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Detecting Type and Size of Road Crack with the Smartphone

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***Abstract*—Detecting crack type and crack size is crucial for road maintenance and management. Mobile crowd sensing is a new way to collect the information of cracks on roads. We propose a system named CrackDetector to detect cracks and estimate their types and size with smart phone in this paper. The type of a crack (i.e., horizontal crack, vertical crack, net crack) is determined by a coordinate transmission method based on three directions, including the direction of the crack in the photo (estimated through an image processing method), the 3D shooting direction (i.e., the rotation of the smartphone while photographing) and the direction of the road (obtained from the OpenStreetMap road network). In order to estimate the size of a crack (i.e., the width and the length of the crack), we use the camera's convex lens imaging theory and readings of the accelerometer and the magnetometer sensor. We collected pictures of 152 cracks with a specifically-developed android application by 8 volunteers. Experimental results show that our approach achieves an accuracy of 90.1% in crack type detection. Meanwhile, we get a 3.2cm RMSE error when estimating the crack width and a 13.2cm RMSE error when estimating the crack length.**

***Keywords*—Mobile crowd sensing, crack type, crack size, smartphone sensing**

I. Introduction

Cracks are common pavement distress that may potentially threaten the road safety. There are well-known economic and safety reasons through fixing a crack before its deterioration. For example, if a small net crack in the middle of the road is not repaired in time, the slope becomes significantly steeper because water penetration and continued loading, as a consequence, this will greatly shorten the service life of the road. Timely road inspections to acquire accurate and up-to-date information about the road surface condition are the most efficient way to extend the road service life at the lowest cost. The type and size of cracks are used to quantify the road condition and identify the source of deterioration.

There are two main approaches for detecting road damage condition. One is manual road inspection, in which raters go all over the road measuring its distress elements. But these surveys are too time-consuming to allow an extensive assessment. Another is using professional detection devices, such as TxDOT [1]. However, professional devices are expensive and still require many staffs to work with them on roads, at the same time, these devices are bulky and can not be used in ordinary residential roads.

With the recent surge of sensor-rich (e.g., GPS, accelerometer, magnetometer, camera, etc.) mobile phone, mobile crowd sensing (MCS) [2], [3] has become an emerging paradigm for large-scale, real-world sensing and information gathering, and there have been numerous MCS-powered applications, such as environment monitoring [4], [5], traffic planning [6], [7], social context sensing [8], [9], public safety [10], social event replay [11], etc. SeeClickFix[1] is a system that allow people to describe and report the road problem they encountered with text. However, while it can acquire road condition information, text-based description is not straightforward for the participants.

In this paper, we propose CrackDetector, a system that enables people to take pictures of road cracks with smart phone and detects the type and size of the cracks, which is important to quantify the road condition and identify the source of deterioration. To save network traffic and transmission cost, it is desirable to process the sensor readings and crack photos with smart phones and then only upload a small-size description data including the type and size of a crack. There are some challenges of detecting the type and size of road cracks with smartphone. First, because people are not required to take photos from the specific shooting direction or location in our application, the type of crack cannot be directly determined according to the crack's posture on the picture. Second, existing methods can estimate object size by using multiple photos. However, taking multiple photos to the same crack from different angles would increase the workload of the participants. So we use only one picture to estimate the physical size of the crack, which is more challenging.

To tackle the above challenges, we make use of powerful sensing capability of various sensors equipped on smartphones, such as GPS, magnetometer, and accelerometer. We record the sensory data while taking a photo of the road crack,

[1]http://seeclickfix.com/

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and then detect the type and estimate the size of the road crack in the photo with the help of sensor readings.

Our contributions can be summarized as follows.

- We propose a method to determine the type of road cracks. Specifically, the type of the crack (i.e., horizontal crack, vertical crack, net crack) is recognized by a coordination transmission method based on three directions, including the direction of the crack in the photo, the 3D shooting direction and the direction of the road.
- We propose a method to estimate the length and width of the crack. Based on the camera's convex lens imaging theory, the length and width of a road crack is calculated according to the crack's direction in the photo, the pixels covered by the crack and readings of the accelerometer, magnetometer and GPS.
- We recruit 8 volunteers, and they collect a set of 152 crack pictures using the data collection application developed on smartphone. Experimental results show that our approach achieves an accuracy of 90.1% in crack type detection and we get a 3.2cm RMSE error when estimating the crack width and a 13.2cm RMSE error when estimating the crack length.

