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## A high-accuracy image-based crack displacement sensor

### Xinxing Chen<sup>1, \*</sup>, Jiannan Xiang<sup>2</sup>, Chaobo Zhang<sup>1</sup>, Chih-Chen Chang<sup>1</sup>, Ming Lin<sup>2</sup>

<sup>1</sup>Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong <sup>2</sup>Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

Corresponding author: xchenak@connect.ust.hk

Abstract. In this study, a new image-based sensor with high accuracy was developed. This wireless sensor is composed by optical sensor, micro-processor, wireless modules and rechargeable battery. Highly sensitive digital sampling moiré (DSM) method is used to calculate displacements. Its high accuracy was demonstrated by a numerical simulation, and a laboratory test was conducted to verify its applicability in crack monitoring.

#### 1. Introduction

Cracks are commonly observed on concrete structures and the measurement of crack propagation is crucial for the health monitoring of structures [1]. A variety of sensors have been developed to monitor the propagations of cracks, such as the crack-meter, linear variable differential transformer (LVDT) and optical fiber [2, 3]. Crack-meters with resolution of 10 µm were installed on the oval drum-dome system for the crack monitoring for 10 years [2]. LVDTs and optical fibers were used to monitor the crack's propagation on a masonry walls during the settlement [3]. However, these sensors can only measure one-dimensional displacement, while the cracks may propagate in multiple directions [4]. To achieve multi-dimensional monitoring of cracks, an image-based crack propagation sensor was developed by Man and Chang in 2016 [5]. This sensor was installed across the crack and captured images of the pattern attached on the other side of crack. Based on the images of the pattern captured between motion, this sensor can calculate the 2D displacement of cracks. The algorithm adopted by the sensor for the displacement calculation is the normalized cross correlation (NCC) method, which can achieve the accuracy of 13.2 µm in the laboratory test [5].

Moiré method is widely used for rotational and translational displacement measurement [6]. The traditional moiré technique requires the overlapping of two gratings to generate the moiré pattern for motion amplification. In 2010, Ri. et al developed the digital sampling moiré (DSM) method [7], which can generate moiré patterns from the images of single grating. It can achieve the accuracy of 1/500 of grating pitch length in the bending test. In this study, a new crack propagation sensor is proposed to use the DSM method to achieve high-accuracy 2D displacement measurement. Specifically, the DSM method is compared with the NCC method at similar computational cost via the numerical simulation. The result shows that the DSM method can achieve higher accuracy than the NCC method. Moreover, the proposed DSM-based sensor is applied for crack monitoring in a corrosion test to verify its applicability for real crack measurement.

#### 2. The proposed sensor



Fig. 1(a) shows the schematics of the proposed sensor. As can be seen, the sensor is fixed at one side of the crack and taking images of the pattern attached on the other side. In this way, the motion of the crack is identical with the relative motion between the fixed support of the sensor and the pattern. Therefore, the crack's motion can be calculated from the captured image of the pattern. Fig. 1(b) illustrates the functionality of four principal components inside the sensor. The optical sensor (ADNS 3080) captures the raw images and sends them to the processor (Arduino UNO) for displacement calculation. The algorithm built inside the processor calculates the translations along *X*- and *Y*-directions, which are presented as  $T_X$  and  $T_Y$ , respectively. Then, the obtained  $T_X$  and  $T_Y$  are sent to XBee for wireless transmission. All these components are powered by a battery connected to Arduino UNO.



Fig. 1 (a) The alignment of the sensor; (b) the functions of principal components

The proposed sensor adopts the DSM method [7] as the algorithm for displacement measurement. Fig. 2 shows the enlarged image of the 2D grating pattern used for the DSM method. The sampling pitch is the integer value of pitch length on the image plane. The sampling pitch of the *X*- and *Y*-directional gratings are  $s_x$  and  $s_y$ , respectively.



Fig. 2 The projection of 2D grating pattern on the image sensor

After the recording of 2D grating pattern, the grating image should be separated into individual dimensions for further processing with the DSM method. As shown in Fig. 3, the 2D grating pattern is decomposed into *X*- and *Y*-directional gratings using image averaging filters. The filtered *X*- and *Y*-directional gratings were shown in Fig. 3(b) and (c), respectively. To demonstrate the procedures of the DSM method, one line of the filtered *X*-directional grating was extracted and processed by the DSM method to calculate its moiré fringes and phase distribution.



Fig. 3 Separation of 2D grating and the calculation processes of the DSM method

Fig. 3(d) shows a line of filtered grating in physical domain and its intensity distribution in image domain is shown in Fig. 3(e). Totally  $s_x$  moiré patterns are generated through down-sampling and up-sampling ( $s_x = 3$ ). Firstly, down-sampling was performed by picking up one pixel in every  $s_x$  pixels. As shown in Fig. 3(f), the 1<sup>st</sup> down-sampled frame pick the 1<sup>st</sup> point from the *x*-directional grating, and then it picks one pixel in every  $s_x$  pixels. Similarly, the 2<sup>nd</sup> and 3<sup>rd</sup> down-sampled frames pick the 2<sup>nd</sup> and 3<sup>rd</sup> points and generate corresponding down-sampled grating lines. Interpolation was then performed to calculate the light intensity of pixels between the down-sampled points. After interpolation, three phase shifted moiré fringes are shown in Fig. 3(g). Finally, the phase distribution of the moiré fringe can be obtained, as shown in Fig. 3(h). Eq. (1) and (2) are the light intensity distributions of the *x*-directional grating and the *k*th moiré fringes, respectively.

