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2D/3D Crack Detection via Particle Filtering and Volume Rendering

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Abstract: Cracks are an important indicator of the safety status of infrastructures. Detection of cracks on civil structure is a vital task for maintaining the structural health and reliability of buildings. The proposed system has the ability to i) identify crack, ii) report the type, iii) estimate the length and width of the crack, iv) also estimate the depth of crack in pillars by 3D approach . This method presents a novel automated crack detection algorithm using particle filter. Cracks can be classified in accordance with their geometrical form as vertical, horizontal, diagonal and complex. The proposed approach eliminates the complex cracks geometry because it is very rare in structures. However, with this proposed method, we can measure 94% of all cracks. This system eliminates the need for manually tuning threshold parameters. In this paper, the system based on machine vision concepts has been developed with the goal to automate the process of crack geometry measurement. A single camera installed in a truck or even in a robot is used to take sequence of images is processed and the crack dimensions are estimated.

Keywords: Image analysis, machine vision, particle filter, crack depth, volume rendering.

I. INTRODUCTION

Crack is an important indicator reflecting the safety status of the civil structures. Unfortunately, throughout the history there has been many building collapses across the world due to poor maintenance. However, due to effects, such as Permeability of concrete, thermal movement, creep, human damage and topographic change, civil structures suffer from breaks in their surfaces and internal structures. So these are principal causes of cracks in buildings .As deterioration process in concrete begins with penetration of various aggressive agents, low permeability is the key to its durability. Thermal movement is most potent causes of crack in buildings. Timely and accurate monitoring about cracks in structures is necessary for the maintenance of concrete buildings and prevention of accidents. Accidents have highlights the tragical results of structural failure and the importance of periodic maintenance.

Corrosion of reinforcement has caused damage to concrete structures within a few years from the time of construction. The best control measure against corrosion is the use of concrete with low permeability. Increased concrete cover over the reinforcing bar is effective in delaying the corrosion process and also in resisting the splitting. Shrinkage cracks in masonry could be minimized by avoiding use of rich cement mortar in masonry and by delaying plaster work till masonry has dried after proper curing and undergoes most of its initial shrinkage. It can be controlled by using temperature reinforcement.

Image based reconstruction in automatic crack detection increases in past few years, this can be applicable in many areas such as laboratory testing, field inspection, quality assurance and construction quality control. Crack detection in experimental testing need specimen, whereas the researchers can take the photograph of the specimen from a distance and have the reconstructed model in digital crack detection.This is an added feature in crack detection. The use of particle filter gives an improved result as compared with previous methods. This can be implemented in a digital signal processor or in a field programmable logic array with many advantages over software program [1].

In past years, inspection of crack has been done manually by careful and experienced inspectors or by using some microscopic instruments. Besides, the poor lighting condition and the height of the structure make it hard for inspecting the cracks from a distance. So that preferring machine vision inspection, in which cracks are identified and classifying based on the image analysis.Where camera is placed in truck or somewhere else.

This paper presents an automatic crack detection, classification and dimension estimation methodology for civil structure safety monitoring. This approach uses particle filter for the automatic detection of crack. It is a statistical filter used to track an object in a clutter and uses machine vision technique to measure crack width and length.The depth of the crack is estimated in pillars and all by constructing 3D view of crack by volume rendering.

The depth information of the crack is also very important. The depth of the crack indicates how severe the crack is. This paper is exposed a method to determine the depth by 3D approach. In order to evaluate the damage in concrete structure, it is very important to quantify the crack geometry including width, length and more importantly the depth of

penetration. The most of the techniques used to obtain depth information focus on relative depth information, such as, shape from shading, from junctions and edges and elevation with respect to horizontal line [2].
To test the methods proposed in this paper, several test were conducted on controlled environment as well as on real concrete structures to validate the method. This paper describes the related work in Section II. Proposed architecture and the different methods in the proposed method are described in Section III. The experimental results and analysis are in Section IV. Finally, the conclusion is in Section V.