II. RELATED WORK

Depending on the degree of human intervention required, road crack detection methods can be categorized into purely manual, semi-automated, and automated. Manual surveys have been used for long time and despite the fact that automated methods are becoming more common, they are still the most frequently used method [12]. Human inspections present several problems, including those related to the lack of consistency among operator criteria and consuming a lot of time and manpower. Semi-automatic systems use different techniques to grab road images and postpone the distress identification to an off-line process running in workstations. The identification of various distress types, as well as their severity from images requires observers who have been well trained in both pavement distress evaluation and in the use of the workstations. A complete method to automatically detect and characterize pavement defects is proposed in [13], which uses grayscale images captured by line scan cameras illuminated by lasers during road surveys performed using a high-speed image acquisition system. However, this kind of automatic crack detection system need professional devices that is expensive as well as that there are a huge number of roads in a city, and it will cost road maintenance staffs much time to check them periodically.

To resolve those problems in tranditional systems, the ideas in our proposed CrackDetector are built on three lines of research: mobile crowd sensing, road crack type detection and road crack size estimation. We survey the most relevant work in each line in the following sections.

A. Mobile Crowd Sensing

Mobile crowd sensing is a technique where a large group of individuals having mobile devices capable of sensing and computing (such as smartphones, tablet computers, wearables) collectively share data and extract information to measure, map, analyze, estimate or infer any processes of common interest. In short, this means crowdsourcing of sensor data from mobile devices. Devices equipped with various sensors have become ubiquitous. Most smartphones can sense ambient light, noise (through the microphone), location (through the GPS), movement (through the accelerometer), and more. These sensors can collect vast quantities of data that are useful in a variety of ways. Mobile crowd sensing applications belong to three main types: environmental (such as monitoring pollution [4], [5]), infrastructure (such as traffic planning [6], [7]), and social (such as tracking exercise data within a community [11], [9], [10], [8]). In this paper we focus on a novel application area of MCS, which aims to leverage crowd power to repost and analyze the distributed public road crack information in urban areas.

B. Road Crack Type Detection

Classifying the road crack type is significant to municipal work. Building appropriate road maintenance repair strategies for different types of cracks become a major problem faced by highway maintenance staff. In the traditional approach of detecting the road crack type, in order to judge the road crack types with higher precision, dual phase scanning road crack identification method was proposed based on 3D data scanning technology [14]. Kaseko et al.[15]presented an approach for automating the processing of highway road video images using an integration of artificial neural network models with conventional image-processing techniques. It is able to classify road surface cracking by the type, severity, and extent of cracks detected in video images. However, the traditional crack detection methods that require specialized equipment are generally used in highways and other major roads. Those methods spend a lot of manpower and resources.

C. Road Crack Size Estimation

National road management department provides evaluation criteria for road damage degree classification. It is necessary to estimate the crack size. Sun et al.[16] used various algorithms of image threshold segmentation to perform a pre-segmentation of disease of crack category, and used crack refinement techniques to calculate the area and length of disease accurately. As the crack photo is captured by professional crack inspection device, the shooting angle and height are fixed. When shooting distance and direction is uncertain, camera-based 3D reconstruction of physical objects is one of the most popular computer vision topics in recent years [17].

III. SYSTEM OVERVIEW

As shown in Fig. 1, the CrackDetector system consists of three modules, including the data capture module, the road crack type detection module, and the road crack size estimation module. We introduce functions of these modules as follows.

Data capture: Three types of sensor readings of smartphones are recorded when people take photos of cracks, including 3D accelerometer, 3D magnetometer, and GPS. The height of the photographer is also required as input. These data are used to describe the situation when the photo of crack is taken, including the phones azimuth, inclination angle, rotation angle, and the place of cracks.

Road crack type detection: This module determines the road crack type. We use the sensor information collected from the data capture module to determine whether the crack is a net crack, a horizontal crack or a vertical crack. Firstly, we use the crack's domain of communication to distinguish the net crack from the horizontal crack and vertical crack. Then, we classify the horizontal crack and vertical crack based on the relationship between road direction, shooting direction and crack direction.

Road crack size estimation: This module estimates the crack size. In order to estimate the crack size, including its width and length. Firstly, we calculate the distance between the camera and the crack based on the photographer's height as well as the inclination angle α, rotation angle β of smartphone when taking photos. Then, we estimate the image size using the crack photo. Finally, we use the convex lens imaging theory to calculate the crack's real physical size.

