

Depthwise Nonlocal Module for Fast Salient Object Detection Using a Single Thread

Haofeng Li¹, Guanbin Li¹, *Member, IEEE*, Binbin Yang¹, Guanqi Chen¹,
Liang Lin¹, *Senior Member, IEEE*, and Yizhou Yu¹, *Fellow, IEEE*

Abstract—Recently, deep convolutional neural networks have achieved significant success in salient object detection. However, existing state-of-the-art methods require high-end GPUs to achieve real-time performance, which makes it hard to adapt to low cost or portable devices. Although generic network architectures have been proposed to speed up inference on mobile devices, they are tailored to the task of image classification or semantic segmentation, and struggle to capture intrachannel and interchannel correlations that are essential for contrast modeling in salient object detection. Motivated by the above observations, we design a new deep-learning algorithm for fast salient object detection. The proposed algorithm for the first time achieves competitive accuracy and high inference efficiency simultaneously with a single CPU thread. Specifically, we propose a novel depthwise nonlocal module (DNL), which implicitly models contrast via harvesting intrachannel and interchannel correlations in a self-attention manner. In addition, we introduce a depthwise nonlocal network architecture that incorporates both DNLs module and inverted residual blocks. The experimental results show that our proposed network attains very competitive accuracy on a wide range of salient object detection datasets while achieving state-of-the-art efficiency among all existing deep-learning-based algorithms.

Index Terms—Deep neural network, nonlocal module, salient object detection.

I. INTRODUCTION

SALIENT object detection, which aims to identify the most visually distinctive objects within an image, has been well studied. Developing an accurate salient object detection model benefits a series of applications, such as person reidentification [1], robotic control [2], object detection [3], visual

tracking [4], and content-aware image editing [5]. Salient object detection usually serves as a preprocessing component, which not only requires acceptable accuracy but also fast speed and small memory consumption on low-cost devices. Recent deep convolutional neural networks (CNNs) exhibit remarkable performance on many computer vision tasks including salient object detection, due to its strong fitting capacity. In particular, dense labeling methods, which make use of the fully convolutional network (FCN) architecture, enjoy high accuracy and efficiency offered by end-to-end training and inference. However, the acceleration of convolution operations is highly dependent on high-performance GPUs, which are typically not supported by mobile devices, embedded devices, and low-cost personal computers. Developing a deep-learning-based salient object detection algorithm, that achieves both fast inference and high-quality results using a single thread, remains a challenging task.

Generic low-cost deep network architectures have been proposed recently for mobile devices. Most of them replace conventional convolutional operators with a combination of depthwise separable convolutions and 1×1 convolutions. The inverted residual (IR) block [6] is one such neural-network module based on depthwise separable convolutions. For example, an IR block first expands the feature at each spatial position to a higher dimension, and then independently applies a convolution operation on each channel slice. Such methods demonstrate desired inference speed on CPUs but their prediction quality is far from satisfactory. The most essential reason behind this is that these lightweight methods directly discard correlation modeling at different channels and spatial positions. Such correlation can be taken as context information, which plays an important role in modeling coherence, contrast, and uniqueness for salient object detection. Simply borrowing the existing generic lightweight network architectures to salient object detection does obtain high efficiency, but their prediction accuracies are far from competitive.

Driven by the above insights, this article proposes a novel DNL module, and a fast salient object detection network framework based on the proposed module. This module aims at exploiting relationships among features located at different channel slices or positions. In contrast to traditional convolutional layers that take the vector across all channels at the same spatial position as a feature, the DNL module considers one column vector or row vector in the same channel as a feature unit, which is described as “depthwise.”

Manuscript received May 29, 2019; revised October 23, 2019; accepted January 18, 2020. Date of publication February 19, 2020; date of current version December 22, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61976250, Grant 61702565, and Grant U1811463, in part by the NSFC-Shenzhen Robotics Projects under Grant U1613211, in part by the Fundamental Research Funds for the Central Universities under Grant 18lgy63, and in part by the National High Level Talents Special Support Plan (Ten Thousand Talents Program). This article was recommended by Associate Editor H. Lu. (*Corresponding authors: Guanbin Li; Yizhou Yu.*)

Haofeng Li and Yizhou Yu are with the Department of Computer Science, University of Hong Kong, Hong Kong (e-mail: lhaof@foxmail.com; yizhouy@acm.org).

Guanbin Li, Binbin Yang, Guanqi Chen, and Liang Lin are with the School of Data and Computer Science, Sun Yat-sen University, Guangzhou 510006, China (e-mail: liguanbin@mail.sysu.edu.cn; yangbb3@mail2.sysu.edu.cn; chengq26@mail2.sysu.edu.cn; linliang@ieee.org).

Color versions of one or more figures in this article are available at <https://doi.org/10.1109/TCYB.2020.2969282>.

Digital Object Identifier 10.1109/TCYB.2020.2969282

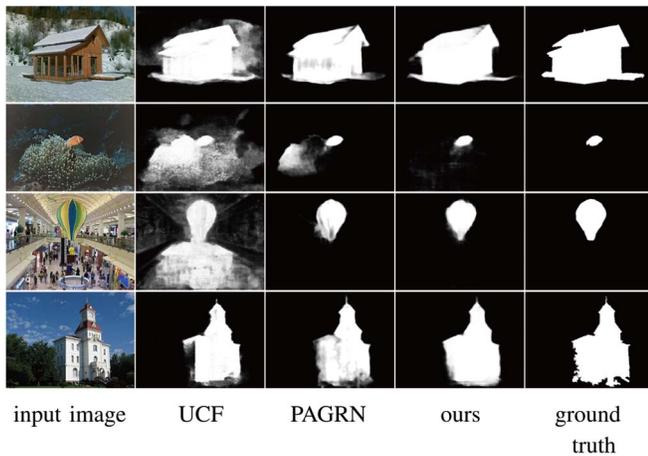


Fig. 1. Comparison among UCF [7], PAGRN [8], and our DNL algorithm. The proposed algorithm not only achieves practical inference time consumption using a single thread but also presents saliency maps of competitive quality.

The proposed module then learns an attention map via calculating pairwise similarity among nonlocal features within each subregion. From the resulting attention map, a feature residual is computed in a self-attention way to update the feature map.

