IMPROVING THE METROLOGICAL PERFORMANCE OF OPTICAL CRACK SIZE MEASUREMENTS IN HIGH-RISE CONCRETE BUILDINGS USING DRONES

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Abstract. This report develops non-contact optical methods for measuring concrete small-sized cracks (less than 3 mm) for remote diagnostics of hard-to-reach building surfaces using unmanned aerial vehicles. The drone's high-resolution digital camera captures remote close-up photography of the concrete surface under high light intensity levels. A special contact landing module made it possible to record the distance between the camera and the concrete surface being photographed. This made it possible to achieve laboratory shooting conditions and increased the accuracy of measurements. The digital image of the crack converted in a data matrix, each element of which contains information about the level of reflected light from the concrete surface and the crack. Using the formulas obtained by us earlier, with the help of computer processing of the image, the morphology of the crack in real geometrical dimensions can be calculated. Using special tools computer programs, the crack's geometrical parameters can be measured maximal accurately as possible. The measurement error of length and width is 0.026 mm. The proposed remote optical method for non-contact detection of cracks in concrete when photographing with a drone from a close distance allows achieving the standard measurement error of depth around 1.52 mm. This optical method can be useful for diagnosing the state of the initial stages of destruction of high-rise concrete buildings, huge dams and bridges under normal weather conditions.

Keywords: Optical measurements, Crack size in concrete, Laboratory Comparisons, Quality Control, and Metrological Support

1. Introduction

Currently, optical measurement methods make it possible to study the geometric characteristics and surface quality of parts, creating three-dimensional (3D) topographies and are extremely effective and important for practical use [1]. Optical measurements are of paramount importance in diferent smart manufacturing [2]. In civil engineering Cracks in concrete can lead to accidents in building structures [3,4], therefore require constant monitoring to ensure public safety. The use of standard contact methods for diagnosing concrete structures requires installing equipment on their surface, which is labor-intensive and expensive [5]. Optical methods for detecting cracks in concrete structures are the most accessible and studied currently (see, for example, [6,7]). Inspection of the surface of buildings using drone (an unmanned aerial vehicle- UAV) is a current area of engineering in connection with the development of UAV technology [8-12]. This inspection is especially invaluable for diagnosing hard-to-reach areas of concrete structures, for example, for high-rise concrete buildings.

Previously, we proposed a method for determining the depth of a crack by processing images obtained at close range and at high light intensity, by mathematical processing of the intensity of image pixels [13]. The method is suitable for precise determination of geometric dimensions for highly scattering surfaces with uniform optical properties. The concrete surface has these properties. The concrete surface reflects light diffusely [14] and has a reflection coefficient (albedo) of the order of 36-69% [15]. This method allows, in the presence of a high light intensity and a close distance to the object of study, to obtain sufficiently accurate results of measuring the geometric dimensions (length, width and depth) of cracks in concrete. However, the application of this method at a considerable distance from the camera to the object of study is limited.

A feature of the photographic image of the concrete surface is that the reflected light rays from the surface elements are collected by the lens into images. When using digital cameras, a matrix of photodetectors that form image pixels. The light intensity registered by each pixel of the image corresponds to the intensity of the reflected radiation of certain areas of the real surface. In the presence of a crack in concrete, a sharp contrast of reflected light appears. Therefore, it is possible to describe the real surface of the material from their images.

In [13], laboratory studies of concrete crack parameters were conducted using a non-contact optical measurement method under conditions of close camera-to-concrete distances and high surface illumination. All photographic parameters were monitored with the highest possible accuracy using precision laboratory equipment. The main difficulty with this method is precisely controlling the distance between the camera and the concrete surface when positioning the drone near the building surface. This also leads to different levels of illumination of the concrete surface when changing the distance between the surface and the light sources, as well as the angle between the camera's optical axis and the perpendicular to the concrete surface. This paper proposes using this method for diagnosing concrete surfaces using a drone docking device that maintains a specified distance between the camera and the surface (corresponding to laboratory conditions).

