on the objects were described. Presented experimental results confirms that in front of passive scanning aperture our system overcomes main recently known optical devices for 3D coordinates recognition in offset uncertainty.

Keywords: *optical instruments, scanning aperture, solid angle, surface figure measurement, measurement result rational approximations, mediants*

1. Introduction. The monitoring of natural movements of terrestrial landscapes is extremely important, for example, for earthquakes prediction. Several of important engineering structures like bridges, electric plants, tunnels, historical buildings, dams, etc. also requires the observation of their natural movements, integrity and deformation during all their operation time. Usually, it named structural health monitoring (SHM). The structure deformation is observing by the periodic determination of their reference points coordinates, fixed on an object. In this framework are using various techniques for nowadays. From classics of geometrical and trigonometrical leveling up to the GPS NAVSTAR technologies are used.

2. State-of-art. Let's try to make classification of these SHM methods for better problem understanding and verification of their advantages and lacks. This analysis has to be useful for final design of the structural monitoring system. It have present clear understanding which lacks and limitations are critical, and, opposite, which system properties are strongly recommended for optimal final design. Such kind of analysis partially presented in [1 42] and [2 43]. In general, all these methods of Civil Engineering Objects Structural Health Monitoring can be grouped in a four groups:

- Vibration-Based and Time-Frequency Wave Propagation Damage detection methods [2-8 1-6];
- Wireless Remote Sensors Networks [9-12 7-10];
- Embedded Fiber-Optics Sensors and Networks [12-15 10-13];
- Optical inspection methods and optoelectronic scanning [16-17 14-17].

The first one is most advanced and well investigated branch recently. They are localized various experimental methods such as acoustic or ultrasonic methods, magnet field methods, radiographs, eddy-current methods and thermal field methods. Most of the papers on this group of SHM represent reports about adaptive and self-calibrating networks of strain sensors for monitoring the deformation of concrete poured highway structures, usually well known bridges (Z24-bridge [4 2], Ashidagawa or Kishwaukee briges [53], I-40 Brige [6 4], etc.). As the rule, there are wire networks. These methods are strong tools for any internal and external damage detection on early stage. However, all these methods are carrying out too much information in very indirect form. For object structural health verification are used very complex algorithms. These algorithms: 1) been processed exceeded time, and 2) can't completely exclude invalid interpretation about damage type and localization. But in a case of large engineering structures integrity monitoring first of all we are interested in a fast and exact detection of pre-disaster situation on the early stage. It can give only fixed information about directed and continued movement of all reference points set. Not about small local displacement of material. In this case mentioned techniques are not very efficient tool.

In the wireless active SHM hardware most off-the-shelf solutions currently available have a deficit in processing power that limits the complexity of the software and SHM process that can be implemented. Also, many integrated systems are inflexible because of tight integration between the embedded software, the hardware, and sensing [18, p.1583]. Current damage-detection methods for "wireless group" is the most recent, promising and perspective branch of SHM. Because of this fact there is no enough statistical information about security and reliability of such nets. But it's very logically to note that for net of thousands wireless sensors in a case of large object we need a same thousands of independent radio channels. This structure is very complex to operate and, at least, it is very sensitive to any kind of electromagnetic noise. For example, in a case of bridge monitoring by system [8] the main problem can occur because of people cellular phones on this bridge.

Fiber optics embedded nets can be very efficient for damage initial point recognition. Any internal microdisplacements of material can be detected with extremely high exactitude by destroyed wavelet or sensor location. But this solution also isn't a perfect solution for our task. Firstly, it can be applied only for the first time created constructions, by "embedding" on creation stage. For historic building, or for yet existing bridges, tunnels, etc. this method properly inapplicable. Also very discussible question in articles in this field is a question about influence of fiber-optical embedded nets on properties of constructional material durability. And finally, we can note that this group is not very economic in a power consuming, especially with enhancement of monitored object volume.

The Optical inspection methods and optoelectronic scanning has the most development stage in 70-80's, parallely with surveying techniques. In this time furthering achievement was stopped because of natural limiting by hardware capacity and accuracy. Also in this time starts intensive development of various remote sensors. But in last 20 years possibilities and technical parameters (especially - Technical reliability and accuracy) of electromechanic systems, as well as laser sources and optical sensing, was growing up essentially. So, we are considering that it is reasonable to use some strong skills of optical systems, which are offered only by them on the modern stage of technical parameters progress. Some works in this branch of SHM [14,15] offers an interesting ideas. But unfortunately, these systems are not have technically completed solutions [15], or are not convenient for automation in proposed form [14].

So, we can conclude, that SHM is a perspective technical branch, which is actively developed now, using various methods. We are considering that the best results can be obtained by synthetic SHM-techniques which combine most competitive skills of various technical solutions.

Also, it is reasonably taking to account some achievements of other technical systems, which are not straightly dedicated to SHM, but have some very useful properties capable to advance us in the problem decision. For such properties or existing completed solution overview it is necessary to observe additionally next techniques.

For the last 20 years in a field of 3D-object visualization and recognition are used successfully laser scanning systems which are involves unique properties of laser ray for surface highlighting. These properties are: fixed frequency of light emission, and correspondingly response; high ability of scanning element to be focused, spatially compressed; well known methods of the noise protection of optical channel.

From the other hand, are exist the "laser scanning systems", which usually using one laser source and one camera [19, 20]. The difference between various is only the laser emission power, camera resolution, and their price correspondingly. But, according to their geometry such systems needs a "reference background base" (geometric standard for dimensions measurement) [19]. These systems properly are not acceptable for SHM because of natural difficulties with such "reference background". Also, the triangulation principle as the rule based on the only one angle measurement, so this is a cause of additional systematic error. From the other hand, these systems proof that the laser ray have lot of properties very useful for spatial coordinates recognition, which not posses any other scanning element.