Our proposed module has the following strengths. First, the DNL module overcomes the limitations of IR blocks by explicitly inferring correlations among features that are neither in the same channel nor in the same spatial position. Second, the depthwise nonlocal (DNL) module can implicitly model connectivity, contrast, and coherence for salient object detection. For example, if image parts are visually similar, their visual features have high attention scores. Thus, their salient features likely update each other and these image parts can be labeled with close saliency values. When a target feature is widely apart from other surrounding features in their latent space, the image region corresponding to the feature may have a different saliency value from other surrounding regions. Third, our proposed module segments an input feature map into subregions and only applies self-attention within each subregion, which lowers its computational cost. As a result, the proposed module adds a very small amount of computation while it considerably enhances the accuracy of a baseline.

This article has the following contributions:

- 1) We propose a novel DNL module, which aims at mining intrachannel and interchannel correlations in context. The proposed module enhances the fitting capacity of IR blocks at the cost of negligible extra inference time.
- 2) We present a fast depthwise nonlocal neural network, which not only demonstrates state-of-the-art inference speed with a single CPU thread but also attains competitive detection accuracy (as shown in Fig. 1) among deep-learning methods.
- 3) We have conducted extensive experiments, which verify the effectiveness and efficiency of the DNL module and the proposed network framework.

II. RELATED WORK

A. Salient Object Detection

Salient object detection can be solved by computing a saliency map with prior knowledge and handcrafted features [9]–[16], or training a deep-learning model for prediction [17]–[29]. MBS [12] exploits the cue that background regions are usually connected to the image boundaries, by computing an approximate minimum barrier distance transform. MST [13] employs similar prior knowledge with MBS, but computes an exact distance transform with a minimum spanning tree to measure boundary connectivity. MDC [14] suggests that background pixels display low contrast in at least 1-D and proposes minimum directional contrast as raw saliency for each pixel. Priors-based methods enjoy real-time efficiency but cannot attain state-of-the-art results. Deep-learning-based salient object detection models can be roughly divided into two groups, including sparse and dense labeling. MDF [17] employs deep CNNs to extract multiscale features and predict saliency values for image segments of different levels. Zeng *et al.* [30] formulated saliency detection as a non-cooperative game, where image regions as players choose to be foreground or background. Zhang *et al.* [31] converted an image into a sparsely connected graph of regions and computed saliency via an absorbing Markov chain. Qin *et al.* [26] developed a single-layer cellular automata (SCA) that can utilize the intrinsic correlations of similar image patches to locate salient objects, based on deep-learning features. These sparse labeling methods require dividing an input image into hundreds of segments and estimating the saliency value for each segment, which is not efficient for real-time applications. To name a few dense labeling methods, DSS [32] introduces a series of side output layers and short connections to combine the advantages of low-level and high-level features. PAGRN [8] is a progressive attention-driven framework based on multipath recurrent feedback. Wang *et al.* [33] proposed a global recurrent localization network to locate salient objects, and a local boundary refinement network to capture pixel relations. Liu *et al.* [34] integrated a global guidance module and a feature aggregation module into a U-shape architecture.

B. Fast Convolutional Neural Network

Designing efficient and lightweight neural networks [35]–[43] has recently become popular in the community. Han *et al.* [36] proposed a network pruning pipeline that is first trained to learn which connections are important, and then discards the unimportant connections. Factorized CNNs [41] unravel the 3-D convolution operation in a convolution layer as spatial convolutions in each channel and a linear projection across channels, to reduce the computation. He *et al.* [42] introduced a channel pruning method which alternatively selects the most representative channels based on a LASSO regression and reconstructed the output feature maps with linear least squares. ShuffleNet [43] proposes a pointwise group convolution that separates convolution filters into groups, and “channel shuffle” that permutes the channels in a group. MobileNetV2 [6] utilizes an IR structure that consists of two pointwise convolutions and a depthwise separable

convolution. Some existing state-of-the-art fast deep neural networks employ depthwise separable convolutions that are lightweight but lack intrachannel and interchannel correlations mining.

C. Self-Attention and Nonlocal Modeling

Computational models that exploit pairwise similarities as self-attention scores among dense positions or nodes within some nonlocal regions, have been widely studied in the field of natural language processing and computer vision [44]–[52]. The self-attention model for machine translation [50] learns a feature for some nodes by attending to all other nodes in the same sequence and taking the weighted summation of their embedded features in some latent space. Nonlocal means algorithm [45] denoises an image by replacing a pixel with a nonlocal averaging of all pixels in the image. The nonlocal averaging utilizes similarity between pixels as weights. Block-matching 3-D (BM3D) [53] applies collaborative filtering on a group of similar nonlocal image patches and achieves competitive image denoising results, even compared to deep-learning-based methods. Efros and Leung [47] synthesized texture by growing one pixel at a time. They determined pixel value by locating all image patches matching with the target position to fill. The dense conditional random field (CRF) [48] models long-range dependencies by introducing a pairwise energy term that is weighted by the similarity of two nodes. Li *et al.* [54] proposed a nonlocally enhanced encoder–decoder network which can learn more accurate features for rain streaks and preserve better image details during de-raining. Besides from low-level tasks, Wang *et al.* [51] proposed a nonlocal neural network that can harvest long-range spatiotemporal relations for high-level problems such as video classifications. Such models can learn features from long-range dependencies that are potential to model contrast and coherency in salient object detection. Most existing nonlocal models work in the spatial dimensions of images or the spatiotemporal dimensions of videos.