II. RELATED WORK

In the past few years cameras based crack inspection systems are the main method used in civil structure monitoring. Many techniques are there to detect and measure the cracks. Image processing technique forautomatic crack detection and identification are the focus of most methods. To detect a crack on surface, the edge and corner information are enough [3]. Most of the crack detection method use simple edge detection and thresholding.
A local binary pattern based operator is used to detect the crack on pavements [4]. In which classify the whole image into smooth and rough area. Further segmentation is performing only on rough areas[5]. This is a texture classification method. Similarly wavelets and neural networks are used for the crack detection [6].
The eddy current test (ECT) is probably one of the most widely used electromagnetic techniques for the inspection of thin defects (cracks) in conductive material [7]. This is relatively low cost and simple hardware setup. Laplacian and Sobel operator is also used to detect the edges in the image [8] [9].

A robust curve fitting can be used for crack detection, where a line segment can be fit to pixels below an average intensity in a neighborhood. The line segments are obtained from each neighborhood in the image and machine learning classification is used to classify these segments into two classes; crack or not crack [3].
Studies have been conducted on radio frequency identification (RFID) tag, it is a promising device for the management of products at low cost. Install large number of low cost RFID sensors on structure, even after the disaster of the structure we can access this sensors wirelessly and very easily [10]. A printed sheet is a part of the structure and a copper wire is connected with the structure and the RFID tag. When crack occur in the structure, the printed sheet is broken resulting increase in resistance. Similarly the crack width can be calculated by the ability of an RFID transmitter to communicate with the tag. Very small steel crack can be identifying by using this method.

Several studies are conducted on nondestructive technique to characterize the surface opening crack depth in concrete. This may be of two types, one is time-of flight based approach and other one is wave transmission based approach [11]. In the time-of flight based method, the depth is measured by using the time required for a longitudinal wave generated by an event on a side of a surface opening crack to diffract at the top of the crack and be captured by a surface mounted receiver placed on the opposite side of the crack. Wave transmission method is performed under laboratory conditions. Among different wave transmission approaches cutoff frequency method is the most commonly used one.

III.METHOD

Image processing technique for the crack detection and measurement are the key ideas of this paper. In Section III-A discusses about the architecture of the proposed system based on particle filter. In Section III-B is an explanation of the crack detection approach using particle filter. Section III-C is the crack measurement approach to estimate length and width of the crack using a single camera. In Section III-D introduces the crack depth measurement on beams based on 3D approach.

A. Proposed method architecture

Cameras are using as a main sensor, which has many advantages over traditional methods [12]. Even though, a correct setup of components in system is important to ensure the accuracy.Fig. 1 shows the block diagram of the proposed system. The system is composed of a camera to take images from the environment, a processing device is there to detect the crack and measure the crack geometries in real time, a remote station to receive the data from the processing device through a channel, and a database is created based on the measurement history. The database is a part of the architecture of proposed system, but it will not be used for comparison purpose. It is used as the history of the state of the cracks for the maintenance process.

B. Crack detection approach

The particle filter is taking place a major role in crack detection algorithm. Different aspects of image are described by colour models. There exists number of colour models. Here we focus on mainly two, red, green and blue (RGB) and hue-saturation-value (HSV).

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1. An RGB colour space is any additive colour space based on the RGB colour model. A particular RGB colourspace is defined by the three chromaticities of the red, green and blue additive primaries, and can produce anychromaticity that is the triangle defined by those primary colours. RGB is an abbreviation of red-green-blue [13].