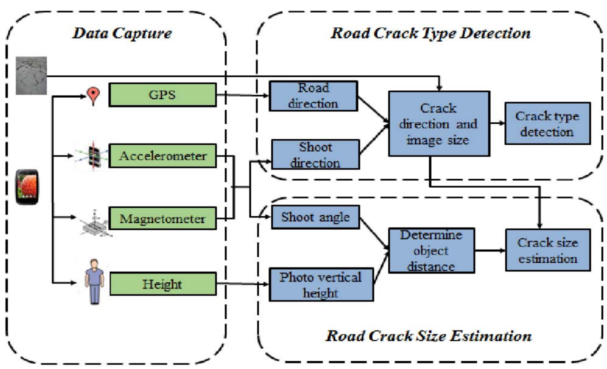


Fig. 1. CrackDetector Overview.

IV. ROAD CRACK TYPE DETECTION

A. Data Model

Readings of smartphone's sensors are saved when people take photos of road cracks using the specially-developed app. The raw data is a 10-tuple denoted by (*img, Ax, Ay, Az, Mx, My, Mz, h, lat, lon*), where *img* denotes the crack photo, (*Ax, Ay, Az*) denotes the 3D accelerometer reading, (*Mx, My, Mz*) denotes the magnetometer reading, *h* denotes the height of the photographer, and *lat* and *lon* denote the latitude and the longitude obtained by the GPS respectively.

B. Road Crack Type Detection

Given a photo of a single road crack, if the relationship between the shooting direction and the road direction is known, then the relationship between the road direction and the crack direction can also be manually observed or computed through the image-analyzing method. In summary, in order to know the type of the road crack, three directions must be known, including the road direction, the shooting direction and the crack direction in the photo. We will introduce our methods to address these problems in the following sections.

1) Distinguishing the Net Road Crack from the Linear Road Crack:
The net cracks have multiple crossed cracks on the road, as shown in Fig. 2, we use the crack's domain of communication to distinguish the net crack from the linear road crack. After the crack image is binarized, the crack part is white area with pixel value 255, the background is black area with pixel value 0. To determine the type of the cracks, our system sets a threshold t (because there are lots of noise in the road cracks, combined with the results of several tests, we chose a threshold value of 10), calculate the connected domain numbers n of the background area which is the region with pixel value 0. If n is larger than t, the crack is a net crack, otherwise, the crack is a linear crack.

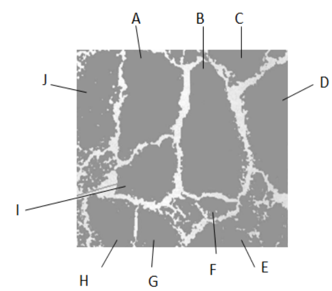


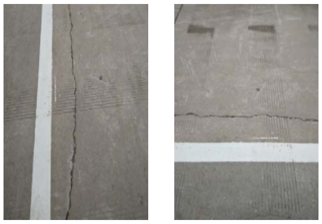
Fig. 2. The connected domain of net crack.

2) Distinguishing the Horizontal Road Crack from the Vertical Road Crack:
To detect the type of a linear crack, as shown in Fig. 3, suppose that we are able to photograph the same crack in different shooting directions, then if the shoot azimuth is parallel to the road direction, the type of crack is a vertical crack in the picture, otherwise, if the shoot azimuth is vertical to the road direction, the type of crack is a horizontal crack in the picture. Therefore, we should determine the relationship between road direction, shooting direction and crack direction. We propose an approach to determine the linear crack type by a coordinate transmission method based on three directions, including the direction of the crack in the photo, the 3D shooting direction and the direction of the road.

1) Sensor-based direction aligning

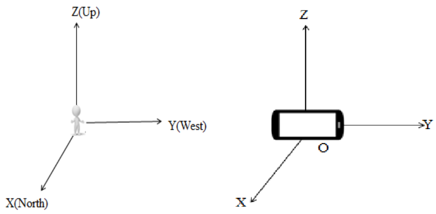
In order to align two directions, i.e., the shooting direction and the road direction, we define two coordinate systems: the human-centric coordinate (HCC) and the phone-centric coordinate (PCC). As shown in Fig. 4, the coordinate (*lon, lat, 0*) is considered as the original point O of HCC, and the center of the phones screen is considered as the original point O of PCC.