2. Drawbacks

A method of using drones to detect concrete in large buildings and structures has been proposed previously by us in [16]. A high-resolution digital camera on a drone takes close-up, remote photographs of the concrete surface under high light intensity. Using special computer programs, the geometric parameters of the crack can be measured with maximum accuracy. However, the method requires precise positioning of the drone near the concrete surface, which is difficult to achieve in windy conditions. Accurate measurement of the distance between the camera lens and the surface is critical for maximum measurement accuracy.

3. Goal

The aim of this study is to improve the metrological performance of optical crack size measurements in concrete buildings using unmanned aerial vehicles. In this paper, we propose to use this method [13] for diagnosing concrete surfaces by drone using docking units (landing gear) with a predetermined distance between the camera and the surface.

4. Experimental setup for imaging cracks on concrete surfaces using drones

We used well-developed machine vision technologies from USA National Instrument ((NI), which have specific tools and equipment for computer image processing [17]. The drone [18] can store high-resolution images in its memory. Mathematical processing of the data requires a powerful processor and time and is possible upon return of the drone. The drone's operation and optical measurement technology are described in more detail in [16].

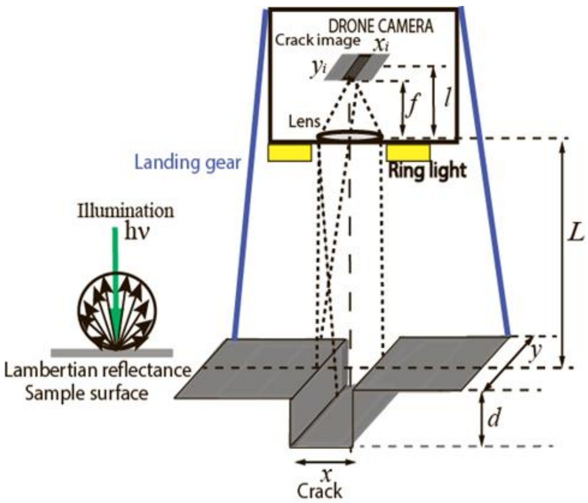

Fig. 1. Optical scheme for obtaining an image of a crack in concrete using a mechanism for docking (landing gear) a drone to a surface.

Figure 1 shows an optical scheme for obtaining an image of small-sized cracks in concrete for maximum close range at high light intensity using a tripod-mechanism for docking (landing gear) a drone to a wall surface. The docking device has an equal-arm tripod, which ensures correct positioning of the camera only on the flat surface of the concrete wall of buildings. High-rise concrete buildings have just such a surface. In this case, the position of the camera on the drone will be strictly perpendicular to the concrete surface. The camera is equipped with a high-intensity (illumination 25 kLux at a fixed distance L) ring LED light source. The illuminance of the concrete surface from a LED ring light lamps is measured with a T10 illuminance meter from Konica Minolta Sensing Inc. It is important to carry out measurements in conditions of significantly lower sunlight illumination. The illumination parameters of the concrete surface also correspond to laboratory values. Therefore, the distance between the camera and the surface will be equal to the specified value L, and the results of optical measurements are close to the laboratory settings of photography parameters and can be as accurate as possible. A typical 16-bit image of a concrete surface with a crack using camera with the resolution of 3280×2464 pixels with a pixel size of 1.12 μm×1.12 μm shows in Figure 2. The focal length of the camera was 3.6 mm.

Typical image of a concrete surface with a crack using camera has the resolution of 3280×2464 pixels with a pixel size of 1.12 μm×1.12 μm is shown Figure 2.

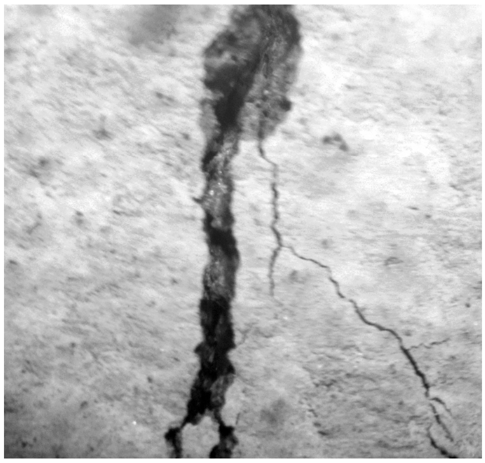

Fig. 2. Typical image of a concrete surface with a crack using camera has the resolution of 3280×2464 pixels with a pixel size of 1.12 μm×1.12 μm