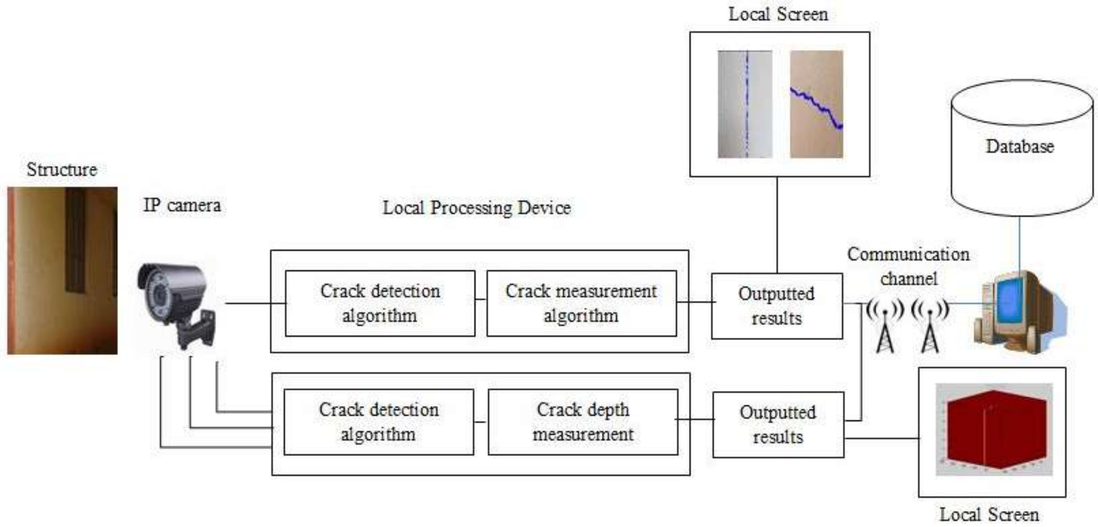

Fig.1. Block diagram of the proposed system

2. HSV stands for hue, saturation and value (or luminosity) and is also often called HSB (B for brightness). The hue of a colour refers to which pure colour it resembles. The saturation of a colour how white the colour is. The value of a colour, also called its lightness, describes how dark the colour is [14].

Fig. 2 shows the block diagram of the crack detection method. Here we are going with RGB colour space. As a pre-processing stage, the system selects a query image then resized it into 256*256*3. RGB planes with size of 256*256 are constructed by considering red, green and blue planes separately. We need a two dimensional matrix to represent a digital image. Where the image has a height of m pixels and width of n pixels. Each element of a matrix is the colour intensity of the pixels at row x and column y, each element can be represented as,

$$(I_{xy}) = [R, G, B]^T \qquad (1)$$

The histogram is calculated in RGB standard space [15]. Histogram is the graphical representation of tonal distribution of a digital image. It plots the number of pixels of each tonal value. So it assigns the colour at location (I_{xy}) corresponding to a matrix element. The colour histogram is represented by,

$$h(rgb) = K\,[R\ G\ B]^T \qquad (2)$$

Crack Detection Algorithm

Input: images of the structure from camera
Output: crack detected on screen
1:Colour identification of the target using h(rgb)
2:Initialize the particle filter with N=40000
3:Input the measurement
4:Resample the weight of each selected particle using likelihood model
5:Estimate the position of the target colour by multiplying the position of the particle with their respective position, $E = \sum_{j=1}^{N} W_j x_j$
6:Show the detected particles on the screen
7:Apply them into crack measurement algorithm after record the pixel

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The colour feature is one of the most widely used visual features. Use of colour histogram is the most common way of extraction, it is the search of a particular colour composition in an image with a standard colour image [16].

By Euclidian distance method, compere the histogram of the standard colour image h(rgb) with the input image $h(I_{xy})$. Then find the distance between these histograms. The comparison can be mathematically represented as,

$$D_i = \|h(rgb) - h(I_{xy})\| \qquad (3)$$

Where we get a m by n matrix.

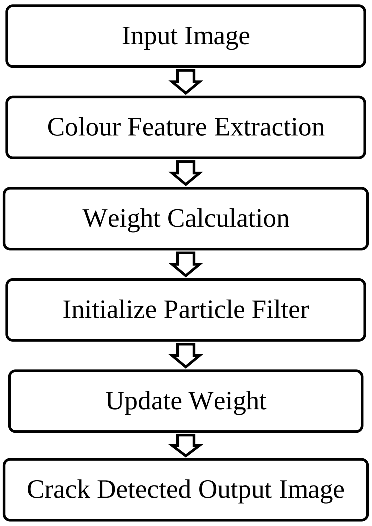

Fig.2. Block diagram of the crack detection method

After finding the distance of each matrix element I_{xy} from the standard colour image. Assign weight to each selected particles of the input image by using Guassian distribution,

$$W_i = \frac{1}{\sqrt{2\pi\sigma}} \exp(-\frac{D_i^2}{2\sigma^2}) \tag{4}$$

Where σ is the variance and it represents the colour spread around a crack.

