

The Devil is in the Crack Orientation: A New Perspective for Crack Detection

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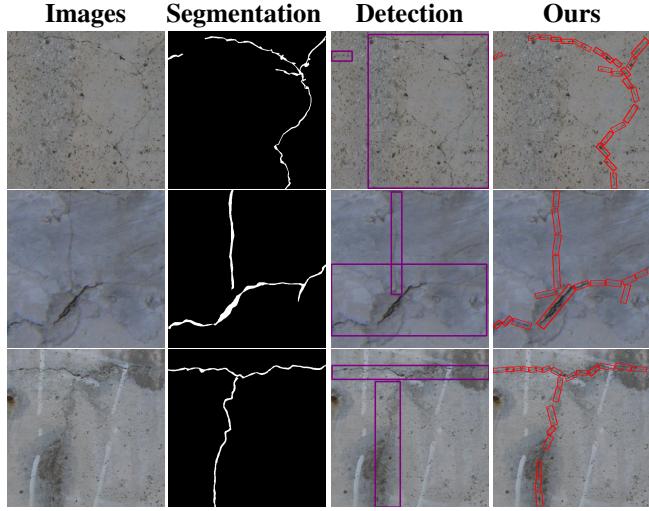
Abstract

Cracks are usually curve-like structures that are the focus of many computer-vision applications (e.g., road safety inspection and surface inspection of the industrial facilities). The existing pixel-based crack segmentation methods rely on time-consuming and costly pixel-level annotations. And the object-based crack detection methods exploit the horizontal box to detect the crack without considering crack orientation, resulting in scale variation and intra-class variation. Considering this, we provide a new perspective for crack detection that models the cracks as a series of sub-cracks with the corresponding orientation. However, the vanilla adaptation of the existing oriented object detection methods to the crack detection tasks will result in limited performance, due to the boundary discontinuity issue and the ambiguities in sub-crack orientation. In this paper, we propose a first-of-its-kind oriented sub-crack detector, dubbed as CrackDet, which is derived from a novel piecewise angle definition, to ease the boundary discontinuity problem. And then, we propose a multi-branch angle regression loss for learning sub-crack orientation and variance together. Since there are no related benchmarks, we construct three fully annotated datasets, namely, ORC, ONPP, and OCCSD, which involve various cracks in road pavement and industrial facilities. Experiments show that our approach outperforms state-of-the-art crack detectors.

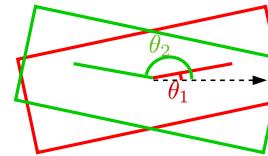
1. Introduction

Crack is a type of defect that appears on the surfaces of many physical structures, e.g., the road pavement [41], the industrial facilities [8]. Inspecting and repairing cracks are crucial tasks for avoiding expansion of the harm to these structures [77]. Besides, a recent study reveals that recognizing the surface cracks caused by earthquakes in time can avoid secondary damage to people's properties

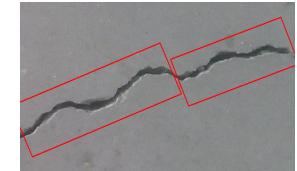
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(a) Visualization of different perspectives for crack detection



(b) Boundary discontinuity



(c) Ambiguities in orientation

Figure 1. Cracks tend to be curve-like structures [77] in real-world applications. (a) We compare our orientation-based perspective with others for crack detection. (b) Boundary discontinuity issue in the existing 180-degree definition. (c) The sub-crack orientation is ambiguous in some cases due to the irregular sub-crack shape.

and lives [67]. However, manual inspection is costly, time-consuming, and prone to human error [34]. Hence, automatic image-based crack detection plays an essential role in a real-world application of crack identification [22, 67].

Currently, image-based crack detection methods can be roughly divided into three categories [36]: patch-level classification [4, 8], object-level detection [54, 31], and pixel-level crack segmentation [76, 49]. Although the first two methods take less labeling cost than the last one, they can only provide a coarse crack localization. Moreover, we are

motivated by the fact that a crack is a line object that has a certain width from a local perspective [77]. Then, we are encouraged to start from an orientation-based perspective that models the cracks as a series of oriented sub-cracks (see Fig. 1 (a)). The advantage of this perspective is three-fold: **(1) eliminating the scale variation, (2) reducing the intra-class variation, and (3) taking less labeling cost than the segmentation methods.** More specifically, in the case of our practice, the price and time cost of the pixel-level annotations are $15\times$ and $30\times$ higher than our oriented sub-crack annotations, respectively. Besides, considering real-world applications, existing works [33, 35] show great power by taking a detection-then-segmentation strategy, i.e., it first identifies and localizes cracks by a detector and then obtains crack details by segmentation-based methods. Hence, the detector based on our perspective can serve as a complement to segmentation-based methods, as it can provide a more fine-grained localization (see Fig. 1 a).