Using sensor readings of 3D accelerometer and 3D magnetometer, we can calculate the relationship between HCC and PCC, i.e., rotation angles around each axis. As shown in Fig.



(a) (b)

Fig. 3. Different photos of the same road crack. (a) The shooting direction is nearly parallel to the road direction. (b) The shooting direction is nearly vertical to the road direction.



(a) Human-centric coordinate(HCC) (b) Phone-centric coordinate(PCC)

Fig. 4. The coordinate system transformation.

5, angles α, β and γ denote the rotation angle around X-axis, Y-axis and Z-axis respectively [18]. According to angles α, β and γ, Point P(x, y, z) in HCC can be projected to the point P'(x', y', z') in PCC by using Equation (1).

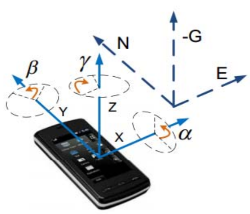


Fig. 5. Different phone orientation angles: pitch(α), roll(β), and yaw(γ). γ is the phone orientation angle relative to North(azimuth angle)

$$(x', y', z', 1) = (x, y, z, 1)R_x(\alpha)R_y(\beta)R_z(\gamma) + \begin{bmatrix} t_x \\ t_y \\ t_z \\ 0 \end{bmatrix} \quad (1)$$

Where (t_x, t_y, t_z) is a translation matrix, because the offset between phone and photographer in the x and y direction is small, we set t_x and t_y equal to zero, t_z approximately equal to the photographer's height. $R_A(b)$ is the rotation matrix representing a rotation with angle b around axis A. In particular:

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(\alpha) & sin(\alpha) & 0 \\ 0 & -sin(\alpha) & cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$R_y(\beta) = \begin{bmatrix} cos(\beta) & 0 & -sin(\beta) & 0 \\ 0 & 1 & 0 & 0 \\ sin(\beta) & 0 & cos(\beta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$R_z(\gamma) = \begin{bmatrix} cos(\gamma) & sin(\gamma) & 0 & 0 \\ -sin(\gamma) & cos(\gamma) & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Suppose points p1(x1 ,y1, 0), p2(x2 ,y2, 0), p3(x3 ,y3, 0) in PCC is projected to the points p1'(x1 ,y1, z1), p2'(x2 , y2, z2), p3'(x3 , y3, z3) in HCC by using Equation (1). The slope of line *p1p2* is *k1*, and slope of line *p2p3* is *k2*, the angle between *p1p2* and *p2p3* is ϵ in PCC. The slope of line *p1'p2'* is *k1'*, and slope of line *p2'p3'* is *k2'*, the angle between *p1'p2'* and *p2'p3'* is ϵ' in PCC. If we know the two lines in HCC, we can calculate the slope and angle between the two lines in HCC by using Equations (6) (7) (8).

$$tan(\epsilon) = \left| \frac{k_1 - k_2}{1 + k_1 k_2} \right| \quad (5)$$

$$k_1' = \left| \frac{sin(\gamma) + \frac{k_1 cos(\alpha)}{cos(\beta)} cos(\gamma)}{cos(\gamma) - \frac{k_1 cos(\alpha)}{cos(\beta)} sin(\gamma)} \right| \quad (6)$$

$$k_2' = \left| \frac{sin(\gamma) + \frac{k_2 cos(\alpha)}{cos(\beta)} cos(\gamma)}{cos(\gamma) - \frac{k_2 cos(\alpha)}{cos(\beta)} sin(\gamma)} \right| \quad (7)$$

$$tan(\epsilon') = \left| \frac{k_1' - k_2'}{1 + k_1' k_2'} \right| \quad (8)$$

2) Road direction determination

Coordinates in HCC of a road segment's two endpoints can be computed, point *S(a, b, 0)* denotes the start point of the road segment, and point *E(c, d, 0)* denotes the end point of the road segment. Assume that two points on a linear road crack are point *M(e, f, 0)* and point *N(g, h, 0)*, we propose a sensor-based direction aligning method to compute the angle between the line *SE* and the line *MN*.