The next advanced step in a field of spatial coordinate's determination is terrestrial laser scanners. 3D terrestrial laser scanning is a relatively new, but already revolutionary, surveying technique [21, 22]. The survey yields a digital data set, which is essentially a dense "point cloud" , where each point is represented by a coordinate in 3D space. The most important advantage of the method is that a very high point density can be achieved, in the order of 5 to 10 mm resolution. But this technique is designed for large area observation from the relatively long distance [22]. And resolution of 5-10 mm is practically 3D-coordinates measurement error. For surveying tasks it been corrected on the surface reconstruction stage (Delaunay triangulation, Voronoy diagrams, NURBS, Fast RBF, etc.), but for SHM this error is not acceptable. Because of all reconstruction algorithms have probabilistic character. Moreover, for this kind of task 3D terrestrial laser scanners use a very expensive units, like superpower laser source, supersensitive receivers, etc. So, as the conclusion we can say that terrestrial laser scanners is a good tool for surveying tasks, not for SHM.

We can find another interesting solution [23] in a group of spatial surface scanning by the structured light (not only lasers). But such systems maximum unambiguous range essentially limited by usual light sources. It can not be sufficiently localized and focused on a long distance.

Sometimes for SHM tasks are using GPS- and, especially, DGPS-technologies (with special pseudosatellite as additional "terrestrial reference point" for accuracy enhancement). However, these techniques are still too expensive. Also the GPS technology cannot be used outside the radio signals receiving zone such as tunnels, mines, etc.; in this case, only traditional geodetic means it is possible to provide. Geodetic tools using on the structure in a process has a low productivity and frequently it is associated with difficulties. The controllable object vibrations, transport movement, etc. inevitably cause some systematic errors or even damage during the geodetic devices functioning. Sometimes the operator of geodetic devices cannot be located in a working zone (radioactivity, strong electromagnetic fields, chemical pollution, etc.).

Therefore it is a reason for automated geodetic measurement tools development.

3. Problem formulation. The main idea of this work is to try on the recent stage of the electronic, optic, electromechanic techniques progress, and modern computing capacity to design the novel system for objects monitoring. Taking to account than such system must to unite some advantages of mentioned above techniques, but not possess their lacks.

We suppose the next advantages can be useful for exact, robust, secure and low-price system:

- remote system like a various wireless sensors nets presented in references overview. The sensing part and analyzing part must be distanced and independent electrically on each other;
- present total information about object statement in a form convenient for storage and mathematical treatment. It must to be easy to compare recent object data with any previous stage for professional analysis;
- register small deformation of the structure on the earliest stage and to show clearly the general character of this deformation;
- provide control with minimal reference points and to have very short and clear algorithm of estimation. In other words, the deformation estimation must to be sufficient, but not redundant. Like an optical control methods it must to give fast and clear response;
- adaptable to it's fast and non-destructive installation on the controlled object. It mustn't to influence any own object properties.

On this basis, the automatic monitoring system would be created.

4. Automatic measurement of plane angles

Any spatial location of the point in 3D can be represented by polar coordinates (radial distance and two plane angle projections) in Cartesian coordinates introduced by Rene Descartes. This postulate is the base of spatial coordinate's determination by now. It is evident that the same unique spatial location of the point can be described using the third plane angle projections instead the radial distance. This circumstance explains why the central question of geodetic surveying is the angle measurement methods. To measure the direction to any certain point always is faster and more precise that to measure the distance up to the same point [43]. This is a point why we are focused in precise spatial angle measurement and its uncertainty reduction for our task solution. This is a key for adequate estimation of slow/fast 3D coordinates changes in a real time system.

In practice, the plane angles can be formed 1) by the shafts mutual turning or 2) by the lines intersection (spatial plane angle). In the first case, the plane angle can be measured automatically, using the shaft angle encoder. In the second case, the special means on theodolite principle design is necessary for the measurement of the spatial plane angles.

The search of a guidance point of the sighting telescope inside the solid angle 4π sr carried out for the measurement of a spatial plane angle with a theodolite. The sighting telescope has expression for the visual solid angle [25]

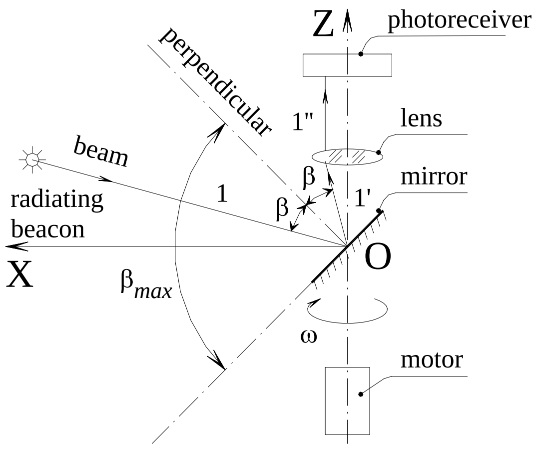
$$\Omega_t = 4\pi \cdot \sin^2 \frac{\beta_t}{4}. \qquad (1)$$

where β_t is the theodolite's sighting telescope plane angle of vision [25, (3.6) on p.35].

For $\beta_t \approx 2^\circ$, $\Omega_t = 9.57 \times 10^{-4}$ sr.