However, it is difficult to directly adopt the state-of-art oriented detectors [16, 39, 23, 37] to crack detection. The reason is two-fold: (1) several existing works (e.g., ReDet [16], DRN [39]) simply ignore the boundary discontinuity problem, and (2) although the remaining works make great efforts on the above problem, these works still suffer from ambiguity issue in the sub-crack orientation. Among existing oriented detection methods, those detectors based on five parameters (x, y, h, w, θ) dominate [58], where (x, y) indicates the center point and (h, w, θ) denotes height, width, and angle, respectively. As shown in Fig. 1 (b), the boundary discontinuity problem indicates that small rotations for oriented objects around the angle period's boundary result in a sudden sharp increase of loss [61]. Moreover, Fig. 1 (c) provides some cases to illustrate the inherent ambiguities in sub-crack orientation. When the growth direction of a crack changes frequently, the orientation of the sub-crack is unclear to judge, making it hard to learn regression functions for estimating orientation.

This paper starts from a new perspective for crack detection that models the cracks as a series of oriented sub-cracks. After that, we adopt CenterNet [73] as our baseline due to its simplicity. Next, we propose a new piecewise angle definition to ease the boundary discontinuity issue. Based on our piecewise definition, we propose the CrackDet that contains a parallel multi-branch architecture, each of which is responsible for predicting a fixed range of angles. Then, to address the ambiguities in sub-crack orientation, we propose a novel multi-branch angle regression loss, namely MAR Loss, which is based on Wasserstein distances [1] for both angle regression and angle variance estimation. The advantage of coupling CrackDet with MAR Loss is three-fold: (1) the ambiguities in sub-crack orientation can be captured to a certain extent. (2) The learned variance from each branch is beneficial during the post-process. We

acquire the estimated variances from each branch and obtain the detection results by variance voting. (3) Since crack orientation is significant in a real-world application [38], the learned variances reveal the level of confidence in the angle prediction, it can potentially help to judge the overall crack orientation. Our main contributions are summarized as follows:

(1) To the best of our knowledge, we are the first ones to start from an oriented sub-crack detection perspective for crack detection by modeling cracks as a series of sub-cracks with their inherent orientations.

(2) Propose a first-of-its-kind oriented sub-crack detector, called as CrackDet, which stems from the proposed piecewise angle definition (see Sec. 3.1), to ease the boundary discontinuity issue.

(3) Propose a multi-branch angle regression loss that enables CrackDet to capture ambiguities in sub-crack orientation via jointly learning sub-crack orientation and the corresponding orientation variance (see Sec. 3.2 and 3.3).

(4) A tale of three datasets has been constructed, namely, ORC, ONPP, and OCCSD. These datasets contain orientation annotations of the sub-cracks in real-world industrial facilities and road pavements, to facilitate the research about oriented sub-crack detection.

2. Related work

By following the previous study [36], the vision-based crack detection can be roughly clustered into three categories: patch-level classification [4, 8], object-level detection [54, 31], and pixel-level segmentation [77, 48].

Patch-level crack classification. Recently, deep learning-based methods are more powerful than the traditional methods (e.g., HOG [42], LBP[42], Gaussian process, SVM [42]) in the patch-level crack classification tasks [36]. Among deep learning-based methods, variants of convolutional neural network (CNN) followed by a fully connected (FC) layer are used to recognize patch-level crack samples. Typically, ResNet [17] and VGG [47] are popular backbones among existing backbones. Moreover, focal loss [26] focuses on the hard samples to learn discriminative features. However, patch-level methods fail in providing orientation and the fine-grained localization of crack objects [36].

Object-level crack detection. For object-level crack detection, a bounding box is exploited to describe the location and the coarse size of a crack object. Most existing crack detectors mainly adopt the general object detectors, such as Faster R-CNN [44], RetinaNet [26], Yolo [43], CenterNet [12], and SSD [28]. Specifically, Fen et al. [13] first design a hybrid approach that uses Faster R-CNN to detect the crack patch. Then, as the crack orientation is important in the post-process, a deep CNN is exploited to obtain the orientation of each detected patch. Ma et al. [31] design an automatic crack detection system by using YOLO v3 [75]. To

detect various cracks, Wang et al. [51] propose a crack detection model by using CenterNet to extract crack features. Moreover, a RetinaNet-based crack detector is proposed to detect the crack in asphalt pavement [50]. Unfortunately, as shown in Fig. 1, the object-level crack detection methods suffer from scale variation and intra-class variation. Moreover, it also can not directly provide the orientation and the fine-grained localization of cracks.

Pixel-level crack segmentation. Since those horizontal bounding boxes can not describe the exact shape of the crack, segmentation-based methods are proposed to detect cracks at the pixel level. Yang et al. [59] design an automatic crack segmentation pipeline by using fully convolutional networks [30] and achieve a noticeable performance gain over traditional approaches [76, 46]. By coupling with Deeplab v3+ [5], CrackSeg [48] is proposed to learn rich features for different scales. Moreover, aiming to learn high-level crack representations, DeepCrack [77] is proposed to capture the line structures by feature fusion. Considering different receptive fields, FPHBN [57] makes great efforts for crack detection by aggregating pyramid features. Besides, by addressing the imbalance problem, Li et al. [22] propose an adaptive weighted cross-entropy loss function, which serves as a complement to the existing methods. However, these segmentation-based methods heavily rely on high-quality labeled datasets [6, 72], which involves a high labeling cost.

Compared to the above methods, we start from a new perspective that turns crack detection into oriented sub-crack detection. Based on this perspective, we are allowed to provide a fine-grained localization of crack objects (See details in Fig. 1), instead of a coarse localization by the patch-level classification or object-level detection methods. Hence, considering the existing detection-then-segmentation strategy [33, 35], the detector based on our perspective can serve as a better candidate for the segmentation-based methods. Besides, when considering a dynamic field without historical human supervision, our perspective can greatly ease the labeling cost than the pixel-level segmentation methods.