Particle filter is from the statistical and probabilistic point of view. The filtering system consists of estimating the internal states in systems when partial observations are made. The objective is to compute the conditional probability of the state of some markov process, given some partial observations [17].

Particle filter method uses a genetic type mutation selection sampling approach with a set of particle to represent the posterior distributions of some stochastic process. The state space model can be nonlinear and the initial can be taking any from required. However, these methods do not perform well when applied to very high dimension system. Particle filter is implementing theprediction updating transition of the filter equation directly. The samples from the distribution are representing by a set of particles, each particle has a likelihood weight assigned to it that represent the probability of that particle. The particles with negligible weights are replaced by new particle in the proximity of the particles with higher weights. The objective of the particle filter is to find the posterior density of the state variable given the observational variable. The filtering problem is to estimate sequentially the values of the states $Y_{k,}$ given the observation process $X_0,\ldots X_k$ at any time k.All Bayesian estimates of Y_k follow from the posterior density $p(y_k|x_0,x_1,\ldots x_k)$. The particle filter method gives an approximation of these conditional probabilities using empirical measure associated with particle algorithm. In signal processing, particle method often assume Y_k and the observations X_k can be modeled as, $Y_0,Y_1,\ldots$ is a markov process on R that evolves according to the transition probability $p(y_k|y_{k-1})$. The observations $X_0,X_1,\ldots..$ take values in some state space on R.

The basic idea of the particle filtering is to approximate the probability distribution by a weighted sampling set $P = \{(s_n, \mu_n) | n = 1,2, \ldots . N\}$, where N is the number of particles selected. Each sample s represents the state of the object and μ is the corresponding discrete sampling probability.

Each element from the set is weighted based on observations and N samples are drawn with replacement. The mean state of an object can be estimated at each time step as,

$$E[P] = \sum_{n=1}^{N} \mu_n s_n \tag{5}$$

The crack detection algorithm shows the sequence of steps needed to detect the crack. The number of particles required is 40000. This number provides better quality and processing speed. If larger cracks are expected, the designer could increase the number of particles.

C. Crack Measurement Approach

The proposed method estimates the length, width and the depth of the crack. First of all, crack is obtained by using crack detection algorithm and then the length, width and depth are measured by approximating the number of pixels

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with the overall length and breadth.Usually, cracks are classified into vertical, horizontal, diagonal and complex based on their geometry. The presence of complex geometry is very rare in structures, it is refers to only 6% of all cases. The proposed method is capable to calculate 94% of all other cases excluding complex geometry.The data outputted from the crack detection algorithm is taken as the input of the crack measurement algorithm. From the classification of cracks, the crack is identified as complex one then output the message 'unable to measure the geometry'. If the classified crack is vertical, as shown in Fig. 3(a), or horizontal, as shown in Fig. 3(b). The length and width can be calculated by counting the pixels on the crack.)

If the crack on a civil structure is not a straight, if it has a curve in the crack then we need to linearize the curve. Linearization is an effective method to approximate the output of a function near. The most common approach for linearization is the linear least squares or polynomial least squares. The first degree polynomial equation is an exact fit through any two points with distinct x coordinates. To estimate the width of a crack with a curve or of a diagonal crack, as shown in Fig. 3(c) and Fig. 3(d,) proposes a method that determines normal direction of curve in the crack. The least square method is a form of mathematical regression analysis that finds a line of best fit for a set of data. Each point is a representative of the relationship between an unknown dependent variable and a known independent variable [18].