III. METHOD

A. Depthwise Nonlocal Module

In this section, we introduce a novel DNL module, that efficiently enhances IR blocks with channel-wise coherence and contrast learning. IR is an efficient neural network block built on top of depthwise separable convolutions. In the following text, we briefly review IR blocks and depthwise separable convolutions as preliminaries. Let I be a $C \times H \times W$ input feature map. C , H , and W denote the channel number (depth), the height, and the width of I respectively. k , i , and j are used as the indices of depth, height, and width, respectively. For example, $I_{i,j}$ is a vector of length C and $I_{k,i}$ has W elements. Consider a regular $K \times K$ convolution layer with C output channels. Its total number of weights is $CK^2 \times C$. The time complexity of applying convolution at one position is C^2K^2 . As for a depthwise separable convolution layer with C output channels, it has C independent convolution kernels, each of which has a total of $K^2 \times 1$ weights. Performing depthwise separable convolution at one position costs CK^2 . As shown in

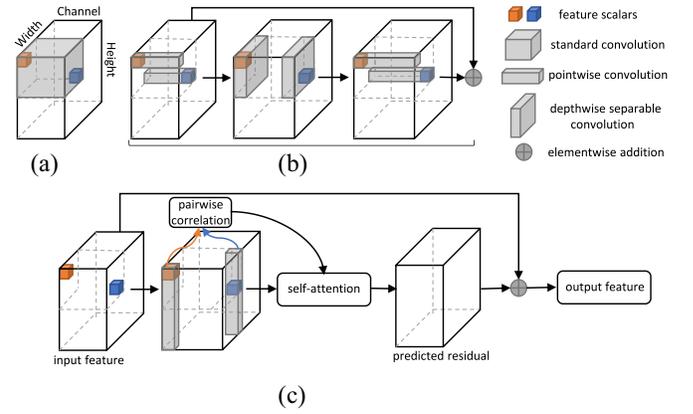


Fig. 2. (a) Standard Convolution. (b) IR. Before the elementwise addition in IR, the shapes of the two feature maps are aligned with each other. Note that the correlation of two spatially close scalars (in orange and blue colors, respectively) is not directly captured in an IR, while a standard convolution can predict outputs based on them together. (c) Our proposed DNL module. The proposed module can capture the correlation between two feature vectors, which are located at different channels and spatial positions.

Fig. 2(b), an IR block consists of a 1×1 convolution, a depthwise convolution, and another 1×1 convolution. These two 1×1 convolutions aim at aggregating features across channels. However, for a pair of positions (the orange and blue feature scalars in Fig. 2), $I_{k,i,j}$ and $I_{k',i',j'}$ ($k \neq k'$ and $(i,j) \neq (i',j')$), their correlation cannot be directly captured by the depthwise separable convolution or the pointwise 1×1 convolutions even when they are located within each other's neighborhood.

To efficiently harvest intrachannel correlations, the DNL module considers $I_{k,i}$ or $I_{k,j}$ [shown in Fig. 4(b)] rather than $I_{i,j}$ [shown in Fig. 4(a)] as a feature vector. $I_{k,i}$ and $I_{k,j}$ represent some features of their corresponding horizontal and vertical image region, respectively. The proposed module is a residual block with two possible types of residual layers. One type of layer is called vertical or *vertical-split* layer and the other is horizontal or *horizontal-split* layer. In a vertical-split layer, we take $I_{k,j}$ as a feature vector. In a horizontal-split layer, $I_{k,i}$ is taken as a feature vector. These two types of layers are designed in a similar and symmetric way.

In the vertical-split layer shown in Fig. 3, the input feature map can be seen as $C \times W$ feature vectors and each vector has H elements. To exploit cross-channel features, we first compute an attention map by measuring pairwise similarities among these CW vectors. Thus, the attention map A is of size $CW \times CW$. Consider two arbitrary features, $I_{k,j}$ and $I_{k',j'}$, whose indices in the attention map are p and q . Their attention score can be calculated in a bilinear form

$$A_{p,q} = I_{k,j}^T U_\theta^T V_\phi I_{k',j'} \quad (1)$$

where U_θ and V_ϕ are two learnable matrices of two embedding layers θ and ϕ . The size of U_θ and V_ϕ is $H^A \times H$. The bilinear form can be seen as mapping $I_{k,j}$ and $I_{k',j'}$ into a latent space R^{H^A} by linear transformations, and then computing the dot product between the transformed features as similarity. Importantly, we discuss whether all $C \times W$ feature vectors share the same transform matrix U_θ as follows: $I_{k,j}$ with the same k but different j , which denotes different spatial region

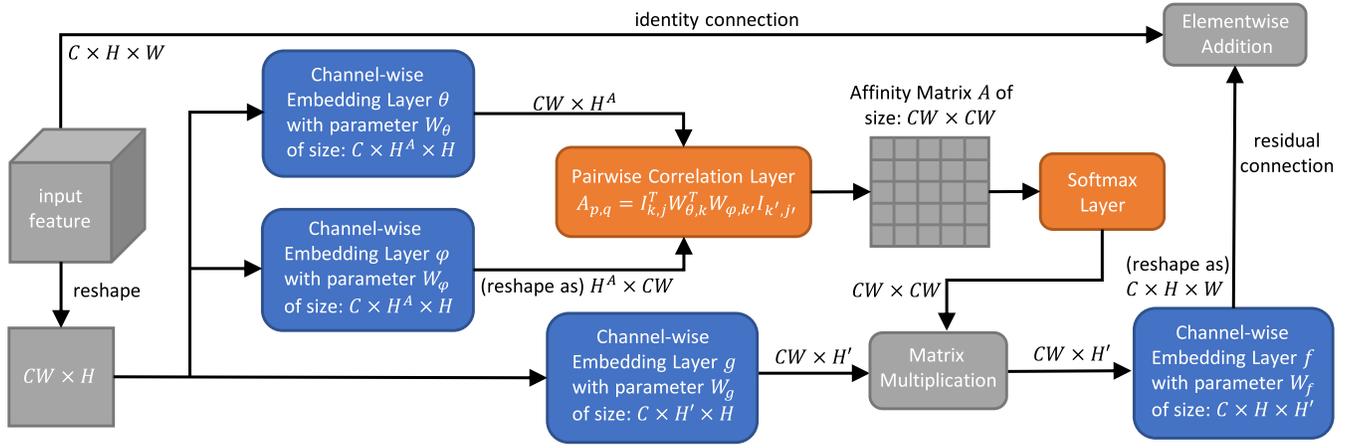


Fig. 3. Vanilla DNL module (vertical-split). The proposed module contains four channel-wise embedding layers, a pairwise correlation layer, and a softmax layer. The softmax layer normalizes each row of the affinity matrix A . The matrix multiplication serves as taking the weighted summation of the output of layer g , with the softmax output as attention weights.