Oriented object detection. Since our oriented sub-crack detection perspective belongs to the oriented object detection category, we give a brief review of related research on this scope. Recently, many powerful rotation detectors are mainly derived from horizontal object detectors by adding an orientation regression branch [23]. For example, ICN [2], ROI-Transformer [11], SCRDet [64], CAD-Net [70], CSL[60], R³Det [62], ReDet [16], Oriented R-CNN [55], and DCL [58] bring satisfied detection results on DOTA dataset [53] and HRSC2016 dataset [29]. Gliding Vertex [56] and RSDet [40] share the same purpose of considering quadrilateral regression prediction. Note that, the boundary discontinuity problem is caused by the periodicity of the

angle when dealing with the angle-based orientation estimation. Then, Yang et al. [60] take a new perspective that turns the angular regression tasks into the angular classification tasks [58]. Moreover, Oriented RepPoints [23] utilize the flexible adaptive points as the box representation to achieve oriented object detection. Unlike these methods, our CrackDet addresses the boundary discontinuity problem via the new piecewise angle definition, which is motivated by the divide-and-conquer strategy. Besides, although KLD [65] and GWD [63] also start from a distribution perspective, it converts the center point, height, width, and orientation of a rotated bounding box as a 2-D Gaussian distribution, and does not focus on learning angle variance. Instead, the proposed CrackDet assumes that the ground-truth orientation obeys a single-variate gaussian distribution, and aims to learn the sub-crack orientation and its variance together.

3. Our method and datasets

The overall framework is shown in Fig. 2. We first introduce the piecewise angle definition in Sec. 3.1, and the network architecture of CrackDet in Sec. 3.2. Then, we give the details of the proposed MAR Loss for estimating ambiguities in sub-crack orientation in Sec. 3.3. Finally, we present the inference step of CrackDet with estimated angle variances in Sec. 3.4, and the proposed datasets in Sec. 3.5.

3.1. Piecewise angle definition

In this section, we recap the boundary discontinuity problem and inconsistency regression problem in the existing 180-degree five-parameter definition. Then, we discuss the details of the proposed piecewise angle definition.

Rethinking the five-parameter definition. Fig. 2 (a) shows that the existing five-parameter definition [53] with the 180-degree angular range includes (x, y, h, w, θ) , where (x, y) indicates the center point and $[h, w, \theta]$ denotes height, width, and angle, respectively. Then, the boundary discontinuity problem refers to a sharp increase of loss at the boundary caused by the periodicity of the angle. As shown in Fig. 3 (a), it can be further explained that when the angle of a rotated box is close to 180°, the angle under the five-parameter definition will suddenly change from 180° to 0°, resulting a sharp increase of angle regression loss. Moreover, the inconsistency regression problem can be attributed to the rotation symmetry in object detection, which includes the equivariant orientation and invariant shape estimation for a rotated bounding box [68]. Specifically speaking, rotation-equivariant features are desired for orientation estimation. In contrast, the shape of the bounding box does not change after a rotation. Thus, rotation-invariant features are needed for predicting its invariant height and width [16].

Discussion on our piecewise angle definition. We are inspired by the divide-and-conquer strategy [7] and propose the following piecewise angle definition, shown in