According to (1), the points quantity m_e examined with a theodolite in the solid angle 4 sr is:

$$m_e = 1/\sin^2(\beta_t/4) \geq 1.31 \cdot 10^4. \qquad (2)$$



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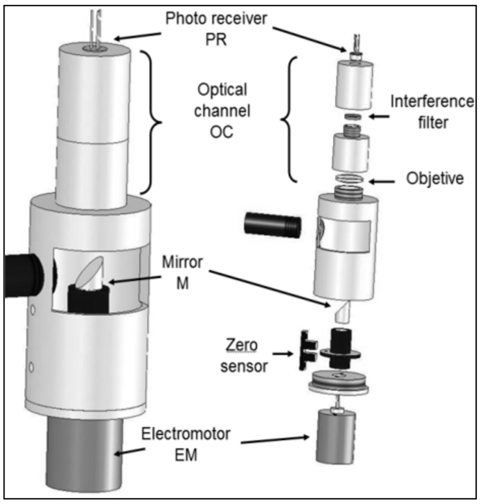

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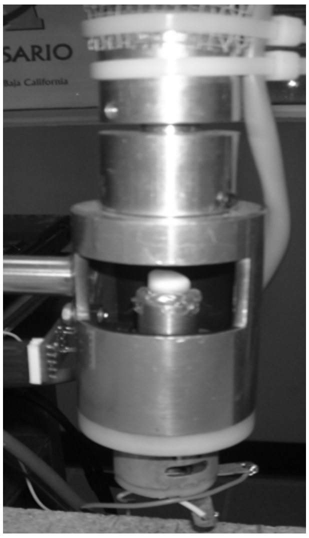


c

Fig.1. POS Operating principle (a) and a prototype design (b,c)

Hence becomes clear the space given point search automation difficulty and the device guidance in it. The problem of a spatial plane angle automatic measurement can be solved by active or passive optical scanners (AOS and POS correspondingly). Against an AOS, a POS solves the double-uniform task: the guidance point search and the plane angle measurement in space.

The principal elements of a POS are represented on Fig.1.

Some variations of this unit are presented in [16, 35, 37, 42]. The emitting beacon (EB) light by a mirror rotation gets through a lens on a photoreceiver, which forms a stop - pulse. A start-pulse is formed by a special independent zero-sensor. The time interval $T_\alpha = \alpha / \omega$ corresponds to the spatial plane angle α between the zero-sensor and the direction on an EB. The intervals T_α and $T_{2\pi} = 2\pi / \omega$ are filled by standard frequency pulses f_0, generating the codes $N_\alpha = T_\alpha f_0$ and $N_{2\pi} = T_{2\pi} f_0$. From the proportion $\alpha / (2\pi) = N_\alpha / N_{2\pi}$ is received:

$$\alpha = 2\pi \frac{N_\alpha}{N_{2\pi}} \qquad (3)$$

It is invariant respect to ω and f_0. Or, in other words, one of the most important advantages of our system is the independence of the measurement result on “time walking effect” or reference source own instability. Because in real time system’s electronic circuit in two independent counters saves two independent counts. They are codes proportional to values of 360° (or 2π) angle and desired (unknown) angle α. It means, practically, the parallel two-channel AD-conversion of the geometrical basis in real time. It permits eliminate the absolute error component of both codes after their division according to (3) because of their natural equality in real time. As shown in [42] the uncertainty of the single measurement of the angle α per one rotation period of the mirror is about 10 seconds of arc. The multiple averaging in the automatically repeated measurements permits to obtain the uncertainty measurement of the angle α no more than 1 second of arc. Because it is widely known that with *n* consecutive repetition of a single act of measurement it is possible to decrease a measurement uncertainty up to $\sqrt{n}$ times.

The average angle is determined as:

$$\overline{\alpha} = 2\pi \cdot \left[\sum_{i=1}^{n} N_{\alpha i} \Big/ \sum_{i=1}^{n} N_{2\pi i} \right] \qquad (4)$$

The ratios $N_{\alpha i} / N_{2\pi i}$ and $N_{\alpha(i+1)} / N_{2\pi(i+1)}$ represent the rational fractions which possess the properties of Farey fractions [26-28].

The ratio of the numerators sum to the denominators sum for such fractions in the formula (4) represents the mediants of the Farey fractions [29]. Mediant is a standard term in theory of numbers: for given a Farey sequence with consecutive terms h/k and h'/k' the mediant is defined as the reduced form of the fraction $(h+h')/(k+k')$ [27, pp.152-154; 26, Lemma on p.14 of US edition]. In mathematics, a rational number is a number which can be expressed as a ratio of two integers. Non-integer rational numbers (commonly called rational fractions) are usually written as the vulgar fraction a/b, where b is not zero. Numbers $N_{\alpha i}$ and $N_{2\pi i}$ in any *i*-th position are count results of two independent counters, so they are integers naturally.

Each rational number can be written in infinitely many forms, such as $3/6 = 2/4 = 1/2$, but it is said to be in simplest form when a and b have no common divisors except 1 (i.e., they are coprime). The Farey sequence F_n for any positive integer *n* is the set of irreducible rational numbers a/b with $0 \le a \le b \le n$ and $(a,b)=1$ arranged in increasing order. The first six for example are

$$F_1 = \left\{\frac{0}{1}, \frac{1}{1}\right\},$$

$$F_2 = \left\{\frac{0}{1}, \frac{1}{2}, \frac{1}{1}\right\},$$

$$F_3 = \left\{\frac{0}{1}, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}, \frac{1}{1}\right\},$$

$$F_4 = \left\{\frac{0}{1}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{1}{1}\right\},$$

$$F_5 = \left\{\frac{0}{1}, \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{2}{5}, \frac{1}{2}, \frac{3}{5}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \frac{1}{1}\right\},$$

$$F_6 = \left\{\frac{0}{1}, \frac{1}{6}, \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{2}{5}, \frac{1}{2}, \frac{3}{5}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}, \frac{5}{6}, \frac{1}{1}\right\}.$$

These two statements are actually equivalent [30, p. 24]. For a method of computing a successive sequence from an existing one of n terms, insert the mediant fraction $(a+b)/(c+d)$ between terms a/c and b/d when $c+d \le n$ [27; 30, pp. 25-26; 31].

Given $0 \le a/b < c/d \le 1$ with $bc - ad = 1$, let h/k be the mediant of a/b and c/d.