within the same latent space, can share the same transform matrix. $I_{k,j}$ with different k should not utilize the same transform matrix, since different k implies different latent space. Thus, only feature vectors with the same channel share the same parameter U_θ . Since layers θ and ϕ embed different channels of an input feature with different weights, we name θ and ϕ as a “channel-wise embedding layer” as displayed in Fig. 3. We reformulate the bilinear form (shown as “pairwise correlation” in Fig. 3) in the following equation:

$$A_{p,q} = I_{k,j}^T W_{\theta,k}^T W_{\phi,k'} I_{k',j'} \quad (2)$$

where W_θ and W_ϕ are $C \times H^A \times H$ matrices. $W_{\theta,k}$ and $W_{\phi,k'}$ are $H^A \times H$ matrices corresponding to U_θ and V_ϕ . We claim that the above attention model is promising in modeling contrast and connectivity for salient object detection. Small $A_{p,q}$ indicates high contrast between $I_{k,j}$ and $I_{k',j'}$. If $I_{k,j}$ and $I_{k',j'}$ are spatially close to each other, large $A_{p,q}$ suggests that their corresponding regions are connected in the saliency map.

To leverage these cues, we conceive a strategy to propagate contrast information or saliency value from $I_{k',j'}$ to $I_{k,j}$, according to their correlation. The strategy learns a feature residual by taking attention weighted transformation of the feature map

$$\tilde{I} = f(\text{softmax}(A)g(I)) \quad (3)$$

where \tilde{I} denotes the above-mentioned feature residual. $\text{softmax}(\cdot)$ normalizes each row of matrix A . $g(\cdot)$ denotes a transformation of the input feature map I . As defined below, $g(\cdot)$ adopts linear transformations with different parameters for different channels of I . Let $g(I) = [I_1^T W_{g,1}, \dots, I_k^T W_{g,k}, \dots, I_C^T W_{g,C}]$, where I_k is an $H \times W$ matrix representing the k th channel of feature map I , $W_{g,k}$ is an $H \times H'$ matrix representing the linear transformation for the k th channel of the feature map, and $[\cdot]$ denotes the concatenation along the first dimension. Thus, $g(I)$ is a $CW \times H'$ matrix. $\text{softmax}(A)g(I)$ is an attention weighted linear transformation of $g(I)$, shown as “matrix multiplication” in Fig. 3. Since the size of $\text{softmax}(A)g(I)$ is $CW \times H'$, another transformation f is required to map it into the R^H space. Let $y = \text{softmax}(A)g(I)$. Then

$f(y) = [(y_1 W_{f,1})^T, \dots, (y_k W_{f,k})^T, \dots, (y_C W_{f,C})^T]$, where y is a $CW \times H'$ matrix, and y is reshaped into a $C \times W \times H'$ tensor before $f(\cdot)$ is applied, W_f is a $C \times H' \times H$ tensor, and $f(y)$ is a $CH \times W$ matrix. Finally, $f(y)$ is reshaped into a $C \times H \times W$ residual tensor \tilde{I} , and I is updated by adding the residual tensor and I together. The output of DNL modules is calculated as $O = I + \tilde{I} = I + f(y)$, where O represents the output feature map, and the reshaping operators are omitted.

The horizontal-split layer is a symmetric form of the vertical-split layer. We simply summarize its process and describe the differences from the vertical one

$$A_{p,q} = I_{k,i}^T W_{\theta,k}^T W_{\phi,k'} I_{k',i'} \quad (4)$$

$$g(I) = [I_1 W_{g,1}, \dots, I_k W_{g,k}, \dots, I_C W_{g,C}] \quad (5)$$

$$O = I + [y_1 W_{f,1}, \dots, y_k W_{f,k}, \dots, y_C W_{f,C}] \quad (6)$$

where the size of attention map A is $CH \times CH$, and $A_{p,q}$ denotes pairwise similarity between two arbitrary features $I_{k,i}$ and $I_{k',i'}$ ($1 \leq k, k' \leq C$, $1 \leq i, i' \leq H$), whose indices in the attention map A are p and q . $I_{k,i}$ is a feature vector of length W . W_θ , W_ϕ , W_g , and W_f are $C \times W^A \times W$, $C \times W^A \times W$, $C \times W \times W'$, and $C \times W' \times W$ tensors, respectively. y is computed in the same way as in the vertical-split layer, and is reshaped into a $C \times H \times W'$ tensor before f is applied. $f(y)$ is converted to a $C \times H \times W$ tensor before I is updated. Note that all channel-wise embedding layers, θ , ϕ , $g(\cdot)$, and $f(\cdot)$, have bias parameters. For example, $y_k W_{f,k}$ should actually be $[y_k^{*T}, 1]^T [W_{f,k}^*, B_{f,k}]$. For simplicity, all bias terms have been omitted in the above formulations.

B. Divide-and-Conquer

In this section, we accelerate the naive DNL module by dividing an input feature map into multiple subtensors. A few rationales support the divide-and-conquer strategy. First, the naive DNL module computes dense pairwise similarities, which is too computationally expensive for a fast neural-network module. Second, the divide-and-conquer strategy still maintains spatial coherence in the resulting saliency map. If there is a strong similarity between spatially adjacent features,