5. Imaging processing for crack's width, length and depth

The digital images of the cracks were converted into a dataset, each element of which contains information about the level of reflected light from the concrete surface and cracks. In Ref. [13] is obtained formulas for width, length and depth of crack: $x = x_i \dfrac{L-f}{f}$; $y = y_i \dfrac{L-f}{f}$; $d \cong L(\dfrac{1}{\sqrt[4]{\xi}} - 1)$, where $\zeta = L/f$, L the distance between the objective of camera and the concrete surface, f is camera focal length. These formulas have to convert to discrete form. The pixel data of the digital image was converted into real geometric parameters (width and length) by the formulas: $x_i = n_i\delta(\zeta - 1)$, $y_j = n_j\delta(\zeta - 1)$, where δ is camera pixel size, i and j are the number of pixels in the width and length of the image captured by the camera (Fig. 2). To obtain crack depth data, the data matrix was recalculated according to the formula: $d_{i,j} \cong L(1/\sqrt[4]{\xi_{i,j}} - 1)$, where $\xi_{i,j} = I_d^{i,j} / I_s$, I_s and $I_d^{i,j}$ are experimental values of luminous intensity from undamaged concrete surface and from different depths of the crack.

The real x, y coordinates and the crack's depth value d from the image data are calculated according to formulas (1) and (2). Algorithm for converting a 16-bit image matrix (a) into a data table (b) with subsequent calculation of the actual geometric dimensions of the crack in the OriginLab program shows in Figure 3. Thus, optical measurements of the geometric dimensions of cracks in concrete can be realized. The measurement error of length and width is 0.026 mm. The accuracy of crack's width and length measurements has to depend on the resolution of the camera. More accurate results can be obtained by decreasing pixel sizes and increasing their number. In our case the standard measurement error of depth is around 1.52 mm. The accuracy of depth measurement depends on the dynamic range of the camera. It is advisable to use HDR (High Dynamic Range) technology as well. The rapid development of nanotechnology will significantly increase the resolution of cameras, which will allow more accurate measurements of crack parameters in concrete in the future.

Figure 4 shows the typical crack 3D graph in concrete with recalculated data for real geometric parameter in OriginLab program. Visualization of a crack in real geometric dimensions is important for analyzing the formation and growth of a crack over time. Multiple drone photographs of cracks at different points in time allow for monitoring the progress of degradation in hard-to-reach areas of concrete structures (especially in high-rise buildings). This is particularly relevant for safety applications in civil engineering.

OriginLab software produces an inverted 3D crack graph. For the first time, crack bottom visualization is available! Figure 5 shows an inverted 3D crack graph in concrete generated by OriginLab, with data converted to real geometric parameters. Using the data in Figure 5, it's easy to determine the depth of the deepest cracks, speeding up the analysis of crack formation mechanisms in concrete. Such data are particularly valuable for research into the destruction processes of concrete structures [19-22].

OriginLab software allows for precise analysis of crack depth distribution profiles across a material's surface. Figure 6 shows an image profile with data recalculated for the actual geometric parameters of a concrete crack using OriginLab software. Computer-aided design allows for obtaining statistical information on the nature of concrete damage in any cross-section. Image data profiles (Figure 6) allow for determining the geometric dimensions of the crack in the *xy* plane, i.e., the actual visible dimensions of the crack on the surface of the concrete structure. Profiles can be obtained for both the vertical and horizontal axes, as well as the inclined (top right).