Here coordinates of points *S* and *E* are obtained from OpenStreetMap[2] road network. While taking a crack photo, we collect the GPS of the crack position, locate the GPS information to the road network, and find the road of the crack. The road information is denoted by *r=(ID, Node1, Node2, Width)*, here *ID* is the road number, *Node1, Node2* are the beginning of the road and ending of the road respectively, *Width* is the road width, *Node1, Node2* are denoted as *S(nlat1,nlng1)* and *E(nlat2, nlng2)*. Then we use Equation (1) to project the point *S* and point *E* in HCC to PCC coordinate. Assume the transformation results of points *(S, E)* are *(S', E')*.

We can not directly get the points *M*, *N*, but we can get the crack points *M'* and *N'* in PCC. We utilize image-processing method to estimate the direction of the line *M'N'* in the following.

[2]http://www.openstreetmap.org/

3) Crack line determination

We use image processing methods to determine the crack line *M'N'* in a taken photo. When process the crack picture, because of the complexity of the road conditions, the road distress image is sensitive to the road noise (such as debris, sand, tire marks, traces of oil, etc.). At the same time, the imaging system itself causes, uneven illumination, different target distance and other factors all have impact on the recognition of crack photo. In order to better identify the cracks, the photos have to be pre-processed to eliminate possible noise, including median smoothing [19], sobel operator sharpen [20] and gray scale processing [21].

Image segmentation is the key to road crack detection. In this paper, we use the OTSU algorithm [22] for image segmentation, while successfully split the crack from the background of road surface, and retain the integrity of the crack. To eliminate the isolated points and small voids, we use mathematical morphology to process them. After applying the closed opening operation, basically eliminating isolated points outside the crack area, and filling the empty area of the crack. The processed binary image matrix is stored as *F*. We conduct operation of expansion, corrosion and thinning on the matrix *F*, extract crack skeleton. After the operation, the matrix is denoted as *G*. We then perform linear fit on the matrix *G*, and get cracking approximate straight line, which is the *M'N'* in the picture.

We can calculate the slope of line *M'N'* and *S'E'* and the angle between this two lines in the PCC coordinate, at the same time, we can calculate the angle between this two lines in the HCC coordinate by using Equations (6) (7) (8). The angle between line *SE* and line *MN* can be determined, denoted as ϵ. If ϵ is larger than 45^o, the crack is a horizontal crack, otherwise the crack is a vertical one.

V. ROAD CRACK SIZE ESTIMATION

A. Principle

We adopt the convex lens imaging theory to estimate the road crack size, as shown in Fig. 6, *d* denotes the distance between the object and the camera, *f* denotes the equivalent focal length of the smartphone camera, *i* denotes the image distance. According to the relationship among *f*, *i* and *d* (shown in Equation (9)) and the relationship between the crack's real physical size and image size (shown in Equation (10)), the road crack's real physical size can be estimated by Equation (11).

Since the equivalent focal length denoted by *f* of the smartphone is provided by the manufacturer, in order to calculate the physical size of the crack, the object distance *d* and the image size must be known. Next we will present how to estimate the object distance and calculate the image size, respectively.

$$\frac{1}{d} + \frac{1}{i} = \frac{1}{f} \tag{9}$$

$$\frac{physical\ size}{image\ size} = \frac{f}{i-f} \tag{10}$$

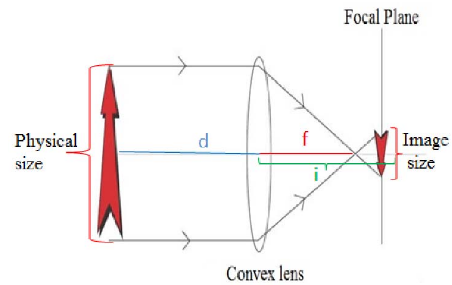


Fig. 6. Convex lens imaging theory.

$$physical\ size = \frac{f(d-f)}{f*d - f(d-f)} * image\ size \tag{11}$$

B. Object Distance Determination

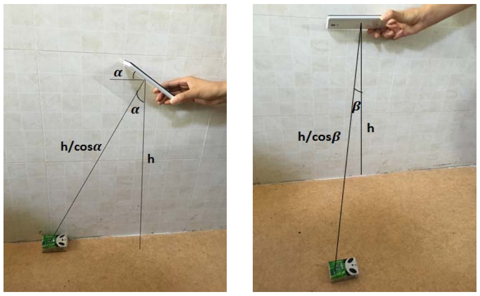
The definition of the object distance refers to the distance between the object and the lens optical center. Because the mobile phone position and height is arbitrary when the general public using a mobile phone to take pictures, the distance from the camera to the crack is unknown. We propose an approach to determine the object distance. While taking a crack picture, photographers are more inclined to keep their most interested object at the approximate center of the phone screen. As shown in Fig. 7, to determine the distance from the crack to the phone camera, we can use the vertical distance *h* from the phone to the ground, the inclination angle α and the rotation angle β of the phone. We can use Equation (12) to calculate the object distance *d*.