Then $a/b < h/k < c/d$, and these fractions satisfy the unimodular relations [31, p. 99]:

$$bh - ak = 1 \qquad ck - dh = 1$$

For a n-th mediant generation in the form of the fraction $\sum_{i=1}^{n} N_{\alpha i} / \sum_{i=1}^{n} N_{2\pi i}$, the sum $\sum_{i=1}^{n} N_{\alpha i}$ discretely on each turn of the POS's mirror is formed. The sum $\sum_{i=1}^{n} N_{2\pi i}$ is formed continuously from the first start-pulse up to the $n+1$ pulse. A computer performs the division operation only once, after the generation of the both sums $\sum_{i=1}^{n} N_{\alpha i}$ and $\sum_{i=1}^{n} N_{2\pi i}$ in the POS.

The average $\overline{\alpha}$ founded with the mediants use, has the higher exactness, in comparison with the classical arithmetic middle averaging exactness for the given value *n*. We can approve it on the base of [26, p.30, in the US edition p.21]: it is immediately clear that the apparatus of systematic fractions is completely unsuitable for approximation problem solving, since denominators of the approximating fraction that it provides are determined exclusively by the choosen system of calculation (in the case of decimal fraction, they are powers of ten); hence, the denominators are completely independent of the arithmetic nature of the number represented. On the other hand, in the case of continued fraction, the denominators of the convergents are completely determined by the number represented. We, therefore, have every reason to expect that these convergents (since they are connected in a close and natural way with the number represented, and are completely determinated by it) will play a significant role in the solution of the problem of the best approximation of a number by a rational fraction. Rigorous proof of this fact is given by Theorems 15, 16, 17 proofs in [26, pp.22-28 of US edition].

This benefit also seems comparably mall to other similar problems in various practical applications.

Thus, the proposed system for precise spatial coordinate's measurement has some obvious advantages over other similar methods [19-21, 36, 38, and 39]. There are the next advantages. Using the robust and precise mechanical scanning and registering principle instead the electronic scanning which is extremely sensible to any kind of vibration and mechanical noise. Using of the special mathematical processing for measurement uncertainty decreasing. Precise spatial coordinate's measurement caused, first of all, considering the scanning tool not the real light beam, but the geometrical axis of this beam of a conic form. Thanks to the concept of the energetic center search of the noisy electrical pulse it is possible to increase spatial resolution of the EB location. This method will be described below.

Also it can be additionally increased exactitude of angle measurement using original method [40, 41] for precise adjustment of initial and final scale coincidence between angle pulse-marks and reference pulse train. This way can be minimized the influence of reference frequency source own jitter.

5. POS operation range. The analysis of the possible positions of a beam, traveling from the EB to the mirror, shows that the maximum value of the angle β between the beam and the perpendicular to the mirror (look Fig.1), can reach 90°. Thus, the POS aperture angle is $\beta \le 90°$.

During the mirror rotation, the solid angle of an all-round vision of a POS is:

$$\Omega = 4\pi\left(1 - 2\sin^2\frac{180° - \beta_s}{4}\right). \quad (5)$$

where β_s is the POS's desirable angle of sight. If $\beta_s = 90°$ for example, then $\Omega = 2.83\pi$ sr; so it's more than half of the space around of a POS.

We shall determine the POS coverage.

Let assume that EB have the diffuse emission power *P*. The uniform emission density in the solid angle 4π sr is

$$I = \frac{P}{4\pi} \quad (6)$$

Let the aperture diameter of the POS be $2r = 3\times10^{-2}$ m, and then the emission power, getting in the POS is:

$$P_a = I\Omega_a, \quad (7)$$

where

$$\Omega_a = \frac{S_a}{D^2} = \frac{\pi r^2}{D^2}. \quad (8)$$

where S_a is the scanning aperture area, and *D* is the distance between EB and the center of SA mirror (detailed distance toward current light source under consideration). According to the expressions (6) and (7), from the proportion (8) we finding the expected operating range

$$D = \frac{r}{2}\sqrt{\frac{P}{P_a}} \quad (9)$$

Let P_a be equal to the minimum threshold optical power value $P_{\min}$.

It can be determined, for example, by the technique given in reference [32, p.70] (this reference is taken intentionally for to show than it possible for very basic hardware, not so advanced):

$$P_{\min} = NEP\frac{R_{\max}}{R(\lambda)}\sqrt{B}\ \text{[W]}. \quad (10)$$

Here *NEP* is the noise equivalent of the power, $R_{\max}$ and $R(\lambda)$ are the maximum sensitivity and the sensitivity on the detecting wave; *B* is the frequencies band in Hz.

For example, the length of the wave for the photoreceiver Model # 2007 [32, pp.56, 66] is 400-1070 nm; $NEP = 3\times10^{-12}$.

For $B = \omega/2\pi \approx 100$ Hz, $R_{\max} = 0.55A/W$ and $R(\lambda) = 0.5A/W$, then:

$$P_{\min} = 3\times10^{-12}\times0.55\times\frac{\sqrt{100}}{0.5} = 3.3\times10^{-11}\ \text{W}. \quad (11)$$

Using as a power source, for example, the lamp HRQ3010-5071 of catalog [33] with power 1,75W, from the expression (9) we finding:

$$D_{\max} = 0.5\cdot1.5\cdot10^{-2}\sqrt{\frac{1,75}{3.3\cdot10^{-11}}} = 1727\ \text{m}. \quad (12)$$

This analysis shows that with a POS it is possible to design networks of polygonometry and triangulation of a high accuracy, which allows observing large spaces on monitoring objects. This distance covers our requirements even taking to account different types of losses inside the optical channel because the optimal distance between scanner and controlled object is 150-500m.

Also it is possible to use more expensive light sources, like special automobile lamps (Philips H11 CrystalVision, type 12362 CV, 12V, 55W) or even CW-lasers, which have proved unambiguous range up to ≥150 m according to [34, p.200-201]. Of course, it has a reason only for civil engineering structures of enhanced importance.