Initially consider an arbitrary point on the curve crack, say p(x, y). We obtain an equation of line l: y=ax+b at the point. Then find a tangent at the point also calculate its slope. For any given function, that can be approximated if it is near a differentiable point. While the concept of local linearity applies the most to the points arbitrarily close to those close well for linear approximation. For calculating the slope, consider the points in the image around the point p(x, y), including the pixels that were detected using crack detection algorithm. Let us now define a neighborhood keeping p(x, y) as the center having size N×N. Then record all the coordinates of the pixels present in the curved crack that were detected. We end up with a set of coordinates, $C_p = \{(x_j, y_j) \in P\}$, where P is the set of points in the crack. As an end step, a linear fitting of these points can be performed with a least square algorithm, as shown in Fig. 4. Now we have the slope of the curve from the straight line equation l on any point on the curved crack.

Crack measurement algorithm
Input: Information from the crack detection algorithm in pixels
Output: The width and length of the crack in mm
If the crack is recognized as horizontal or vertical**then**
Estimate the length and width and show them on screen
else if the crack is recognized as diagonal**then**
Determine the normal direction of the curve in crack
Estimate the length and width and show them on screen
else
Display the message ("the crack is recognized as complex, so unable to measure the geometry")
End if

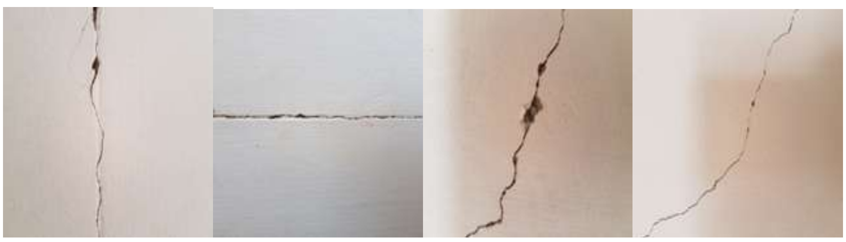
Keep on rotating the curve about an angle ψ (calculated from slope, is an angle normal to the curve), we can linearize the curve. Then calculate the width by averaging the pixels in every cross section,

$$\overline{W_c} = \frac{\sum P_{cs}}{n_{cs}} \quad (6)$$

Where P_{cs} is the number of pixels in each cross section and n_{cs} is the number of cross section.

D. Depth estimation by 3D approach

The 3D geometry of a crack and mainly the depth has been investigated on the surface. The 3D structure is constructed by the 2D observation of the field on the surface. The depth of the crack in a pillar is generally obtained by this method. Take the images by using a camera from different perspective of the structure and then combine the images to build a 3D view.



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

Fig. 3.vertical crack with curves (a), horizontal crack (b), diagonal crack with high cross section (c) and diagonal crack with low cross section (d).

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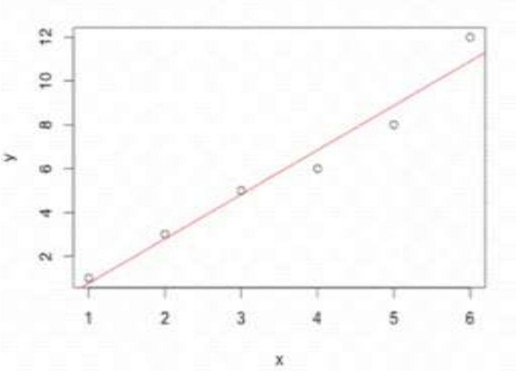


Fig. 4. Least square fitting

The depth can be estimated by counting the pixels along length wise as mentioned in the Section III-C. This can be converting into cm, by combining it with camera pixel resolution. We can use volume rendering for 3D crack. Volume rendering is a set of technique used to display a 2D projection of a 3D discretely sampled data set [19]. Here we are using a texture based volume rendering algorithm for 3D construction. It consists of mainly three steps (1) initialize (2) update and (3) draw. The initialize stage performed only once. The update and draw stages are executed whenever receives the user input.

To render a 2D projection of 3D data set, one first need to define a camera relative to the volume. Also need to define the opacity and the colour of every voxel. This is usually defined on RGBA (for red, green, blue, alpha). Similarly, we can use texture based volume rendering. The volume rendering by 2D texture mapping use planes parallel to base plane (from face of volume which is "most orthogonal" to view ray).