	729	730	731	732	733
71	47005	46177	46453	47005	47283
72	47283	47283	47283	47283	47283
73	47727	48281	48003	46895	46895
74	48559	49115	48559	47449	47173
75	49395	49115	48837	48559	48559
76	49395	48559	48281	49115	49395
77	49041	48763	49041	49319	49319
78	49319	49319	49319	49599	49599
79	49599	49599	49599	49599	49599
80	49041	49041	49319	49599	49599
81	49041	49041	49041	49599	50157
82	49319	49319	49319	49599	50157
83	49319	49599	49599	49599	49599
84	49319	49877	49877	49041	48763
85	49599	49599	49599	48763	48207
86	48763	49041	49599	49599	49319
87	49041	48763	48763	48763	49041
88	49041	48485	48207	47929	47929
89	48207	47929	48207	48485	48485
90	48207	47929	48207	48485	48763
91	48763	47929	47651	48207	48763
92	47929	47375	47651	49041	49599
93	47375	47375	47929	48763	48763
94	48207	47651	47929	48485	47929
95	48485	47651	47651	47929	47097
96	47651	46821	47097	47375	46821
97	47375	46545	46545	47097	46545
98	47375	46821	46545	46545	45993
99	47375	47097	46821	46545	45993
100	47097	47097	47097	46269	45993
101	47619	46789	46513	46513	46789
102	47619	47065	46789	46513	46513
103	47619	47619	47343	47343	46789
104	46789	47343	47897	48175	47343
105	45687	46513	47897	48453	47897
106	46513	47065	47897	48175	47619

a

	A(X1)	B(Y1)	C(Z1)	D(X2)	E(Y2)	F(Z2)
Long Name				x	y	d
Units				mm	mm	mm
Comments						
F(x)=				A*0,026	B*0,026	(52685/C)^0
473473	293	1156	41023	7,618	30,056	8,39113
473474	293	1157	41023	7,618	30,082	8,39113
473475	293	1158	40215	7,618	30,108	9,08109
473476	293	1159	39139	7,618	30,134	10,02728
473477	293	1160	38335	7,618	30,16	10,75578
473478	293	1161	38069	7,618	30,186	11,00101
473479	293	1162	38719	7,618	30,212	10,40548
473480	293	1163	39523	7,618	30,238	9,68592
473481	293	1164	38855	7,618	30,264	10,28246
473482	293	1165	39123	7,618	30,29	10,0416
473483	293	1166	39123	7,618	30,316	10,0416
473484	293	1167	38855	7,618	30,342	10,28246
473485	293	1168	38451	7,618	30,368	10,6495
473486	293	1169	38451	7,618	30,394	10,6495
473487	293	1170	38881	7,618	30,42	10,259
473488	293	1171	39151	7,618	30,446	10,01655
473489	293	1172	38269	7,618	30,472	10,81643
473490	293	1173	38803	7,618	30,498	10,32943
473491	293	1174	39121	7,618	30,524	10,04339
473492	293	1175	39387	7,618	30,55	9,80634
473493	293	1176	39657	7,618	30,576	9,56777
473494	293	1177	40195	7,618	30,602	9,09839
473495	293	1178	39925	7,618	30,628	9,33296
473496	293	1179	39121	7,618	30,654	10,04339
473497	293	1180	38851	7,618	30,68	10,28607
473498	293	1181	39657	7,618	30,706	9,56777
473499	293	1182	39955	7,618	30,732	9,3068
473500	293	1183	39955	7,618	30,758	9,3068
473501	293	1184	39687	7,618	30,784	9,54139
473502	293	1185	39687	7,618	30,81	9,54139
473503	293	1186	39417	7,618	30,836	9,77973

b

Fig. 3. Algorithm for converting a 16-bit image matrix (a) into a data table (b) with subsequent calculation of the actual geometric dimensions of the crack in the OriginLab program

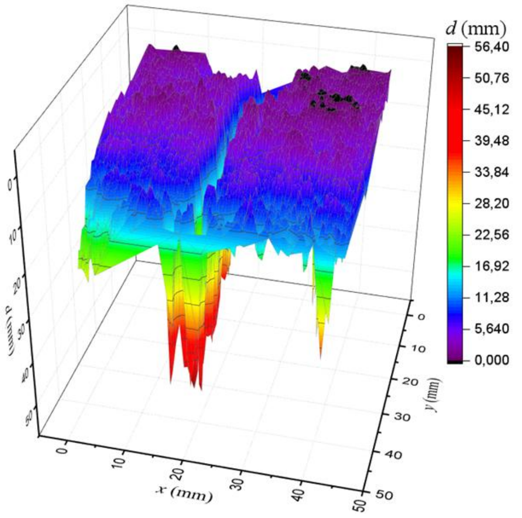

Fig. 4. The typical crack 3D morphology in concrete with recalculated data for real geometric parameter in OriginLab program