6. POS adoption on the monitored objects. The above-described POS with the vertical axis of rotation is destined for the measurement of the horizontal angles. Let's call it a vertical POS. The vertical angles between the RBs are measured by the POS with the horizontal axis of the rotation. This POS is the horizontal POS. The system, which consist of the vertical and horizontal POSs, permits to measure the displacement of the radiative (or emitive) beacons (RB or EB) in horizontal and vertical planes.

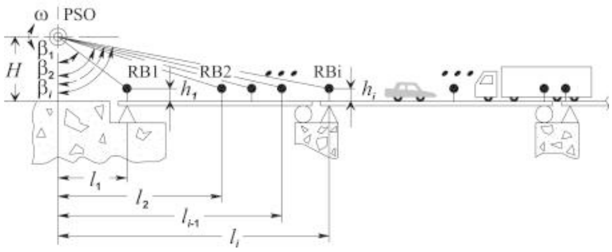


Fig.2. Horizontal POS placement f
or bridge monitoring

Fig.2 shows the adoption of the horizontal POS for the realization of the bridge points monitoring in a vertical plane. It is extremely important that such scheme is very efficient for registration of the results of natural disasters, for example earthquake, on the object under monitoring.

The POS is placed outside the bridge and measures the vertical angles β_i. The RBs are installed with the same height h_i above the bridge surface. As RB it is possible to use any sufficiently cheap light source, for example mentioned above lamp HRQ3010-5071. The distances l_i are measured during the installation of the RB.

In the absence of a deformation, for each RBi, the following expression is valid:

$$\frac{H-h}{l_i}=\tan\left(\frac{\pi}{2}-\beta_i\right). \quad (13)$$

For the bridge deformation with the magnitude Δh_i in the placement point of the beacon EBi, the angle β_i, measured by the POS, will change on the magnitude $\Delta\beta_i$. As a result the expression (13) will receive the form:

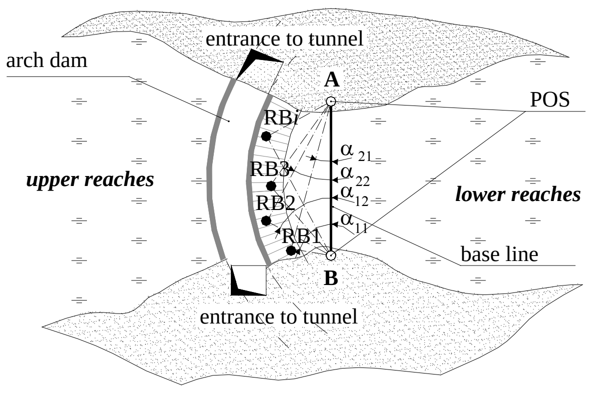
$$\frac{H-h\pm\Delta h}{l_i}=\tan\left(\frac{\pi}{2}-\beta_i\pm\Delta\beta_i\right). \quad (14)$$

Therefore:

$$\Delta h_i=(H-h)-l_i\tan\left(\frac{\pi}{2}-\beta_i\pm\Delta\beta_i\right). \quad (15)$$

In a similar manner the POS for tunnel monitoring is installed. In extended tunnels several functionally connected POS can be placed along its axis.

Fig.3 shows the placement of two vertical POSs for the arch dam monitoring of a hydroelectric power station.



Practically

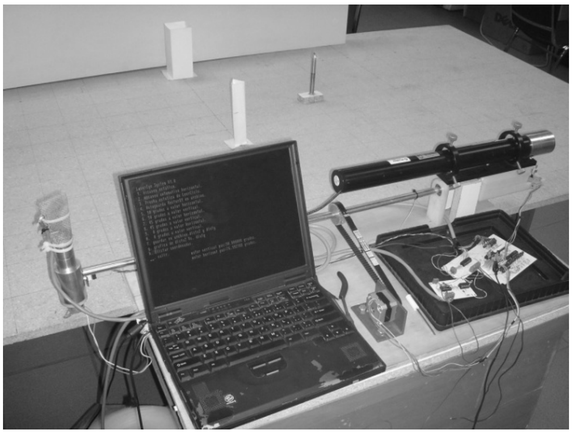
Fig.3. Placement of two vertical POSs for arch dam monitoring.

The POSs measure in pairs the horizontal angles α_{1i} and α_{2i} between the base line AB and the EBi. The length of the base line D and the Cartesian coordinates of the POS are determined beforehand by known geodetic methods. The angles ∠EBi are found conform to the formula:

$$\angle RBi=180^\circ-(\alpha_{1i}+\alpha_{2i}). \quad (16)$$

According the sine theorem we find the triangles sides, which have the vertex A, B, EBi ; and the coordinates x_i, y_i of the points EBi, in the national system or conditional Cartesian coordinate system. The change of coordinates of the points RBi in the repeated measurements of the angles α_{1i} and α_{2i} reveal the dam deformation.

7. Experimental results. Practical working capacity of the given method has been checked out on a scanning aperture prototype (see Fig.4), with preliminary experimentations, still without ECS-circuit implementation. This experimentation was made using a movable light source, varying its position on a table with grid-scale, in which was situated a network with 45 designated points.



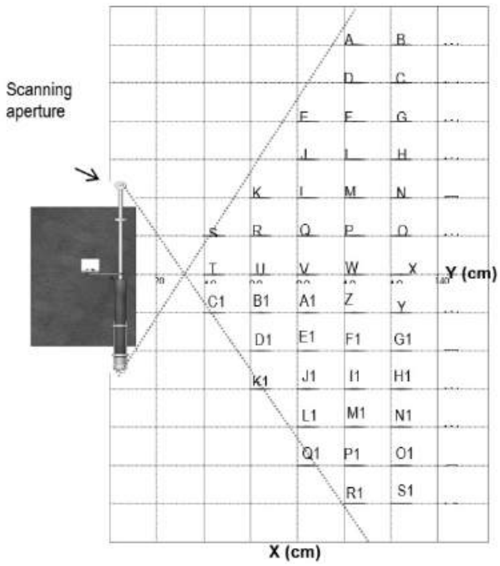


Fig.4. EBs' and POS positioning on the experimental table with grid-scale.