$$d = h/(cos|\alpha|cos|\beta|) \tag{12}$$

Where *h* is the vertical distance from the phone to the ground, α is the inclination angle of smartphone, that is starting from standstill, flipping back and forth, when taking the phone horizontally, the inclination angle is 0^o, β is the rotation angle of smartphone, that is starting from standstill, flipping left and right, when taking the phone horizontally, the rotation angle is 0^o. We can calculate α and β through the accelerometer and magnetometer sensor. As shown in Fig. 8, the height of cameras *h* can be approximately estimated by subtracting 0.1m (the common distance between the top of human's head and eyes) from the photographer's height.

C. Image Size Calculation

When quantitatively calculate vertical crack's width, scanning matrix *F's* each row, getting the number of crack pixels in each row stored as *n*, multiplied by each pixel's length *L*, calculate the width of each row. Then sum the width of each row, divided by the number of rows to obtain the average crack width *HW*. The same way, When quantitatively calculate horizontal crack's width, scanning matrix *F's* each column, getting the number of crack pixels in each column stored as *n*, multiplied by each pixel's length *L*, calculate



(a) (b)

Fig. 7. The inclination angle α and rotation angle β of smartphone when taking photos.

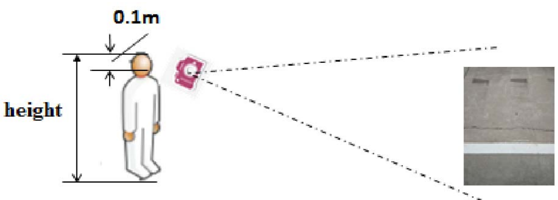


Fig. 8. Illustration of user taking photos.

the width of each column. Then sum the width of each column, divided by the number of column to obtain the average crack width *VW*. When calculate the length of linear crack, scanning the thinning matrix G to obtain the number of crack pixel, multiplied by L, obtained the crack length *CL*. When quantitatively calculate net crack, as shown in Fig. 9, the system firstly scan the matrix *F's* each row, finding the maximum ordinate pixel *y1* and the minimum ordinate pixel *y2* in the pixels value of 255, secondly, the system scan the matrix *F's* each column, finding the maximum abscissa pixel *x1* and the minimum abscissa pixel *x2* in the pixels value of 255. Then, we use Equation (13) compute the area s of the net crack.

$$s = (y_1 - y_2) * (x_1 - x_2) \tag{13}$$

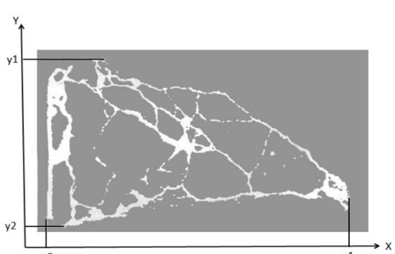


Fig. 9. Net crack area calculation.

VI. EXPERIMENTAL RESULTS

In this section, we first introduce the experimental set up and the data collection. We then present and analyze the evaluation results of road crack type detection as well as the road crack size estimation.

TABLE I
ACCURACY OF CRACK TYPE DETECTION

	Horizontal crack	Vertical crack	Net crack	Sum	Accuracy
Horizontal crack	68	8	1	77	88.31%
Vertical crack	5	50	0	55	90.91%
Net crack	0	1	19	20	95.00%
Sum	73	59	20	152	90.13%

A. Experiment Setup and Data Collection

We developed a data collection application, for crack photo taking based on commodity smartphones running Android. During photo taking, it also records GPS, accelerometer and magnetic sensor data. For performance evaluation, we get a set of 152 crack pictures collected by 8 volunteers in Xi'an with three different smart phones. The volunteers manually tag the cracks including the crack type (e.g. horizontal crack, vertical crack and net crack) and crack size (e.g. crack width and crack length) measured by ruler as the ground truth.