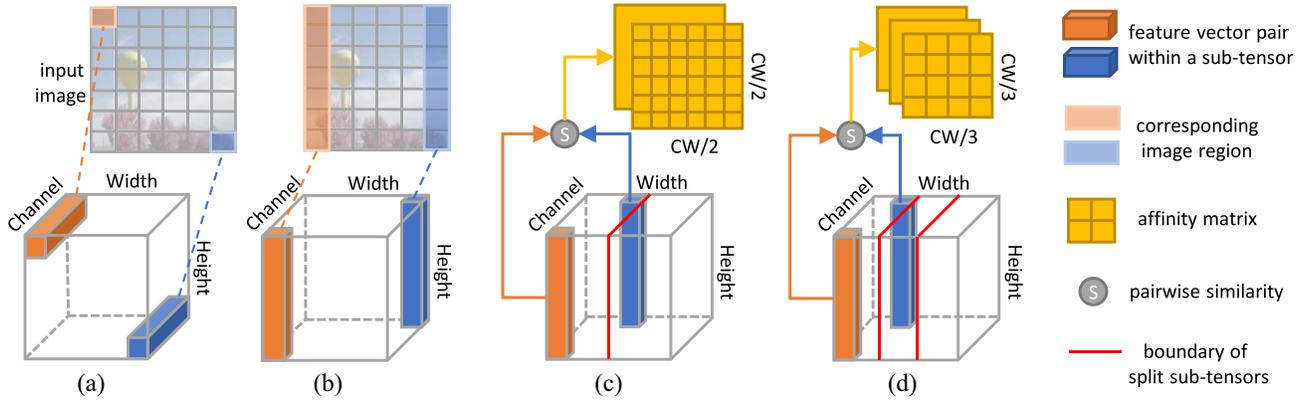


Fig. 4. (a) Vanilla (spatial) nonlocal module. (b) Vanilla DNL module (vertical-split). (c) Divide-and-conquer DNL module (vertical-split, split number, $s = 2$). (d) Split number, $s = 3$. Dense pairwise similarity is computed between each pair of feature vectors (the orange bar and the blue bar) within the same region/subregion. In (c), the $C \times W$ plane is split into two subregions.

it is most likely that these two features or segments belong to the same object. Propagating saliency values between such pairs of features can likely improve the accuracy of saliency prediction. In the naive vertical-split DNL module, all pairs of feature vectors on the $C \times W$ plane are used to measure similarity, as shown in Fig. 4(b). For the divide-and-conquer DNL shown in Fig. 4(c), the feature tensor is divided into two sub-tensors, and vector pairs are only sampled from the same sub-tensor. For each sub-tensor, a smaller affinity matrix is obtained by calculating the pairwise correlation. The softmax operation is separately applied for each affinity matrix. Different sub-tensors still share the same W_θ and W_ϕ . The number of sub-tensors is controlled by split number s .

C. Complexity Analysis

In this section, we analyze the space and time complexities of the vanilla DNL module and its divide-and-conquer version. This analysis can help us determine the values of hyperparameters and the location of the proposed module in our network architecture.

Let us first discuss the space complexity of a vanilla DNL module. We assume that all variables are released after inference. Only parameters and intermediate variables are considered. The size of W_θ , W_ϕ , W_g , and W_f in a vertical-split layer is, respectively, $C \times H^A \times H$, $C \times H^A \times H$, $C \times H \times H'$, and $C \times H' \times H$ while their size is $C \times W^A \times W$, $C \times W^A \times W$, $C \times W \times W'$, and $C \times W' \times W$ in a horizontal-split layer. Without taking bias terms into account, the total number of parameters is $2C(H(H^A + H') + W(W^A + W'))$. The size of intermediate variables A , $g(I)$, y , and \tilde{I} is, respectively, $CW \times CW$, $CW \times W'$, $CW \times W'$, and $C \times H \times W$ in a vertical layer. In a horizontal one, their size is $CH \times CH$, $CH \times H'$, $CH \times H'$, and $C \times H \times W$. The space complexity of intermediate variables is $C^2(H^2 + W^2) + 2C(HH' + HW + WW')$. The space complexity of a DNL module is $\mathcal{O}(C^2(H^2 + W^2))$.

For time complexity, we count the number of multiplications and additions (MAdds). In a vertical-split layer, applying transformations W_θ and W_ϕ costs $CWHH^A$ while computing pairwise similarity costs $C^2W^2H^A$. The time complexity of $\text{softmax}(\cdot)$, $g(\cdot)$, $f(\cdot)$, and $\text{softmax}(A)g(I)$ is, respectively,

TABLE I
COMPLEXITY OF VANILLA DNL MODULE AND ITS
DIVIDE-AND-CONQUER VARIANT

Complexity	Vanilla	Divide-and-Conquer
Space	$\mathcal{O}(C^2(H^2 + W^2))$	$\mathcal{O}(\frac{1}{s}C^2(H^2 + W^2))$
Time	$\mathcal{O}(C^2HW(H + W))$	$\mathcal{O}(\frac{1}{s}C^2HW(H + W))$

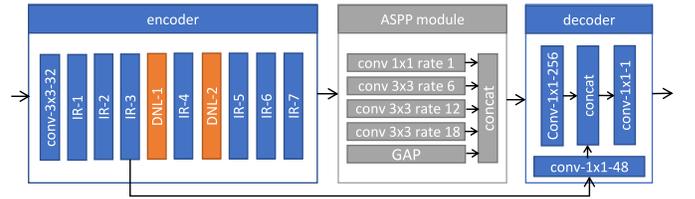


Fig. 5. Depthwise nonlocal deep neural network. As shown in the above, IR denotes the IR module while DNL denotes the DNL module. “Rate” refers to the dilation rate of a convolution. GAP denotes global average pooling.

C^2W^2 , $CWHH'$, $CWHH'$, and C^2W^2H' . In a horizontal-split layer, computing A costs $2CHWW^A + C^2H^2W^A$. The time complexity of $\text{softmax}(\cdot)$, $g(\cdot)$, $f(\cdot)$, and $\text{softmax}(A)g(I)$ is, respectively, C^2H^2 , $CHWW'$, $CHWW'$, and C^2H^2W' . The total number of MAdds is $C^2W^2(H^A + H' + 1) + C^2H^2(W^A + W' + 1) + 2CHW(H^A + H' + W^A + W')$. The time complexity of the proposed module is $\mathcal{O}(C^2HW(H + W))$.

Next, we analyze the computational cost of a divide-and-conquer DNL module, which is summarized in Table I. Its space complexity is reduced by a factor of s since the size of A becomes $(1/s)C^2W^2$ in a vertical layer and $(1/s)C^2H^2$ in a horizontal layer. As for time complexity, computing attention scores in a vertical-split layer costs $2CWHH^A + s(CW/s)^2H^A$. The time complexity of $\text{softmax}(\cdot)$, $g(\cdot)$, $f(\cdot)$, and $\text{softmax}(A)g(I)$ is, respectively, $[(C^2W^2)/s]$, $CWHH'$, $CWHH'$, and $s(CW/s)^2H'$. The computation in a vertical-split layer costs $(1/s)C^2W^2(H^A + H' + 1) + 2CHW(H^A + H')$ and a horizontal-split layer $(1/s)C^2H^2(W^A + W' + 1) + 2CHW(W^A + W')$. The time complexity of the accelerated variant is $\mathcal{O}([1/s]C^2HW(H + W))$. Note that H^A/H' and W^A/W' are set as $H/2$ and $W/2$, respectively, in our implementation.