The points were chosen according to the detection pattern of the system within a maximum range of 1 m. The separation distance between each point is of 20 cm in coordinate X and Y, with an error of ±0.1 cm. The light source used in the experiment, is a regular incandescent automobile lamp of 12 volts DC. Also the prototype gives the possibility to highlight same points with laser ray by 20mW laser (JDS Uniphase, model 1136P). The lamp was located in each point of the network, where 10 optical scannings were made. An average of the reception angle for each point was obtained (see table 1). Additionally, the value of the emission angle (angle C) for each point in test was obtained using trigonometrical formalism in [35, p.342]. Using the value of angle C, the final coordinates X and Y that describe the experimental position of each point, were obtained. Each point coordinate value has an measurement error. This error must due to many causes, but mainly due to the errors in reflection angle measurement at optical aperture. Principle known causes of error are detected:

- Instability of motor speed in optical aperture.
- Electrical signal center shifting caused by low operating velocity.
- Improper calibration of reference instrument.

All these causes are been taking to account in the present process of a second prototype design.

Basing in data analysis is possible to determine a zone in the table 1 where the obtained data is more accurate. It is shown on a Fig.5. All the experiments were carried out not less at 95% confidence level. But in the Fig.5 are presented real points and measured points, ant it is evident that appears two zones of different accuracy in this measurement. Most exact data was obtained in frontal zone, where the experimental data's have an error less than in the zones nearby edge. Thus, the zone of more accurate measurement from the system can be known.

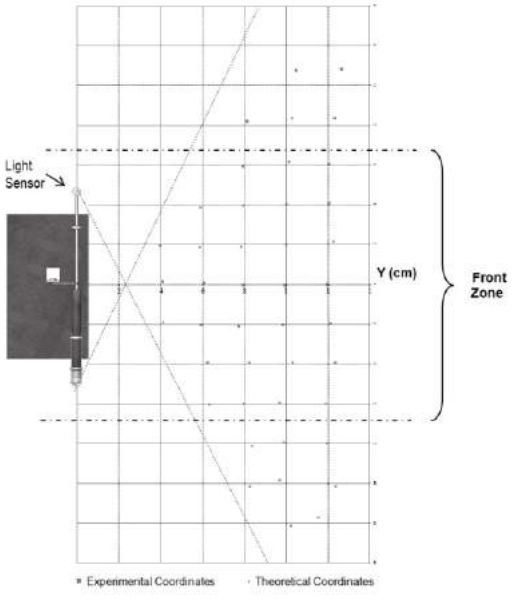


Fig.5. Measured coordinates points positioning on the grid-scale.

In general behavior of uncertainty repeats graphic on figure 6 in [36, p.1765], however accuracy nearby edge is advanced. Also accuracy in a central part of angle of view is 2-7 times better in a different checked points respect to [36] for example.

8. Accuracy improvement by the method of pulse energetic center search.

The mentioned above considerations are still strongly theoretical. Because in the geometrical scheme we considering a pure geometrical objects, i.e. the straight line is precisely straight, without any curvature, have only length, all another sizes are zero; points have no any sizes and its location is characterized only by three Cartesian coordinates in the space.

Practically it is different. The optical ray it is a cone in general, or even more complex shape depending on medium properties. The vertex of this cone also isn't a point, but distributed in some small spatial scope. The divergence inside this cone it is caused by many natural factors. It causes that practically the stop-pulse in photo receiver is not a short pulse of the standard form, but it is formed as shown on Fig. 6 (a-e).

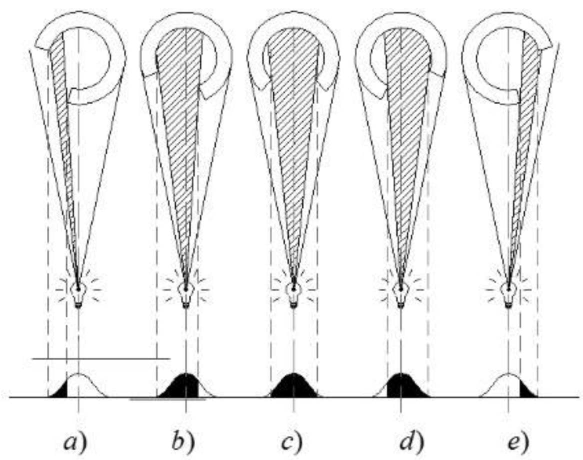
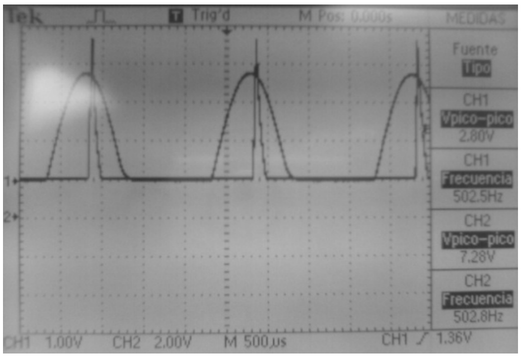


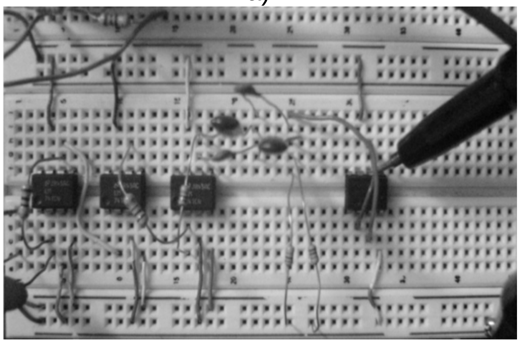
Fig.6. The principle of noisy electrical stop-pulse formation during rotational scanning.