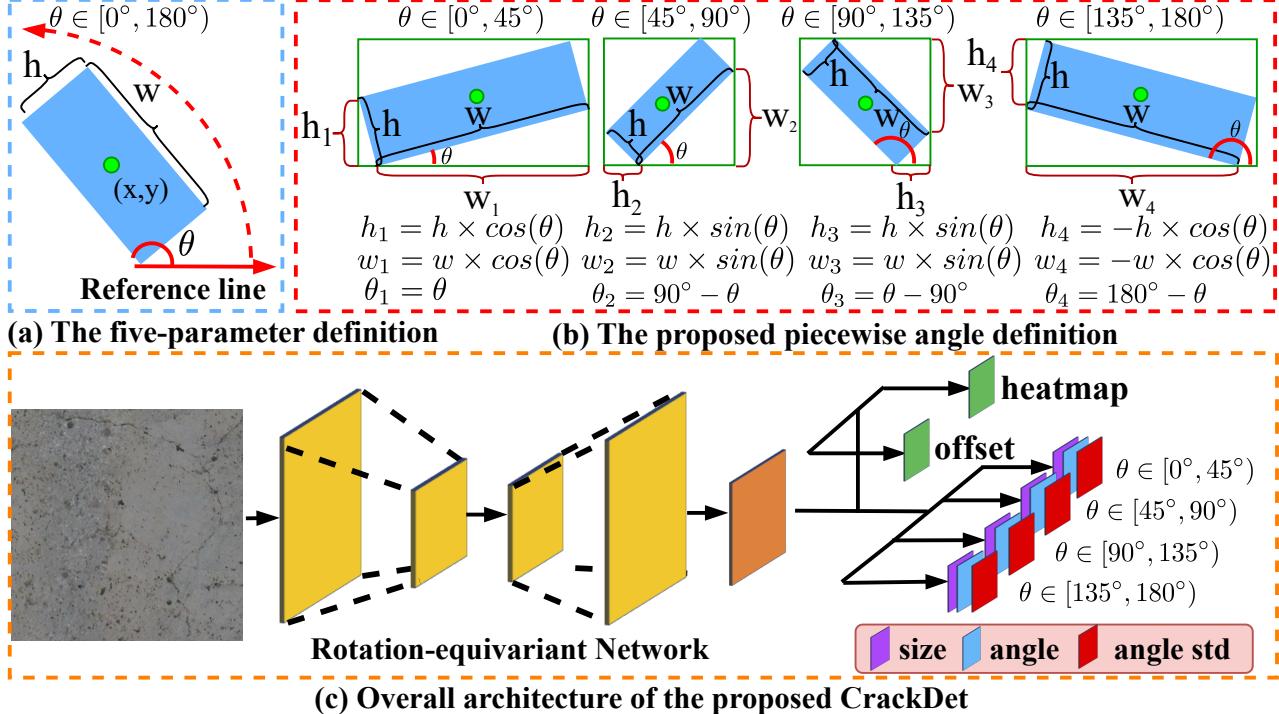


Figure 2. (a) The existing five-parameter definition with long-side definition. (b) Our piecewise angle definition is inspired by the divide-and-conquer strategy and built upon the above five-parameter definition. It breaks down the existing 180-degree regression tasks into four sub-tasks for addressing the discontinuity problem. (c) Based on our piecewise angle definition, we present an overview of CrackDet that can estimate standard deviations (**std**) along with angle regression for capturing ambiguities in the sub-crack orientation. Note that, the heatmap branch and offset branch are responsible for the center (i.e., x and y) of the predicted bounding box as in the original CenterNet.

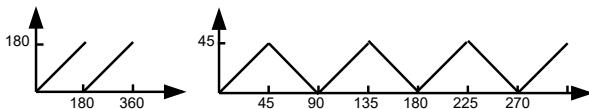


Figure 3. The horizontal axis denotes the angle of a rotated box in anti-clockwise order. And the vertical axis denotes the angle definition in different methods. Due to the periodicity of the angle, Figure (a) shows that there is a sudden change when the angle of a rotated box closes to 180° with the 180-degree definition.

Fig. 2 (b). On the one hand, Fig. 3 (b) shows that there is no sudden change of the angle in our piecewise angle definition. Thus, ours is free of the boundary discontinuity problem. On the other hand, rotation equivariance can be easily achieved by group convolutions [52], while rotation invariance relies on a larger capacity network or a larger number of training samples. Hence, we focus on rotation-equivariant features. And then, we are allowed to transform the invariant size estimation into equivariant size estimation by adding a factor $\sin(\theta)$ or $\cos(\theta)$ to the height and width (see Fig. 2 (b)). That way, the box size is enforced to change equivalently when the box orientation changes. Ac-

cordingly, both box size and angle regressions can benefit from rotation-equivariant features.

3.2. Network architecture

As discussed before, we aim to extract rotation-equivariant features for box size regression and angle regression. Therefore, we adopt rotation-equivariant networks as the backbone to extract rotation-equivariant features. Then, we design a parallel multi-branch architecture based on the proposed piecewise angle definition. The overall architecture of CrackDet is shown in Fig. 2 (c).

Rotation-equivariant backbone. We first adopt CenterNet [73] as our baseline, which takes an object as a single point (i.e., the center point of the bounding box) and regresses the object size and offset. Then, we re-implement all layers of the fully-convolutional encoder-decoder networks (i.e., up-convolutional residual networks [20]) in CenterNet based on e2cnn [52], named as ReEDNet. Importantly, e2cnn includes rotation-equivariant convolution, rotation-equivariant up-convolution, and pooling, etc. Thanks to the rotation weight sharing and group representations in e2cnn, our ReEDNet takes smaller parameters than the original encoder-decoder networks in CenterNet and enjoys the capability of equivariance.



Figure 4. A visualization of our angle-based variance voting. Firstly, the red, blue, orange, and teal textboxes are the corresponding standard deviation obtained from branch 1, 2, 3, and 4, respectively. Then, for each oriented bounding box, we select branch i that has the smallest standard deviation to obtain its final detection result. Note that, the red background box is associated with the selected branch.

Multi-branch architecture. According to our piecewise angle definition, we define a valid range $[l_i, r_i)$ for each branch i . During the training, we only select the ground truth boxes whose angles fall in the corresponding valid range of one branch. Specifically, referring to the existing 180-degree definition, for an oriented bounding box with angle θ on the input image, it is valid for branch i when:

$$l_i \leq \theta < r_i. \quad (1)$$

As shown in Fig. 2 (c), the valid ranges of four branches are set to $[0^\circ, 45^\circ]$, $[45^\circ, 90^\circ]$, $[90^\circ, 135^\circ]$ and $[135^\circ, 180^\circ]$, respectively. For branch i , we redefine the ground-truth θ , height h , and width w in the 180-degree definition into θ_i , h_i , and w_i , according to our piecewise definition in Fig. 2 (b). Moreover, we aim to estimate the angle and angle confidence together. To this end, each branch of our parallel multi-branch architecture contains three detection heads on the top of the rotation-equivariant backbone for predicting size (i.e., height and width), angle, and angle confidence. Note that, we simply implement each head with a fully-connected layer. That way, our network enables us to predict multiple probability distributions instead of only one angle. For simplicity, we assume each predicted angle from each branch is independent and obeys a single-variate gaussian distribution. The corresponding equation is shown as follows:

$$P_{\Theta_i}(\theta) = \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(\theta-\theta_i^e)^2}{2\sigma_i^2}}, i \in \{1, 2, 3, 4\} \quad (2)$$

where Θ_i is the parameters of the angle detection head from branch i , θ_i^e denotes the estimated angle from branch i , and standard deviation σ_i measures the angle confidence of the estimation on branch i . When σ_i is very close to 0, it means the branch i is extremely confident about the estimated angle. Accordingly, we suppose to have the redefined ground-truth angle θ_i that is in the valid range of branch i . Similarly, θ_i can also be formulated as a gaussian distribution $\mathcal{N}(\theta_i, \sigma_{gt}^2)$ with its standard deviation $\sigma_{gt} \rightarrow 0$. Then, this gaussian distribution can be viewed as: $P_i^{gt}(\theta) = \delta(\theta - \theta_i)$, where $\delta(\cdot)$ indicates Dirac delta function.

3.3. The proposed MAR Loss

Suppose the angle of a ground-truth bounding box lies in the valid range of branch i , our multi-branch angle regression loss (MAR Loss) aims to minimize the distribution discrepancy between the predicted angle distribution from branch i and the redefined ground-truth angle distribution. Meanwhile, we expect the other three branches to be able to predict larger variance so that we can filter those inaccurate predictions by variance voting in the inference step. More specifically, we first exploit the Wasserstein distance as the distance metric and minimize the distance between $P_{\Theta_i}(\theta)$ and $P_i^{gt}(\theta)$. Secondly, we maximize the estimated variance from the other three branches. The equation is shown as:

$$\begin{aligned} L_{MAR} &= \frac{D_W(P_{\Theta_i}(\theta) \| P_i^{gt}(\theta))}{\frac{1}{2} + \sigma_i^2} - \sum_{j=1, j \neq i}^4 \sigma_j^2 \\ &= \frac{\|\theta_i^e - \theta_i\|_2^2 + \sigma_i^2}{\frac{1}{2} + \sigma_i^2} - \sum_{j=1, j \neq i}^4 \sigma_j^2 \end{aligned} \quad (3)$$

where $D_W(\cdot)$ is unfolded based on Wasserstein distance [3]:

$$D_W(P_{\Theta_i}(\theta) \| P_i^{gt}(\theta)) = \|\theta_i^e - \theta_i\|_2^2 + \sigma_i^2. \quad (4)$$

Importantly, we exploit Wasserstein distance instead of KL-Divergence [18] for angle regression, because KL-Divergence heavily relies on a non-negligible intersection between two distributions [1, 18]. Note that, when θ_i^e is estimated accurately, i.e., $\|\theta_i^e - \theta_i\|_2^2 \rightarrow 0$, the branch i is expected to predict smaller variance. In addition, a term $\frac{1}{2} + \sigma_i^2$ is added for the following reason: due to the ambiguities in sub-crack orientation, when the angle θ_i^e is estimated inaccurately, i.e., $\|\theta_i^e - \theta_i\|_2^2 > \frac{1}{2}$, we expect the branch i to be able to predict larger variance σ_i^2 so that L_{MAR} will be lower. Moreover, according to our piecewise angle definition, the size regression loss L_{size} for the redefined ground truth height h_i and width w_i is defined as $L_{size} = |h_i^e - h_i| + |w_i^e - w_i|$ where h_i^e and w_i^e indicate the estimated height and width from the valid branch i . Then,

the overall training objective is shown below:

$$L_{\text{CrackDet}} = L_k + \lambda_{off} L_{off} + \lambda_{size} L_{size} + \lambda_{MAR} L_{MAR} \quad (5)$$

where L_k and L_{off} are the losses of center point recognition and offset regression by following CenterNet [73]. The hyper-parameter λ_{off} , λ_{size} , and λ_{MAR} are constant factors to control the balance of the above losses.

3.4. Inference

At the inference step, there are four branches, each of which will predict the height, width, angle, and standard deviation. Thus, we can not directly decide which one should be adopted. Fortunately, with the help of MAR Loss, we design an angle-based variance voting for obtaining the final bounding boxes. Firstly, we extract the peaks in the heatmap by following CenterNet [73]. Then, we get standard deviations $\sigma_1, \sigma_2, \sigma_3, \sigma_4$ from four branches at each peak. As shown in Fig. 4, for each peak, we choose branch i that has the minimum estimated variance to obtain the raw output: $i^* = \operatorname{argmin}_{i=\{1,2,3,4\}} \sigma_i^2$. Next, according to CenterNet [73], we obtain the center (i.e., x and y) of the oriented bounding box according to the above peaks and the offset branch. Finally, we acquire the final height $h_o = h_{i^*}^e / \Delta(\theta_{i^*}^e)$, width $w_o = w_{i^*}^e / \Delta(\theta_{i^*}^e)$, and angle $\theta_o = \Gamma(\theta_{i^*}^e)$ of the bounding box by the following equation:

$$\Gamma(\theta_i^e) \triangleq \begin{cases} \theta_i^e, & i = 1, \\ 90^\circ - \theta_i^e, & i = 2, \\ 90^\circ + \theta_i^e, & i = 3, \\ 180^\circ - \theta_i^e, & i = 4. \end{cases} \quad (6)$$

$$\Delta(\theta_i^e) \triangleq \begin{cases} \cos(\theta_i^e), & i = 1, \\ \sin(90^\circ - \theta_i^e), & i = 2, \\ \sin(90^\circ + \theta_i^e), & i = 3, \\ -\cos(180^\circ - \theta_i^e), & i = 4. \end{cases} \quad (7)$$

where i denotes the index of the selected branch. θ_i^e indicate the estimated angle from branch i . It is worth noting that the remaining inference step is the same as CenterNet [73].