IV. EXPERIMENTAL INVESTIGATION AND RESULTS

This section describes the experiment to access the feasibility of the proposed method. In Section IV-A describes about the outline of the experimental setup provided. In Section IV-B explains the application of the crack detection method. Section IV-C describes the applications of crack measurement method and also showing some practical results obtained. Section IV-D explains the applications in depth estimation by 3D approach. In Section IV-E show the overall result analysis of the system.

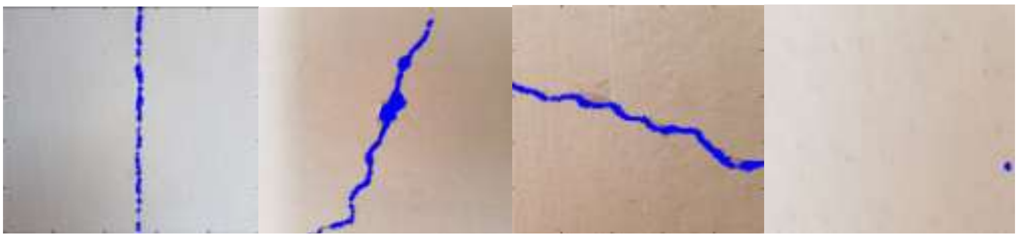
A. Outline of the Experiment Setup

The experimental setup is composed of a robot with a camera travelling on the wall. To test the reliability of the system, collect number of images from various structures. The implementation of the proposed system was carried out and the results were recorded.

In order to measure the crack length and width not in pixels, it is necessary to know the camera pixel resolution and the only needed parameter is the camera pixel resolution, which is Pr= 0.3776. Camera pixel resolution means, the amount of details that the camera captures and is measured in pixels. The more pixels a camera has, the more details it can capture. If a new camera was used, a new calibration method must be performed.

B. Application of the Crack Detection Method

Crack detection approach is based on a crack detection algorithm. Number of runs with different materials was performed, the samples are taken from the real concrete structures. The experiment with real concrete structures influences the light, light was allowed to vary. Then all the samples were processed in order to detect the crack only by using image.



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

Fig. 5. A vertical crack (a) and a diagonal crack (b), (c)and a surface with no crack (d) are recognized on a real concrete structure.

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Inputting the images that have been taken from the real concrete structures, each sample is processed and the crack detection algorithm is outputting an image with blue dots, showing the crack. Fig. 5(a) showing an image with recognized vertical crack, Fig. 5(b) and 5(c) showing an image with recognized diagonal crack and Fig 5(d) showing the output in a non-crack area.

For cracks classified as vertical, the length and the width of the crack in pixels can be estimated by,

$$l_p = y_i - y_j \quad (7)$$

and

$$w_p = x_i - x_j \quad (8)$$

where l_p and w_p are the length and width of the crack in pixels respectively and the x_i, x_j, y_i and y_j are obtained from the crack detection algorithm. From Fig. 5(a), the points of a vertical crack can be extracted. Similar method can be applicable in cracks classified as horizontal. But we need to invert the x and y axis in order to standardize the measurement. If the crack is classified as diagonal, then the algorithm output$\overline{W_c}$. The summary of the results obtained from samples are listed in Table I.

TABLE I CRACK MEASUREMENT USING THE CRACK DETECTION ALGORITHM

Trial	Length of the crack(pixels)	Width of the crack(pixels)
Sample 1	67	12
Sample 2	78	1
Sample 3	62	7
Sample 4	68	2
Sample 5	86	6
Sample 6	63	3
Sample 7	44	11

C. Application of Crack Measurement Method

The data from the crack detection algorithm is inputted into the crack measurement algorithm, to estimate the crack dimensions. By using the length and width in pixels as shown in Table I and the camera pixel resolution is mentioned in Section IV-A, the algorithm is able to output the dimensions of the crack.

To verify the accuracy of the method proposed, the cracks have been measured using a verniercaliper with a least count of 0.01 cm. The error can be calculated between the real dimensions of the crack and the results obtained from the crack measurement algorithm. For the length, the error is,

$$L_e = \frac{l_{pm} - l_{vc}}{l_{vc}} * 100 \quad (9)$$

Where L_e is the error in length, l_{pm} is the length measured from the proposed method and l_{vc} is the length measured using vernier caliper.