It growth (Fig. 6,a) and falling down (Fig. 6,e), and fluctuating around its maximum area in figs. 6 (b-d). Taking to account the presence of some natural noise (as rule, white Gaussian noise) in this process, we can conclude that finally we need to operate the single electric signal of non-regular shape presented on Fig.7,a. Moreover, the shape and the width of this pulse are closely related to scanning velocity. But the scanning velocity in practical case is not a constant also. In this case the best problem solution is adequate signal processing. And our contribution is based on simple idea. What is it the red point on the Fig. 7.a? In the point of view of electric signals area on the graphic limited by signal curve is the energy transferred by this electric signal.

So, this red point with certain small uncertainty is the signal energetic center. It is essential to note that position of the energetic center coincides for both pulses on the Fig.7,a: ideal theoretical square pulse, and its real noisy performance. Much more essential is to note in this case, that the energetic center position uncertainty the less depends on noise, than becomes more the pulse area. In our task is the same like less scanning velocity.



a)



b)

Fig.7. Method of the signal energetic center search: a) general purpose; b) differentiator circuit functioning screenshot

From the other hand, as we consider this pulse as the optic blur equivalent registered by photosensor, it is the center of optical ray spatial cone. Such way we can detect in noisy electric signal the truth position of the unique straight line which belongs the same time the center of light source (active target, or EB) and the center of photoreceiver.

It is possible to provide practically using another strong and simple rule: the function (signal curve) maximum it is always where its derivative is zero. In another words, after finding the zero-cross position of first derivate function of the registered signal, we can find a real position of the EB in our coordinate system.

The practical realization of described operation it is possible in a several ways. Which one of them is the most efficient in this case it is a complex question. We still consider it as a whole problem for furthering research and a topic of another publication. However, in our primary experimentation we realize this operation using standard differentiator circuit (Fig.7,b). On the operation screenshot on Fig.7,b it is clear evident that it is completely possible in a real time scale to obtain an electrical mark of the real light source position. Of cause it is a certain delay between real maximum position and its mark by pin-pulse (Fig.7,b) because of differentiator circuit operating time. But it is strongly evident that it has a constant character and can be eliminated on the processing stage by simple correction factor.

The circuit of Fig.7 is processing the signal as shown on Fig.8.

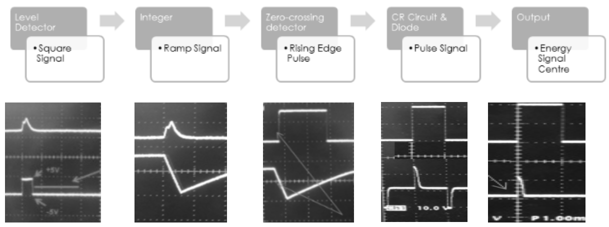


Fig 8. Analogue Processing by Electronic Circuit.

Also, as shown in [43,44], it is still possible to improve the accuracy of real spatial positioning of light signals using different geometrical methods and mathematical techniques, such as Geometric Centroid, Power Specrtum Centroid, Rising Edge, Peak Detection, and Support Vector Machines.

The comparative results between them are finally summarized on Fig.9.

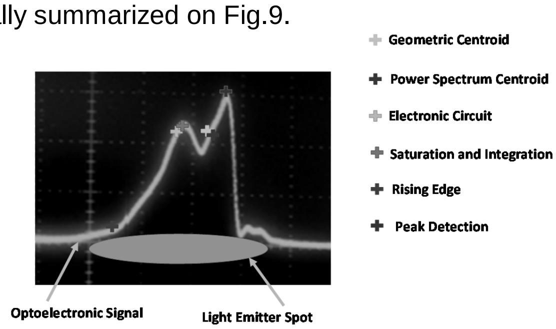


Fig.9 Energy Centre Localization Methods.

Combining with our mentioned above method of spatial angle measurement it permits to conclude that our method gives more accurate angular resolution than any of known in [15, 21, 38].

9. Conclusions.

1. The stationary system of the any structure or environmental objects deformation monitoring, based on the POS, possess the following inherent properties:

- A possibility to receive the data about structure deformation every minute, in all check points, with the millimeter's uncertainties, for the structure of any size and configuration;
- The complete measurement automation, the data registration for the significant distance between the processing center and the observable structure;
- The operation of the monitoring system without interruption of the structure functioning;

- A possibility of the operation under ground: in tunnels, subways, mountain excavation;
- High durability and a simple service;
- The possibility of many years round-the-clock control of the earthquakes development centers with it prediction purpose.

2. On the POS-base can be constructed: the mobile robots navigation systems, the automatic adjustment system for the compound space crafts, the mutual orientation system for the six freedom degrees structures, the ships and aircrafts deformation monitoring system in dynamics, automatic region mapping systems and others.

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Appendix A. Table 1.