3.5. The proposed datasets

To promote the research on oriented sub-crack detection, we propose ONPP, ORC, and OCCSD datasets, which are collected from industrial facilities, road pavement, and various buildings in real-world applications.

ONPP: This dataset is collected from the industrial facilities in real-world applications by a high-resolution camera, comprising 200 images with the size of 7360×4912 . The width of the crack in the collected images varies from 0.05 mm to 10 mm. Moreover, the collected images contain different kinds of noise, such as various concrete types and light intensity. To extend this dataset without compromising the resolution, we directly slice these images into 512×512 pixels, constructing a final dataset with 3,104 samples.

ORC: This dataset is collected from road pavement by a mobile vehicle equipped with a high-resolution camera. It contains 300 images with a size of 3489×3489 . The images of this dataset include various sizes of cracks in the road. It also contains a lot of noise, such as well covers and various appearances of the crosswalk. Similar to ONPP, we slice these images into 512×512 pixels, constructing a final road pavement dataset with 1,303 samples.

OCCSD: This dataset is extended from the concrete crack segmentation dataset [71], which contains 458 high-resolution images (4032×3024 pixels). We construct an oriented sub-crack detection dataset with 1,875 samples by slicing these images into 512×512 pixels and relabeling them from an oriented sub-crack detection perspective.

4. Experiments

4.1. Experiment details

Evaluation testbed. We conduct experiments for oriented sub-crack detection on three datasets, i.e., ONPP, ORC, and OCCSD. By following the existing crack detection work [8, 31], we divide each dataset into the training, validation, and test set, with the proportion of 8 : 1 : 1. Moreover, to further verify the effectiveness of CrackDet, we also provide the experiment results on the HRSC2016 dataset [29]. HRSC2016 dataset contains 1,061 samples. Its resolution ranges from 300×300 to 1500×900 . For fairness, according to previous works [55, 16, 23], we exploit the training set (436 images) and validation set (181 images) for training, and the testing set (444 images) for evaluation.

Implementation details. We adopt Adam as the optimizer for training. The total epoch for training the CrackDet is set as 60, 60, 60, and 140 on ONPP, ORC, OCCSD, and HRSC2016 datasets, respectively. For the first three datasets, the initial learning rate is set to $4e-4$ and reduced by a factor of 10 after 20, and 40 epochs. For the last one, the initial learning rate is $4e-4$ and reduced by a factor of 10 after 90, and 120 epochs by following the previous work [39]. The batch size for ONPP, ORC, OCCSD, and HRSC2016 is set to 32, 32, 32, and 8, respectively. More importantly, the input resolutions of four datasets are 512×512 , 512×512 , 512×512 , and 768×768 , respectively. By following the previous work [16], we only use random flipping for data augmentation. We implement our ReEDNet based on ResNet50 and e2cnn [52], and denote it as ReED-R-50. We train all models on four RTX 3090 GPUs and test on a single RTX 3090 GPU. According to our hyper-parameter sensitivity study, we set $\lambda_{off} = 0.1$, $\lambda_{size} = 0.2$, and $\lambda_{MAR} = 0.1$ in our next experiments.

Evaluation metrics. Following previous works [75, 54], we evaluate the performance of CrackDet on oriented crack detection, in terms of Precision and Recall. Moreover, we adopt the mean orientation error (MOE) to verify the effec-

Method	ONPP			ORC		
	Precision \uparrow	Recall \uparrow	MOE \downarrow	Precision \uparrow	Recall \uparrow	MOE \downarrow
FCrack-O ₂₀₂₀ [13]	0.7037	0.8263	0.2785	0.6631	0.8714	0.3397
ReCrack-O ₂₀₂₁ [50]	0.7506	0.6719	0.3987	0.7432	0.8254	0.3282
CABF-FCOS-O ₂₀₂₁ [69]	0.7893	0.8413	0.3263	0.7630	0.8851	0.3744
Y ³ Crack-O ₂₀₂₂ [31]	0.7134	0.7379	0.3350	0.7103	0.8514	0.3632
CenterCrack-O ₂₀₂₂ [51]	0.7226	0.6132	0.3574	0.7731	0.8102	0.3085
Yolo-ViT-O ₂₀₂₂ [54]	0.7766	0.8379	0.3503	0.7982	0.8461	0.2978
CrackDet	0.8204	0.9106	0.1680	0.8578	0.8926	0.1166

Table 1. Comparison with the state-of-the-art crack detectors on ONPP and ORC. MOE denotes the mean orientation error.

tiveness of the proposed method for estimating crack orientation. For the detection accuracy on the HRSC2016, we adopt the mean average precision (mAP) as an evaluation criterion, which is consistent with VOC2007 metrics.