D. Model Architecture

In this section, we develop a depthwise nonlocal neural network based on our proposed module. The proposed network consists of an encoder, an atrous spatial pyramid pooling (ASPP) module [55], and a decoder, as shown in Fig. 5. The encoder contains seven IR modules, two DNL modules, and several regular convolution layers. Each IR module consists of one or multiple IR blocks. The hyperparameters of these above-mentioned IR modules follow the setting in [6].

Our proposed DNL modules are located between some of the IR modules to strengthen nonlocal correlations among all feature map channels. Since the computational complexity of the proposed module grows quadratically with respect to the number of channels and cubically with respect to the spatial resolution of the input feature map, we place the proposed module at the middle levels of the network. The first DNL module is placed behind the third IR module. The second one is inserted after the fourth IR module. After the third IR module, the feature map has shrunk to the smallest spatial size, 1/8 of the original image size, while the number of channels is still reasonably small. Thus, positioning the proposed modules at middle levels helps lower the computational cost incurred by these modules. Theoretically, DNL modules can be placed at any position of a backbone network. How the position of a DNL module affect its performance and efficiency is investigated in Section IV-C.

The ASPP module in Fig. 5 concatenates the feature maps produced from the five parallel layers along the depth dimension. These five parallel layers are, respectively, a 1×1 pointwise convolution, three dilated 3×3 convolutions, and an image pooling layer. The dilation rates of the three atrous convolutions are 6, 12, and 18, respectively. All of these five parallel layers produce 256-channel feature maps. The image pooling layer consists of a global spatial averaging sublayer and a pointwise convolution that converts the number of output channels to 256. The ASPP module produces a 1280-channel feature map. The decoder takes the output of both the ASPP module and the third IR module as a combination of high-level and low-level inputs. The decoder reduces the number of channels in the high-level input to 256 while increasing the number of channels in the low-level input to 48 using pointwise convolutions following a 2-D batch normalization layer. Finally, the low-level and high-level features are concatenated to predict a dense saliency map via a 1×1 convolution.

IV. EXPERIMENTS

In the experiment section, salient object detection methods are tested on DUT-OMRON [56], ECSSD [57], HKU-IS [58] test set, PASCAL-S [59], and DUTS [60]. All the above datasets provide dense pixel-level annotations. DUT-OMRON contains 5168 challenging images which have one or more salient objects. ECSSD has 1000 images. HKU-IS includes a train set of 2500 images, a validation set of 500 images, and a test set of 1447 images. PASCAL-S consists of 850 images. Threshold is chosen as 0.5 to binarize masks of PASCAL-S, as suggested in [59]. Note that all salient object detection models are not trained on any subsets of DUT-OMRON and all 5168

images are utilized as testing samples. Thus, DUT-OMRON is a challenging benchmark that can reveal the generalization capability of a salient object detection model. HKU-IS is another challenging dataset in which many images contain multiple ground-truth objects. Our proposed method is trained with 5000 images from the MSRA-B train set and the HKU-IS train set. The optimization algorithm is SGD with weight decay $5e-4$, momentum 0.9, and initial learning rate $1e-7$. We adopt poly policy with power 0.9 to tune the learning rate. The proposed network is trained for 300 epochs. Pytorch 0.4.1 with MKL backend is used for all deep-learning methods. For the methods whose released model is not trained with Pytorch, their model weights are copied to an implementation of Pytorch. For fair comparisons, the efficiency of the mentioned salient object detection algorithms is evaluated on the same personal computer, which has an Intel i7-6850k CPU with 3.60-GHz base frequency, a GeForce GTX 1080 Ti GPU, and 32-GB memory.

A. Comparison on Quality of Saliency Maps

To evaluate the quality of saliency maps, we adopt maximum F -measure (maxF) [61], mean absolute error (MAE), and structure-measure [62] (S-m) as criteria. To compute maxF, we first sample a list of thresholds. Given a threshold, the average of precision and recall is computed for all saliency predictions in a dataset. Then, F_β is defined as

$$F_\beta = \frac{(1 + \beta^2) \cdot \text{Precision} \cdot \text{Recall}}{\beta^2 \cdot \text{Precision} + \text{Recall}} \quad (7)$$

where β controls the relative importance between precision and recall. β^2 is selected as 0.3, according to [61]. MAE is computed as the average of pixel-level absolute difference between predictions and ground-truth annotations, as shown in

$$\text{MAE} = \frac{1}{HW} \sum_{h=1}^H \sum_{w=1}^W |P_{h,w} - G_{h,w}| \quad (8)$$

where P denotes a binarized saliency prediction and G denotes its corresponding binary ground truth. H and W are height and width of images. h and w are the corresponding indices. Different from estimating pixelwise errors, S-measure, recently proposed in [62], is adopted to estimate structural similarity between predictions and ground truth. It is defined as a weighted sum of an object-aware measure and a region-aware measure. Formal definition of S-m can be found in [62].

As shown in Table II and Fig. 6, the proposed DNL network is compared with existing salient object detection models, RAS [27], PAGRN [8], UCF [7], NLDF [22], DSS [32], RFCN [23], DCL [63], DS [20], MDF [58], and two generic lightweight architectures originally proposed for image classification and semantic segmentation, including MobileNet-V2 [6] and ShuffleNet [43]. As suggested in [6], MobileNet-V2 serves as an encoder integrated with a DeepLab-V3+ architecture [55] to solve semantic segmentation tasks. To detect salient objects, the output channels of the last convolution in DeepLab-V3+ is adjusted to 1. Similar to MobileNet-V2, ShuffleNet is also modified as an encoder with DeepLab-V3+. We fine-tune these two generic

TABLE II
COMPARISON AMONG THE STATE-OF-THE-ART AND OURS. * METHODS ARE ORIGINALLY
PROPOSED FOR IMAGE CLASSIFICATIONS AND SEGMENTATIONS