$$I_{x}(u,v) = L_{a}(u,v)\cos[\varphi_{x}(u,v)] + L_{b}(u,v)$$
(1)

$$I_m(u,v;k) = L_a(u,v)\cos\left[\theta_x(u,v) + \frac{2\pi(k-1)}{s_x}\right] + L_b(u,v) \quad (k=1,\cdots,s_x)$$
(2)

where  $L_a(u, v)$  is the amplitude of light intensity of the grating;  $L_b(u, v)$  is the light intensity of the background;  $\varphi_x(u, v)$  is the phase distribution of the x-directional grating;  $\theta_x(u, v)$  is the phase distribution of the moiré fringe, and its wrapped value can be obtained with Eq. (3):

$$\theta_{\chi_w}(u,v) = -atan \frac{\sum_{k=1}^{s_x} l_m(u,v;k) \times \sin\left(\frac{2\pi k}{s_x}\right)}{\sum_{k=1}^{s_x} l_m(u,v;k) \times \cos\left(\frac{2\pi k}{s_x}\right)}$$
(3)

The wrapped phase value  $\theta_{x_w}$  is discontinuous and it ranges between  $-\pi$  and  $\pi$ . Unwrapping should be performed to get  $\theta_x$ .

The DSM method calculates the translation based on the phase difference.  $\theta_x(u, v)$  and  $\theta'_x(u, v)$  are the phase distributions of the moiré fringes before and after motion. Translation along X-direction  $T_X$  can be obtained from Eq. (4):

$$T_X(u,v) = \left[\theta_x(u,v) - \theta'_x(u,v)\right] \times \frac{P_X}{2\pi}$$
(4)

 $T_Y$  can be calculated following the similar procedures.

#### 3. Simulation

In this section, the DSM method is compared with the NCC method at similar computational cost via numerical simulation. As an image-based displacement measurement algorithm, the NCC method has been used in a crack propagation sensor with an accuracy of 13.2  $\mu$ m [5]. Fig. 4 shows the computational cost of the DSM and NCC methods as the function of searching step. As can be seen, the computational cost of the NCC method decreased with the increase of searching step, while the computational cost of the DSM method remains stable and is slightly larger than that of the NCC method with searching step equal to 0.2 pixel. It should be noticed that the NCC method in a critical way, the searching step of the NCC method is set as 0.1 pixel in the simulation.



Fig. 4 Computational cost of the NCC and DSM methods

The NCC method was firstly calibrated to obtain the scaling factor using the method stated by Man and Chang (2016). As shown in Fig. 5, the pattern was simulated to do step motion and its displacements were calculated by the NCC method. A line was used to fit the step motion results, and the obtained scale factor is 16.5 pixel/mm when  $P_X$  equal to 0.24mm. Then, the pattern was simulated to do harmonic motion, and the displacements measured by the NCC and DSM methods are shown in

Fig. 6. It demonstrates that both two methods track 2D motion successfully. Fig. 7 shows the corresponding errors of two methods in the harmonic motion detection. As can be seen, the errors of the NCC method are significantly larger than those of the DSM method. Therefore, it can be concluded that the DSM method is of higher accuracy comparing with the NCC method.



Fig. 5 Calibration for the NCC method



Fig. 6 Displacement results of the DSM and the NCC methods



Fig. 7 Displacement errors of the DSM and the NCC methods

#### 4. Laboratory experiment

Corrosion of steel bars is the major cause of concrete structures' failure. After the initiation of corrosion in steel, products of corrosion expand usually result in the formation of crack on the concrete [8].

As shown in Fig. 8, an accelerated corrosion test was carried out on a rectangular concreter sample with an embedded steel bar. To accelerate corrosion, specimens were partially immersed in sodium-chloride solution in tanks. Meanwhile, direct electric current was impressed on the steel bar with controlled current intensity.



Fig. 8 The proposed sensor on the concrete cubic

The test was performed for 14 days. With the expanded corrosion of the embedded bar, crack was observed on the concrete specimen. The proposed sensor was installed across the crack to monitor its displacement. A LVDT with a resolution of 5  $\mu$ m was installed under the proposed sensor to provide ground truth.

The measured displacements of the crack were shown in Fig. 9. The proposed sensor can track 2D displacements of the crack simultaneously, while the LVDT provided the single dimensional measurement along Y direction. The results show that the Y-directional displacement measured by the LVDT matches well with that measured by the proposed sensor. This test demonstrates the applicability of the proposed sensor in the long-term monitoring of the 2D propagation of cracks.



Fig. 9 Crack displacement monitoring result

#### 5. Conclusion

In this study, a new wireless sensor has been proposed for 2D displacement monitoring of cracks. Comparing with the previous sensor using the NCC method, this proposed sensor adopts the DSM method as algorithm and can achieve higher accuracy. Numerical simulation and laboratory test have been performed to show its accuracy and applicability. The results demonstrate that this sensor can be used as a powerful tool for long-term monitoring of crack propagations.

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