4.2. Comparison with crack detection approaches

In this section, our method is compared to several baselines including state-of-the-art robust crack detection methods: FCrack uses Faster R-CNN to detect the crack patch [13], Y³Crack designs a intelligent system based on YOLO v3 for detecting crack [31], CenterCrack proposes a crack detection model by using CenterNet [51] , ReCrack utilizes the RetinaNet to find the crack in asphalt pavement [50], CABF-FCOS proposes a one-stage network that can detect various defects including crack [69]. Yolo-ViT applies the Transformer to YOLO v5 for crack detection [54]. Note that, all of these methods can not detect the orientation of cracks. For a fair comparison, we add a branch to these methods for the regression of crack orientation and denote them as FCrack-O, Y³Crack-O, CenterCrack-O, ReCrack-O, CABF-FCOS-O, and Yolo-ViT-O respectively. All experiments are independently carried out on ONPP and ORC datasets. Table 1 provides the performance of various approaches from our oriented sub-crack detection perspective for crack detection. Bold denotes the best results. It can be found that the proposed method compares favorably to other competitive crack detection approaches. For example, compared with the Yolo-ViT-O, the precision and recall of CrackDet are 0.8204 and 0.9106 while the Yolo-ViT-O only achieves 0.7766 and 0.8379 on ONPP dataset. For the ORC dataset, CrackDet brings performance gains over Yolo-ViT-O around 6.0% and 4.7% under the precision and recall metrics. Moreover, in terms of MOE metric, the proposed CrackDet achieves consistent improvements on all datasets. The results above together show the necessity that the boundary discontinuity problem and the ambiguities in orientation should be treated properly under the oriented sub-crack detection tasks.

4.3. Discussion on the segmentation-based methods

In this section, considering the detection-then-segmentation strategy in the real-world application [33, 35], we further verify that the proposed method can serve as a complement to segmentation-based methods. More specifically, for the pixel-level segmentation task, we replace the oriented box annotation with pixel-level annotation for the OCCSD dataset. Table 3 shows that the proposed method can improve the segmentation results, especially for the segmentation model with limited performance. The reason attributes that the proposed method can provide a more fine-grained localization, which can effectively promote the segmentation model being influenced by the noise background.

4.4. Comparison with oriented detection methods

To further validate our method, we conduct a series of experiments on both crack datasets and HRSC2016, and report quantitative results to verify the effectiveness of CrackDet. As CrackDet shows the purpose of detecting the oriented object, we compare it with existing state-of-the-art oriented detectors with the help of [74], including Oriented RepPoints [23], Oriented R-CNN [55], SASM [19], etc.

Results on oriented sub-crack detection. Table 2 provides the comparison results over the existing powerful oriented object detectors. We can observe that, first, our CrackDet outperforms the existing detectors by a large margin in terms of Precision. The reason is that the proposed piecewise angle definition can promote the proposed detector to take advantage of rotation-equivariant features and be free of the boundary discontinuity problem. Secondly, CrackDet yields significant and consistent improvement on all three datasets in terms of MOE metric. The reason can be explained as CrackDet can estimate the angle confidence with the help of the multi-branch architecture and MAR Loss. Thus, according to the corresponding angle confidence from each branch, the angle-based variance voting improves the angle estimation results.

Results on HRSC2016. For fairness, we follow the same settings in Oriented RepPoints [23], and report the results

Method	ONPP			ORC		
	Precision \uparrow	Recall \uparrow	MOE \downarrow	Precision \uparrow	Recall \uparrow	MOE \downarrow
CSL_ECCV'20 [60]	0.7309	0.8146	0.2633	0.7943	0.7437	0.3285
R ³ Det AAAI'21 [62]	0.7835	0.7433	0.2977	0.7697	0.7312	0.4280
S ² ANet TGRS'21 [15]	0.7773	0.7773	0.4133	0.7068	0.7868	0.4640
ReDet CVPR'21 [16]	0.7844	0.8059	0.2743	0.7191	0.8684	0.3335
Beyond Bounding-Box CVPR'21 [14]	0.7790	0.8468	0.3003	0.6076	0.9039	0.3441
Oriented R-CNN ICCV'21 [55]	0.8032	0.7355	0.2172	0.7087	0.7416	0.3470
GWD ICML'21 [63]	0.7169	0.7884	0.4401	0.7576	0.8632	0.3014
KLD NeurIPS'21 [65]	0.7466	0.6407	0.3446	0.7424	0.9076	0.2818
SASM AAAI'22 [19]	0.7416	0.8303	0.3062	0.7653	0.9038	0.3489
Oriented RepPoints CVPR'22 [23]	0.7880	0.8782	0.3008	0.7851	0.9101	0.3497
CrackDet	0.8204	0.9106	0.1680	0.8578	0.8926	0.1166

Table 2. We provide a detailed comparison over general oriented detection approaches on ONPP and ORC.