	DUT-OMRON			ECSSD			HKU-IS			PASCAL-S			DUTS		
	maxF	MAE	S-m	maxF	MAE	S-m	maxF	MAE	S-m	maxF	MAE	S-m	maxF	MAE	S-m
RAS	0.7848	0.0633	0.8119	0.9203	0.0551	0.8935	0.9116	0.0449	0.8875	0.8319	0.1021	0.7978	0.8310	0.0591	0.8281
PAGR _N	0.7709	0.0709	0.7751	0.9268	0.0609	0.8892	0.9187	0.0475	0.8891	0.8531	0.0921	0.8190	0.8541	0.0549	0.8254
UCF	0.7365	0.1318	0.7578	0.9097	0.0790	0.8816	0.8866	0.0749	0.8643	0.8217	0.1292	0.7999	0.7700	0.1178	0.7710
NLDF	0.7532	0.0796	0.7704	0.9050	0.0626	0.8747	0.9017	0.0480	0.8782	0.8278	0.0990	0.8036	0.8156	0.0649	0.8052
DSS	0.7604	0.0744	0.7892	0.9078	0.0620	0.8836	0.9005	0.0499	0.8805	0.8262	0.1029	0.8025	0.8130	0.0647	0.8168
RFCN	0.7332	0.0782	0.7503	0.8867	0.0765	0.8368	0.8832	0.0572	0.8361	0.8284	0.0996	0.7895	0.7702	0.0744	0.7506
DCL	0.7260	0.0944	0.7498	0.8884	0.0717	0.8672	0.8823	0.0584	0.8650	0.8053	0.1092	0.7930	0.7756	0.0787	0.7859
DS	0.7449	0.1204	0.7502	0.8824	0.1217	0.8206	0.8661	0.0791	0.8531	0.8109	0.1472	0.7715	0.7756	0.0894	0.7916
MDF	0.6944	0.0916	0.7208	0.8316	0.1050	0.7761	0.8605	0.1291	0.8101	0.7655	0.1451	0.6935	0.7285	0.0995	0.7232
*MobileNetV2	0.7446	0.0871	0.7595	0.8901	0.0737	0.8614	0.8979	0.0537	0.8756	0.7716	0.1318	0.7592	0.7613	0.0806	0.7720
*ShuffleNet	0.7300	0.0946	0.7506	0.8763	0.0830	0.8443	0.8914	0.0558	0.8701	0.7856	0.1216	0.7709	0.7698	0.0845	0.7740
ours	0.7795	0.0779	0.7981	0.9096	0.0646	0.8851	0.9133	0.0451	0.8974	0.8229	0.1065	0.8031	0.8081	0.0731	0.8071

frameworks with our training data for saliency prediction. The proposed method significantly outperforms MobileNet-V2 and ShuffleNet on all four benchmarks and three criteria since they fail to capture the contrast as well as the channel-wise coherence information which is essential for saliency inference. Our proposed model obtains the second best maxF of 0.7795 and the best S-measure of 0.7981 on the large and challenging dataset DUT-OMRON. The DNL network outperforms the third best PAGR_N by 0.9% maxF and DSS by 0.9% S-measure. Noted that our method is not trained on any subsets of DUT-OMRON but tested on the all 5168 images, which suggests that the DNL network possesses strong generalization capability to achieve stable performance in real applications. The proposed DNL network presents the second best maxF, the second smallest MAE, and the best S-measure on the HKU-IS dataset. Particularly, the proposed method surpasses the second best PAGR_N by 0.8% S-measure. Our proposed method shows the best results on two challenging benchmarks DUT-OMRON and HKU-IS, which indicates that the proposed network enjoys superior generalization and is comparable to the state-of-the-arts.

B. Comparison on Efficiency

To evaluate the efficiency of the proposed methods and existing neural-network models, this section utilizes CPU time, GPU time, memory usage (denoted as Mem), number of parameters (denoted as Params), MAdds [6], and time complexity as criteria. CPU time is computed using a single CPU thread while GPU time is measured with a single GPU. Batch size is set as 1 for all neural models. Time cost by file input/output is not included but time-consuming pre-processings, such as computing prior maps and superpixel segmentation are taken into accounts. Each model sequentially infers 50 randomly selected images from HKU-IS. The peak memory cost during inference is logged as the memory usage. Params is the number of learnable parameters in a neural model and it determines the disk space consumed. MAdds is the number of MAdds, calculated by setting the input size of each method as its default size. Time

TABLE III
EFFICIENCY OF THE STATE-OF-THE-ART AND OURS

	CPUTime /secs	GPUTime /secs	Mem /MB	Params /M	MAdds /B	Complexity /HW
RAS	2.0457	0.0355	5023	20.23	54.56	421.0K
PAGR _N	—	—	—	23.63	100.4	805.8K
UCF	3.4696	0.0886	5307	29.43	123.3	614.4K
NLDF	2.6051	0.0340	1709	35.48	354.6	2863K
DSS	3.4451	0.0339	1587	62.22	127.5	984.0K
RFCN	2.7190	0.0691	4833	53.00	113.9	455.7K
DCL	2.5820	0.0867	4069	66.31	797.6	3031K
DS	2.4588	0.0609	4799	50.37	106.7	426.7K
MDF	897.68	24.996	1591	75.68	7533	149.9M
ours	0.3993	0.0113	605	5.320	9.567	73.82K

complexity denoted as “Complexity” in Table III is the number of MAdds with respect to input size that is viewed as variables H and W .

As shown in Table III, MB denotes million bytes. K, M, and B denote thousands, millions, and billions, respectively. HW represents the product of input height and width. Since the implementation of PAGR_N is not available, we only present its theoretical efficiency, including parameters, MAdds, and time complexity. Most existing CNN-based methods predict a saliency map with more than 2.5 s on CPU while our proposed network takes less than 0.4 s to infer an image. Achieving the fastest CPU inference, our method is 5× faster than the second best RAS. The proposed method also demonstrates the most efficient inference with GPU, and it is 3× faster than the second best DSS. Most methods use 1500–5000-MB memory during inference, which is too expensive for a pre-processing component. Meanwhile, our proposed method costs 600-MB running memory, less than 40% of the second best. Besides, our proposed method has the least parameters, less than 25% of the second least. Most models consume more than 100-MB storage while our method only costs about 20 MB. Our proposed method obtains the minimum MAdds less than 20% of the second best. The time complexity of the DNL network is also the lowest and six times less than the second lowest RAS. Note that the time complexity of DNL modules actually contains terms with respect to $HW(H + W)$.