Similarly, for the width, the error is,

$$W_e = \frac{w_{pm} - w_{vc}}{w_{vc}} * 100 \quad (10)$$

Where W_e is the error in width, w_{pm} is the width measured using the proposed method and w_{vc} is the width measured using vernier caliper.The results are summarized in Table II. Next section, compere the error rate of the proposed system with the previous method.

TABLE II CRACK DIMENSIONS USING THE CRACK MEASUREMENT ALGORITHM

Trail	Type of geometry	l_{vc} (cm)	l_{pm} (cm)	L_e (%)	w_{vc} (cm)	w_{pm} (cm)	W_e (%)
Sample 1	Horizontal	8.65	9.25	6.93	0.21	0.18	14.28
Sample 2	Vertical	7.48	8.00	6.95	0.08	0.07	12.50
Sample 3	Diagonal	6.57	5.96	9.28	0.06	0.07	16.67
Sample 4	Curve	8.64	9.10	5.32	0.35	0.37	5.71
Sample 5	Curve	8.39	9.44	12.51	0.12	0.11	8.33
Sample 6	Diagonal	8.25	9.32	12.96	0.36	0.38	5.55
Sample 7	curve	9.93	9.21	7.25	0.17	0.15	11.76

D. Application of depth estimation by 3D method

As mention in the Section IV-D, the depth of crack in a pillar is measured by constructing a 3D view. This experiment was conducted in a controlled environment. The detected crack on pillar is shown in Fig. 6.

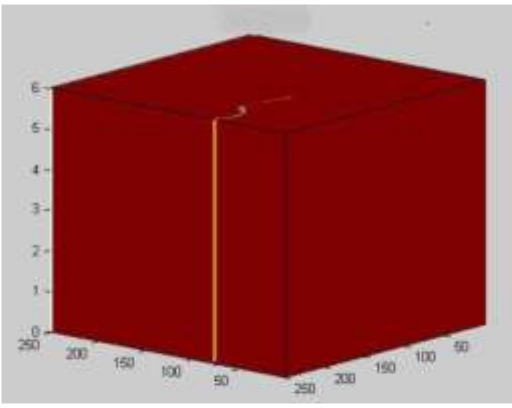

Fig. 6.3D view of a crack in a pillar.

E. Analysis of the Overall Result

The crack detection algorithm developed in this paper is able to detect the cracks in different materials such as, concrete, plastics and others. Using RGB colour model combined with particle filter provided a better search for cracks with great accuracy. In terms of computational performance and several trails accomplished, each image was processed in an average time of 5s. In the crack measurement algorithm, from the geometry classification, the algorithm is able to output the length as well as the width of the crack using only pixel position and camera resolution, as shown in Table I.The results demonstrate that the method can measure almost all kind of real cracks.

To check the applicability of the proposed system, our method is compared with the other crack detection and measurement methods. This is also given a good detection method. The average error of the proposed method was estimated at 8.74% for the length and 10.68% for the width. In comparison with other literature methods, the proposed method proved more accurate than the vision system developed in [20], where the average error estimated at 13.9% as well as in [21], where the average error has been estimated at 15%. In depth estimation in pillars used a 3D approach by volume rendering. This experiment was conducted in a controlled environment. We are not able to find any estimation of computational resources in literature, so in comparison with the manual method used nowadays, our proposed method is more efficient and faster [22].

V. CONCLUSION

In this paper proposed an efficient crack detection method using particle filter and also proposed a method to find the dimensions of the crack like length, width and the depth of the crack by 3D approach. The result validated the proposed approach consistently and may even better than other methods in the literature. Classification task is also enhanced by this method. The incorporation of digital crack detection and digital crack measurement can help in field such as quality assurance, field inspection and research.

The resolution of the image and image processing system will affect the result. And if the measurement area observed is too large, the measurement of fine crack is impossible. To optimise the processing algorithm in order to minimise the processing time, the algorithm can be ported a dedicated DSP or an FPGA chip.

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