Precision \uparrow	Crackformer ICCV'21 [27]	JTFN ICCV'21 [10]	LIOT TIP'22 [45]
w/o CrackDet	0.781	0.754	0.803
w/ CrackDet	0.814	0.798	0.819

Table 3. Segmentation performance with CrackDet on OCCSD.

under the VOC2007 metric. Table 4 shows the comparison results. The proposed CrackDet achieves the best performance, even compared with strong FPN-based baselines. Such results further validate that the proposed CrackDet has the potential in more oriented object detection tasks.

Methods	Backbone	mAP ₅₀ (07) \uparrow
R ³ Det AAAI'21 [62]	R-101-FPN	89.26
R ³ Det-DCL CVPR'21 [58]	R-101-FPN	89.46
FPN-CSL ECCV'20 [60]	R-101-FPN	89.62
ReDet CVPR'21 [16]	Re-R-50	90.46
DAL AAAI'21 [32]	R-101-FPN	89.77
S ² A-Net TGRS'21 [15]	R-101-FPN	90.17
S ² A-Net-DHRec PAMI'22 [37]	R-101-FPN	90.22
Oriented R-CNN ICCV'21 [55]	R-50-FPN	90.40
Oriented RepPoints CVPR'22 [23]	R-50-FPN	90.38
CrackDet	ReED-R-50	90.60

Table 4. We report results on the HRSC2016 test set. mAP(07) denotes detection results under VOC2007 mAP metrics.

4.5. Ablation study

To examine the contribution of each component in our proposed detector: rotation-equivariant network, the number of valid ranges in the proposed piecewise angle definition, and MAR Loss, a series of ablation experiments are performed on ONPP and ORC datasets.

Evaluation on the rotation-equivariant network. As expected, CrackDet achieves better results by combining the rotation-equivariant network. Table 5 shows that it improves the precision, recall, and MOE by 0.91%, 1.5%, and 0.023 with the help of the rotation-equivariant network, respectively. The reason behind this effect is that rotation-

equivariant features extracted by the rotation-equivariant network are beneficial to size and angle regression within the proposed piecewise angle definition.

Methods	ONPP		
	Precision \uparrow	Recall \uparrow	MOE \downarrow
w/o Rotation-equivariant network [17]	0.8113	0.8952	0.1914
w/ Rotation-equivariant network	0.8204	0.9106	0.1680

Table 5. Performance comparisons of with- and without rotation-equivariant backbone on ONPP dataset.

Evaluation on the number of valid angle ranges. We study the effect of the number of valid angle ranges in our piecewise angle definition. For fairness, we do not add the factor $\sin(\theta)$ or $\cos(\theta)$ for all settings. Table 6 shows the results using one to five ranges. The corresponding results demonstrate that our four ranges definition improves over the single range (baseline) with a 0.14 decrease. As can be noticed, the five ranges do not bring further improvement over the four ranges. By considering the complexity and performance, we choose four ranges as the default setting.

Num	Valid Angle Ranges	MOE \downarrow
1	[0°, 180°)	0.33
2	[0°, 90°), [90°, 180°)	0.30
3	[0°, 60°), [60°, 120°), [120°, 180°)	0.21
4	[0°, 45°), [45°, 90°), [90°, 135°), [135°, 180°)	0.19
5	[0°, 36°), [36°, 72°), [72°, 108°), [108°, 144°), [144°, 180°)	0.22

Table 6. Results from the different number of ranges on ONPP.

Evaluation on MAR loss. It is to be expected that CrackDet combined with MAR Loss achieves consistent improvements on ONPP and ORC datasets, shown in Table 7. The reason is three-fold: (1) KL Loss may fail when two distributions do not have a non-negligible intersection. (2) By learning to estimate high variances for the ambiguous crack orientation during training, our model is able to learn confidence in predicting sub-crack orientation. (3) MAR Loss incorporates learning angle confidence which can potentially help the network to learn discriminative features. The

learned variances through our MAR Loss are interpretable (see Fig. 4). Our network will output higher variances for ambiguous crack orientation, which can be useful in judging the overall orientation in real-world applications [38].

Methods	ONPP			ORC		
	Precision \uparrow	Recall \uparrow	MOE \downarrow	Precision \uparrow	Recall \uparrow	MOE \downarrow
KL Loss [18]	0.7865	0.8718	0.2425	0.8149	0.8537	0.1986
MAR Loss	0.8204	0.9106	0.1680	0.8578	0.8926	0.1166

Table 7. Performance comparisons of MAR Loss and KL Loss.

5. Conclusion

In this work, by starting from a new perspective for crack detection, we propose CrackDet, a first-of-its-kind oriented sub-crack detector that overcomes the boundary discontinuity problem. Meanwhile, we propose the MAR loss to capture the ambiguities in crack orientation by combining CrackDet. The experiments demonstrate that our method outperforms state-of-the-art crack detectors and oriented detectors. On one hand, as we also construct three datasets for oriented sub-crack detection, this work should also give a direction to researchers for designing the crack detector from the oriented sub-crack detection perspective. On the other hand, it highlights the key drawback of existing perspectives of crack detection (i.e., a high labeling cost of pixel-level segmentation, and a coarse crack localization of patch-level classification and object-level detection). We believe this paper has the potential to inspire the following works: (1) multi-model learning [24, 25] for boosting the detection performance in a novel field with limited target data [21], (2) semi-supervised learning and active learning [9] to further alleviate its labeling cost in real-world applications, and (3) oriented sub-crack detection via horizontal annotations [66].

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