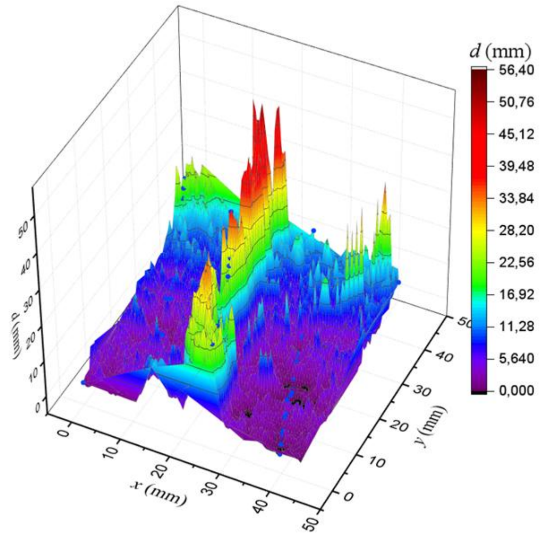

Fig. 5. The inverted crack 3D graph in concrete with recalculated data for real geometric parameter in OriginLab program

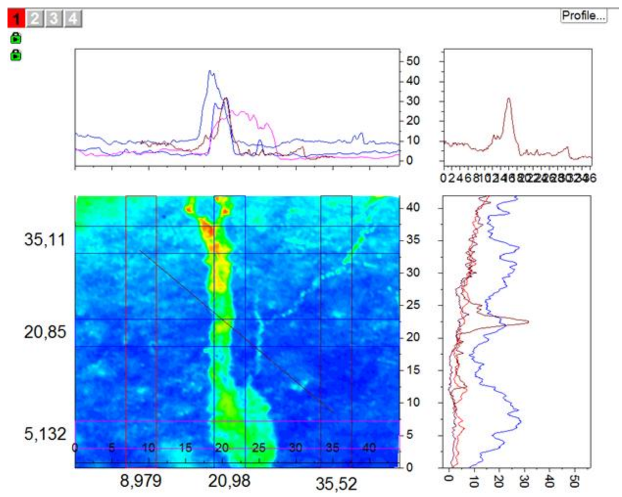

Fig. 6. Precise analysis of crack depth distribution profiles across a material's surface using OriginLab software

In practice, it would be important to obtain the actual geometric dimensions of concrete cracks in real-time measurements. Transferring large-volume image data to a laboratory computer for calculating the geometric dimensions of concrete cracks using our method is possible with the development of 6G wireless communication technology. Such studies could be the subject of future research.

5. Conclusions

Remote optic measurements using UAV with an installed high-resolution camera can be effectively used for monitoring the condition of concrete structures in hard-to-reach places and allows you to get high-quality images of the damaged concrete surface at close range. In this case, the use of computer image processing using the method proposed in [15] makes it possible to calculate the geometric dimensions of cracks in concrete to assess the critical state of the structure. Using the latest, higher resolution megapixel cameras with advanced optics can improve measurement accuracy. However, increasing the size of the image leads to problems with computer processing of big data. Further development of this optical method will be associated with the development of new software and hardware. National Instrument hardware and Origen Lab software modules have also been developed for the geometrical method determination of cracks in building structures and for drone control and communication. Use of the newest optical matrices with high resolution and special lenses allows increasing metrological accuracy of measurements of geometrical parameters of cracks in concrete. It is also important to note the possibility of obtaining an inverted image of the crack cavity, which allows one to study its morphology in more detail.

The proposed optical method is designed for the most accurate measurement of small-sized cracks in concrete (initial stages of concrete destruction), the monitoring of which is important for public safety tasks. However, the method is not applicable in conditions of heavy fog, pouring rain, storm wind, snow sticking to the concrete surface, extreme high temperatures (building fire), etc. The destruction of a concrete structure due to the formation and growth of cracks is a fairly long process. For continuous monitoring of the condition of a high-rise building using this optical method, comfortable identical environmental conditions are suitable.

Conflict of Interest

The authors state that there are no financial or other potential conflicts regarding this work.

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