B. Road Crack Type Detection

To evaluate the performance of crack type detection, we compute the accuracy by comparing the detected crack type against the human tagged ground truth crack type. Table 1 is the classification confusion matrix. There are 77 horizontal crack images, 55 vertical crack images and 20 net crack images. The accuracy of detecting the horizontal crack is 83.3%, the vertical crack is 90.9%, and the net crack is 95%. The total accuracy is 90.1%. The accuracy of net crack is the highest, because the identification of the net crack is only related to the connected domain. When classify the linear crack, the type of the horizontal crack and vertical crack is related to the road direction, the crack direction and the azimuth of the smartphone, as a result, the direction error may lead to a classification error.

We take pictures (from the 152 crack pictures) with a same linear crack from four different directions, as shown in Fig. 10. The first shoot direction is approximately parallel with the road direction, the second and the third have an angle with the road direction, the last is perpendicular to the road direction. We calculate the road direction and crack direction in the HCC coordinate, from Table 2, we can conclude that whatever the shoot direction, we can correctly detect the road crack type.

Because the linear crack type is related to the shoot direction, to illustrate the process of detection the linear crack type at great length, Fig. 11 is the linear crack picture randomly selected from the 132 linear crack pictures captured by our volunteers. We calculate the crack direction in PCC coordinates through processing the crack picture, at the same time, we project the road direction in HCC to PCC by using Equation (1), then we use Equation (8) to calculate the angle between the road direction and the crack direction in HCC. If

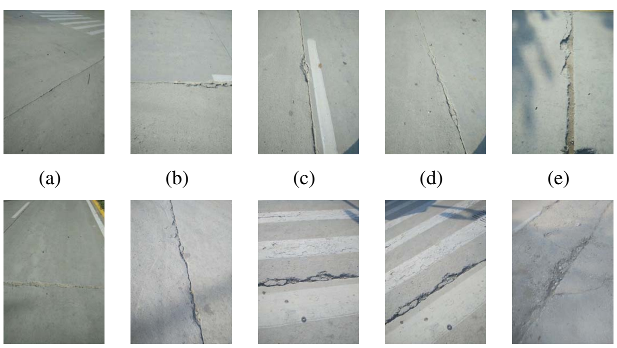
TABLE II
DIFFERENT SHOOT DIRECTION OF THE SAME CRACK

	Road direction	Crack direction	Crack type	Real crack type
11.a	60^o	144^o	Horizontal crack	Horizontal crack
11.b	60^o	139^o	Horizontal crack	Horizontal crack
11.c	60^o	142^o	Horizontal crack	Horizontal crack
11.d	60^o	151^o	Horizontal crack	Horizontal crack

the angle is larger than 45^o, the crack is a horizontal crack, otherwise the crack type is a vertical crack.

(a) (b) (c) (d)

Fig. 10. One same crack taken in different direction.



(a) (b) (c) (d) (e)

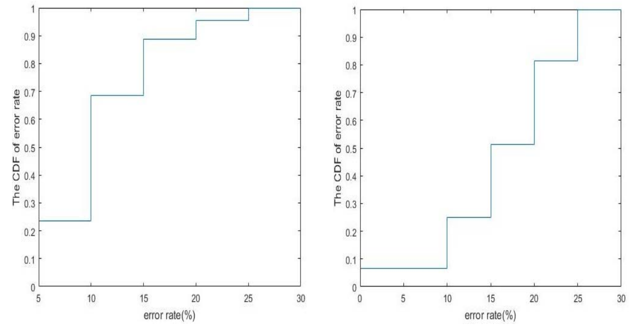
(f) (g) (h) (i) (j)

Fig. 11. 10 linear crack pictures we randomly select to illustrate the process of horizontal crack and vertical crack detemination.

C. Road Crack Size Estimation

To evaluate the crack size estimation, we compute the accuracy by comparing the estimated crack size against the human measured ground-truth crack size. We use the root mean square error (RMSE) between estimated values and real values as the evaluation measure. For crack width, we get a 3.2cm RMSE error. For the length of crack, the RMSE error is 13.2cm. Fig. 12.a shows the results of error rate CDF when calculate the crack length. The probability that the length error rate less than 15% is 0.7 and probability that the length error rate less than 20% is 0.89. Fig. 12.b shows the results of error rate CDF when calculate crack width. The probability that the width error rate less than 20% is 0.54 and probability that the length error less than 25% is 0.83.