Test Point	Theoretical Value				Measured Value				Relative Error [%] (offset)
	X (m)	Y (m)	B (°)	C (°)	X(m)	Y(m)	B (°)	C (°)	
A	100	120	124.99	30.47	111.94	140.3	128.89	30.47	3.12
B	120	120	120.26	35.22	139.01	146.93	124.89	35.22	3.85
C	120	100	112.62	38.66	126.53	108.16	114.69	38.66	1.83
D	100	100	116.57	33.69	104.91	107.37	118.67	33.69	1.81
E	80	80	110.56	31.61	81.2	81.949	111.48	31.61	0.83
F	100	80	106.70	37.57	102.73	83.555	108.09	37.57	1.30
G	120	80	104.04	42.71	123.21	83.475	105.2	42.71	1.12
H	120	60	94.76	47.49	120.52	60.481	94.97	47.49	0.22
I	100	60	95.71	42.27	101.36	61.499	96.472	42.27	0.80
J	80	60	97.13	36.03	79.405	59.182	96.596	36.03	0.54
K	60	40	80.54	33.69	58.935	38.403	78.868	33.69	2.07
L	80	40	82.87	41.63	79.567	39.513	82.492	41.63	0.46
M	100	40	84.29	48.01	100.17	40.157	84.388	48.01	0.12
N	120	40	85.24	53.13	120.67	40.499	85.498	53.13	0.31
O	120	20	75.96	59.74	122.59	21.509	76.916	59.74	1.25
P	100	20	73.30	55.01	99.755	19.829	73.172	55.01	0.18
Q	80	20	69.44	48.81	78.538	18.721	68.284	48.81	1.67
R	60	20	63.43	40.60	58.791	18.59	61.886	40.60	2.44
S	40	20	53.13	29.74	39.652	19.391	52.334	29.74	1.50
T	40	0	38.66	38.66	41.083	1.3538	40.182	38.66	3.94
U	60	0	50.19	50.19	60.67	0.5579	50.822	50.19	1.25
V	80	0	57.99	57.99	79.392	-0.3799	57.602	57.99	0.68
W	100	0	63.43	63.43	99.259	-0.3703	63.094	63.43	0.54
X	120	0	67.38	67.38	119.63	-0.1522	67.256	67.38	0.18
Y	120	-20	59.74	75.96	121.09	-19.729	60.064	75.96	0.54
Z	100	-20	55.01	73.30	98.417	-20.475	54.394	73.30	1.12
A1	80	-20	48.81	69.44	77.312	-21.008	47.434	69.44	2.83
B1	60	-20	40.60	63.43	59.276	-20.362	40.112	63.43	1.21
C1	40	-20	29.74	53.13	41.172	-19.121	30.78	53.13	3.48
D1	60	-40	33.69	80.54	62.278	-39.62	34.796	80.54	3.28
E1	80	-40	41.63	82.87	82.325	-39.709	42.542	82.87	2.18
F1	100	-40	48.01	84.29	103.12	-39.688	48.986	84.29	2.03
G1	120	-40	53.13	85.24	123.5	-39.708	54.006	85.24	1.65
H1	120	-60	47.49	94.76	119.04	-59.92	47.282	94.76	0.44
I1	100	-60	42.27	95.71	96.858	-59.686	41.446	95.71	1.96
J1	80	-60	36.03	97.13	79.77	-59.971	35.956	97.13	0.20
K1	60	-60	28.61	99.46	63.354	-60.559	29.814	99.46	4.21
L1	80	-80	31.61	110.56	83.619	-81.357	32.48	110.56	2.76
M1	100	-80	37.57	106.70	98.923	-79.677	37.338	106.70	0.61
N1	120	-80	42.71	104.04	119.63	-79.908	42.642	104.04	0.16
O1	120	-100	38.66	112.62	123.77	-101.57	39.234	112.62	1.49
P1	100	-100	33.69	116.57	96.833	-98.416	33.122	116.57	1.69
Q1	80	-100	28.07	122.01	82.59	-101.62	28.578	122.01	1.80
R1	100	-120	30.47	124.99	102.2	-121.54	30.786	124.99	1.05
S1	120	-120	35.22	120.26	115.43	-117.33	34.598	120.26	1.76

Анотація

Моніторінг об’єктів та оточуючого середовища за допомогою оптоелектронного сканера

О.Ю.Сергіенко, В.Флорес-Фуентес, В.В.Тирса, П.Меркореллі

Об'єктам навколишнього середовища, екологічним ландшафтам і великим інженерним спорудам потрібно геометричний моніторинг, що дозволяє прогнозувати структурний стан об'єктів протягом усього часу використання. Моніторинг за допомогою геодезичних приладів, бездротових мереж або систем GPS не завжди оптимальний. Запропонований метод базується на автоматизації геодезичних вимірювань, що використовують локальні оптичні сканери для моніторингу навколишнього простору. Метод ґрунтується на новітньою методикою високоточного вимірювання плоских просторових кутів. Такого роду контроль не завжди є оптимальним. У статті пропонується метод моніторингу, заснований на автоматизації геодезичних вимірювань із застосуванням локальних оптичних сканерів. Використовується високоточне вимірювання плоских просторових кутів. Розглянуто Робастное аналого-цифрове перетворення кут-код для миттєвого визначення динамічного кута, метод знаходження енергетичного центру сигналу, початкова регулювання еталонної шкали і зниження невизначеності за допомогою визначення медіант дробів. Експериментальні результати підтверджують, що наша система випереджає відомі оптичні пристрої для розпізнавання тривимірних координат в зоні невизначеності.

Ключові слова: *оптичні прилади, скануюча апертура, просторовий кут, вимірювання поверхонь, раціональні наближення, медіанти*

Анотация

Мониторинг объектов и окружающей среды посредством оптоэлектронного сканера

О.Ю.Сергиенко, В.Флорес-Фуентес,В.В.Тырса, П.Меркорелли

Объектам окружающей среды, экологическим ландшафтам и крупным инженерным сооружениям требуется геометрический мониторинг, позволяющий прогнозировать структурное состояние объектов в течение всего времени использования. Мониторинг с помощью геодезических устройств, беспроводных сетей или систем GPS не всегда оптимален. Предложенный метод базируется на автоматизации геодезических измерений, использующих локальные оптические сканеры для мониторинга окружающего пространства. Метод основывается на новейшей методике высокоточного измерения плоских пространственных углов. Такого рода контроль не всегда является оптимальным. В статье предлагается метод мониторинга, основанный на автоматизации геодезических измерений с применением локальных оптических сканеров. Используется высокоточное измерение плоских пространственных углов. Рассмотрены робастное аналого-цифровое преобразование угол-код для мгновенного определения динамического угла, метод нахождения энергетического центра сигнала, начальная регулировка эталонной шкалы и снижение неопределенности с помощью определения медиант дробей. Экспериментальные результаты подтверждают, что наша система опережает известные оптические устройства для распознавания трехмерных координат в зоне неопределенности.

Ключевые слова*: оптические приборы, сканирующая апертура, пространственный угол, измерение поверхностей, рациональные приближения, медианты.*

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