Statistical study of accuracy of the video-positioning system for GPR

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Abstract. Here we present results of the statistical study of the accuracy of the local optical positioning system for the industrial GPR OKO-2. The results of measurement are forming a statistical set. The statistical set should verify the accuracy LPS. The proposed LPS uses special tapes with a special periodic pattern as a reference object. The video camera records the image of the marker tapes, was located on a fast mechanical scanner. The scanner produced an accurate movement of the camera perpendicular to the tape. During the moving process, LPS measures the distance between the camera and tape and compared it with the scanner data.

1. Introduction
Modern radio-tomographic methods [1–4] make it possible to restore the shape of objects hidden behind radio-transparent barriers. Obviously, the use of such methods in GPR systems [5] will make it possible to restore the shape and position of hidden objects underground. Difference between georadars and radio wave tomographs-scanning method for synthesis of aperture. Radiotomographic complexes use a fast mechanical scanning system, providing accurate positioning of the antenna unit, but GPR use in open areas. So, the Operator performs scanning by manually moving an antenna unit. The ground penetration research provides according to the following scheme. It provides accuracy. In the first stage, the operator makes a marking of linear traces, which are equidistant from each other. In the second stage, the operator moves the radio wave unit along each of the paths, making radio measurements through equidistant segments. An encoder installed in the GPR to provide the identity of distances between the points of the linear traces. Therefore, the radio wave module synthesizes a virtual aperture in the plane, the accuracy of positioning is determined along one axis by the GPR encoder, and along with the other by marked traces. The method proposed by the authors [6] of the local positioning system makes it possible to refuse the classical positioning scheme and going to an arbitrary trajectory, which simplifies and accelerates the process of ground penetration research. In the measurement automatization widely uses LPS. And it could be built on various physical principles: laser, radio wave or ultrasonic radiation [7, 8]. In early work, we showed the possibility of the cooperative work of a video positioner and an industrial GPR. In this article, we represent the static research of the positioner accuracy in laboratory tests. We understand that the accuracy and the working area of the system depend on the selected cameras, the spatial frequency of the markers, and we do not set a task to cover all possible variations of the LPS. However, the obtained statistical set allows us to make the conclusion about the error distribution and the possibility to use this system with GPR.
2. Video Positioner

The proposed system includes a pair of digital cameras located on the GPR body and notebook for computing. Special tapes has bounded a scanning area, they also work as markers. We orient cameras in such a way that one tape state into the field of view of one camera, i.e. each camera sees "its" tape. The ribbons has a periodic pattern used for recognition into the scene. A laptop is used for receives and processes video streams, radio wave data and recovers radio images.

The procedure of measurement the position of a GPR inside a bounded plane consists of several stages. First, you have to recognize the tape in the scene, it has special periodic pattern. The criterion for recognition is the spatial periodicity of the pattern. Let’s define a frame of a video sequence as a two-dimensional discrete function of a light intensity of light. $f(\xi, \eta)$, where $\xi$ is number of row and $\eta$ - column number. The first step in the tape recognition process will be a one-dimensional FFT in the $\xi$ variable. The transformation result will be defined as $F(\alpha, \eta)$. The periodic nature of the pattern will create a maximum of the spatial spectrum $F(\alpha, \eta)$ in those lines where the marker is locate, and the position $\alpha_{max}(\eta)$ of the frequency maximum corresponds to the period of the marker pattern. This maximum is located in the interval between $\eta \in [\eta_1, \eta_2]$, where $\eta_1, \eta_2$ is the first and last line of the image containing the marker tape. They determine the position of the tape in the scene. We will define $\gamma$ as the most likely value $\alpha_{max}(\eta)$. At the last step of the marker recognition algorithm we define the area of the image as including marker, if it’s satisfy the condition: $\gamma - \Delta < \alpha_{max}(\eta) < \gamma + \Delta$, where $\Delta$ is an empirical value and in our case it is 2.5. Further, we have to determine the distance to it based on the spatial spectrum of the tape. The distance between the marker tape and the camera lens is strictly dependent from the value $\alpha_0$. And the distance could be calculated as:

$$r = \frac{\alpha_0 T}{2\pi} \tan\left(\frac{\theta}{2}\right),$$

where $T$ - the spatial period of marker tape drawing, $\theta$ - the horizontal angle of view of the camera. Value of $\alpha_0$ could be compute as maximum of the sum of spectrum, which was recognized as including marker. This allows you to increase the selective characteristics and cut off random maxima in the spectrum:

$$\alpha_0 = \max \left| \sum_{\eta = \eta_1}^{\eta_2} F_{1,2}(\alpha, \eta) \right|.$$  

3. Experiments

As a measure of the accuracy of the proposed method, we decided to use the “standard deviation” from a more accuracy positioning system. Also, it is necessary to construct the distribution of the measurement error for illustration situation with the measurement error. It get the accurate statistical picture of accuracy. With this approach, it demand to make a lot of controlled experiments to generate a statistically satisfactory set of the measurement.

Figure 1 shows the scheme of our experiment. The digital webcam was located on the mechanical linear scanner, which one away from the marker tape at a distance $d$. Into a work area, the scanner moves in 1 cm increments. During moving process the scanner through equal intervals capture photographic image of scene with tapes. Captured image transferred to the computer through USB-cable. The computer calculate the distance to the tape $v_{pos}$. At the moment of capturing a photographic picture, the computer demands a position from mechanical scanner, define it as the scanner $m_{pos}$, and sum it with distance $d$. 

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The standard deviation is the square root of the variance. For a limited set of measurement, we can calculate the sample variance and the sample standard deviation by using the following formula:

$$S = \sqrt{S^2} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X})^2},$$

where $S$ – standard deviation, $N$ – number of measurement in a set, $X_i$ – $i$-th measurement, $\bar{X}$ – an average of set. Since the accuracy of a mechanical scanner is a fraction of a millimeter and a lot lesser than a discrete on a videopositioner measure scale, then we take the mechanical scanner measurements as absolutely accurate. Taking the scanner readings as absolutely accurate, let us replace the average with the scanner position. We rewrite the sample standard deviation to classical the standard deviation, which will be written as follows:

$$S = \sqrt{S^2} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - X_{\text{absolute}} i)^2},$$

and after apply replacement we will get the formula:

$$S_{\text{exp}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (v_{\text{pos}} - (m_{\text{pos}} + d))^2}.$$

We use this formula to calculate the positioner accuracy.

4. Results
The experiment was repeated several times. Each of experiments gives approximately one thousand measurements from both, video positioner and mechanical scanner. The distance was a unique for each of the experiments, and this approach eliminates possibility of the "highly sensitive" zones of the investigated positioner. The final the statistical set consisted of near to 6000 measurements. Figure 2 shows distribution of the error.
In the shown distribution, we have to paying attention to the discreteness of the resulting distribution. This effect is a consequence of the discreteness of positioning, as mentioned above, of the used system ~ 0.5 cm. After computing we got $S^2 = 0.28$ and standart deviation $S = 0.53$.

5. Conclusion
The proposed LPS was created for working with GPR. GPR systems use a frequency band up to 1 GHz and therefore the wavelengths used are longer than 30 cm. The required accuracy of approximately is 1/8 wavelength, other words the required accuracy should be 4cm. The LPS has been designed to achieve 1cm But we show that the proposed method is more accurate than we proposed. The Statistical research shows that the standard deviation is about 0.5cm. This research of accuracy cannot be called "Final", because all measurements provided in laboratory conditions. The research should also be provided in natural light. The authors plan to provide a similar statistical experiment in the open air.

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