Fig. 13 shows 10 pictures randomly selected from the 152 images to illustrate the process of the approach we calculate



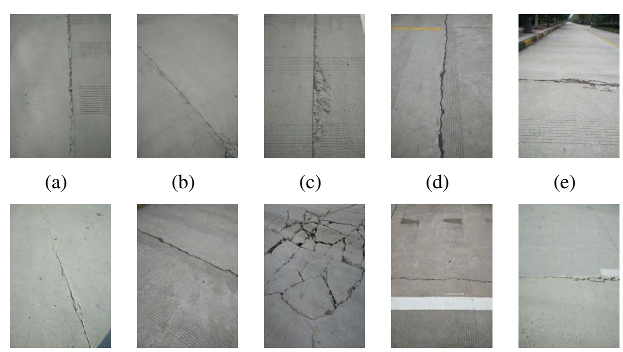
(a) (b)

Fig. 12. The CDF of crack length and width error rate.

TABLE III
ACCURACY OF CRACK SIZE ESTIMATION

	H	IA	RA	IS	PS	RPS	WE	LE
15.a	145	7^o	28^o	0.18*1.83	10*106	14*121	4	15
15.b	153	30^o	2^o	0.31*1.96	19*121	25*140	6	19
15.c	160	5^o	20^o	0.40*1.75	24*105	17*111	3	6
15.d	160	13^o	12^o	0.16*1.91	9*112	15*133	6	21
15.e	170	32^o	1^o	0.25*1.62	17*114	24*134	7	20
15.f	145	8^o	12^o	0.09*1.18	4*62	6*65	4	3
15.g	176	25^o	10^o	0.13*1.64	9*113	15*128	6	15
15.h	155	5^o	2^o	0.32*1.87	17*102	24*130	7	28
15.i	168	6^o	29^o	0.07*1.18	5*80	10*91	5	11
15.j	153	31^o	12^o	0.16*0.86	10*55	15*70	5	15

the crack physical size. Table 3 is the result of those pictures' crack size. *H* denotes the vertical height from photo to ground(cm), *IA* denotes the inclination angle of phone, *RA* denotes the rotate angle of phone, *IS* denotes the image size calculated from the pictures(cm), *PS* denotes the physical size we calculated by our method(cm), *RPS* is the real physical size we manually measured by ruler as the ground-truth(cm), *WE* is the absolute error of crack width(cm) and *LE* is the absolute error of crack length(cm) comparing with ground truth.



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Fig. 13. 10 crack pictures we randomly select to illustrate the process of crack size estimation.

At the same time, we take pictures of a same crack from four different heights and angles, Fig. 14 is the picture captured from different heights and angles, the first and the third is near

TABLE IV
DIFFERENT HEIGHT AND ANGLE OF THE SAME CRACK.

	H	IA	RA	IS	PS	RPS	WE	LE
16.a	165	10^o	5^o	0.21*2.30	12*135	10*120	2	15
16.b	168	18^o	12^o	0.16*1.70	10*107	10*120	0	13
16.c	155	25^o	20^o	0.18*1.73	11*110	10*120	1	10
16.d	155	40^o	20^o	0.16*1.71	12*129	10*120	2	9

to the crack, the last is far away from the crack. From Table 4, we can conclude that whatever the photo height and angle, we can calculate the object distance correctly and estimate the road crack size with a little absolute error.

(a) (b) (c) (d)

Fig. 14. Four crack taken in different height and angle.

VII. CONCLUSIONS

In this paper, we propose a system to detect the crack type and estimate the crack size with smartphones. Specifically, the type of a crack is determined with a coordinate transmission method based on three directions, including the direction of the crack in the photo (estimated through an image processing method), the 3D shooting direction (i.e., the rotation of the smartphone while photographing) and the direction of the road (obtained from the OpenStreetMap road network). The size of a crack is estimated by using the camera's convex lens imaging theory, in which readings of the accelerometer and the magnetometer sensor are used. Experimental results verified the effectiveness of our proposed approach.

In the future, we plan to improve the performance of our system. For example, due to the limitation of distance or camera perspective, the photo may do not show a complete crack. In this situation, we may not be able to estimate the crack physical size of a complete crack. In the future, we need to analyze multiple photos for the same crack at different angles captured by different users, then two or more photographs with same overlapped parts are aligned and matched by a certain method of image screening and picture stitching. We can obtain a complete scene of the crack to calculate the physical size of the crack. In addition, There are unavoidable noise in the crack photos, we need to propose more robust image processing algorithms to overcome those limitations.

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