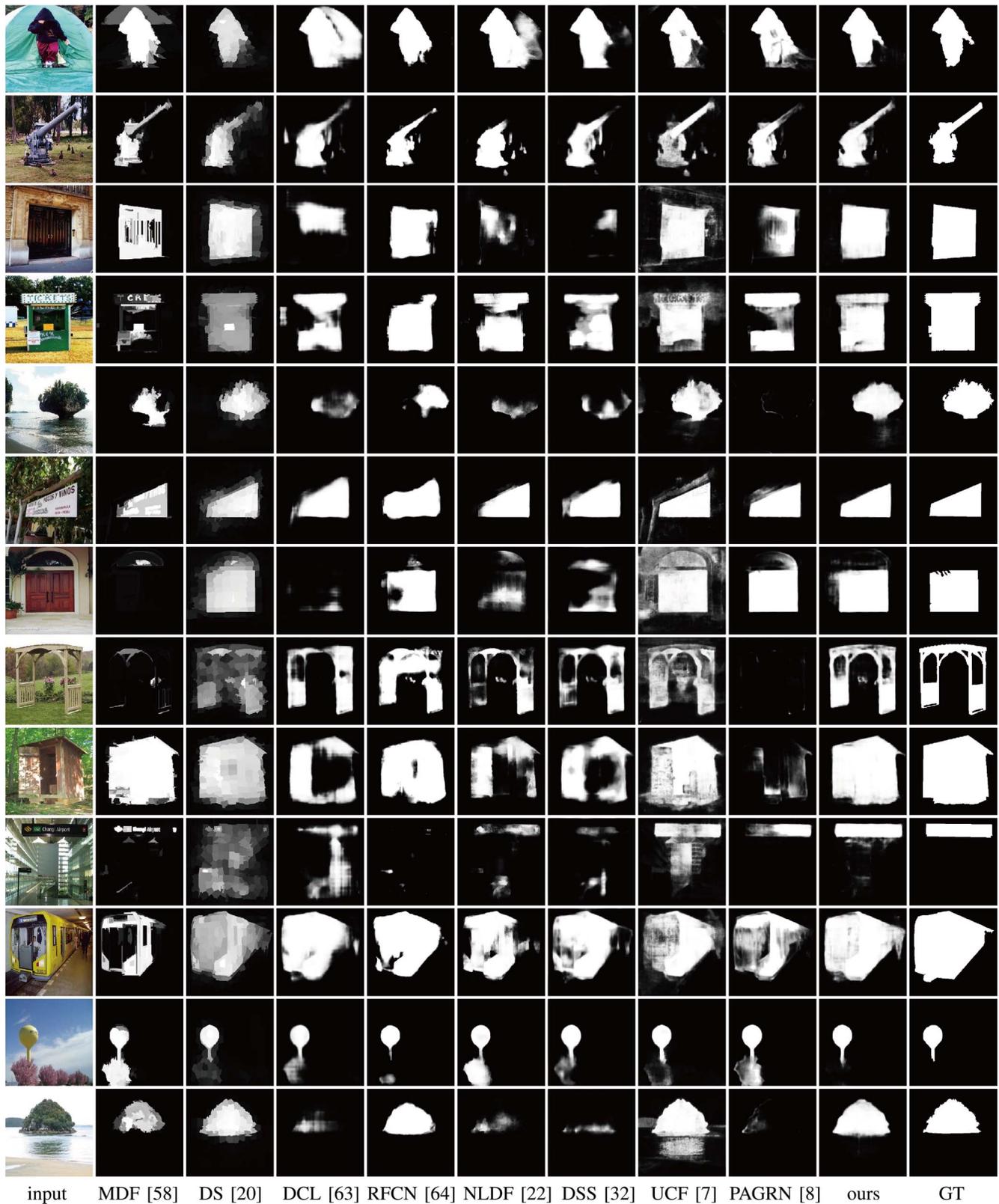


Fig. 6. Qualitative comparison among the state-of-the-art and ours. As shown in the above, the proposed method is compared with MDF, DS, DCL, RFCN, NLDF, DSS, UCF, and PAGRN on the DUT-OMRON benchmark. Our proposed method successfully segments complete foreground objects with consistent saliency value and sharp boundaries.

For convenient comparison, we simplify the formula by fixing input size $H \times W$ as default size 360×360 . To summarize, our proposed network enjoys the fastest inference speed on both

CPU and GPU, consumes the least memory and disk storage, and shows the lowest theoretical complexity, in comparison to existing deep-learning models.

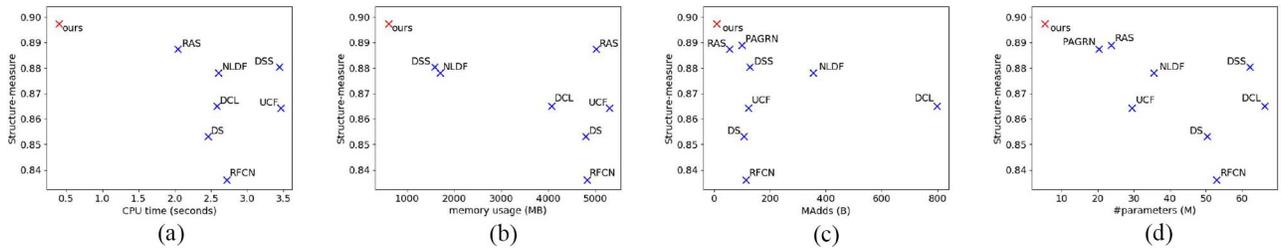


Fig. 7. Comparisons on efficiency and quality. To measure the efficiency and quality of salient object detection models at the same time, the above scatter diagrams take an efficiency metric as horizontal axis and a quality metric as vertical axis. Our proposed method is always located at the upper left of these diagrams, which indicate the best tradeoff between efficiency and accuracy. (a) Smeasure-CPU time. (b) Smeasure-Mem. (c) Smeasure-MAdds. (d) Smeasure-Params.

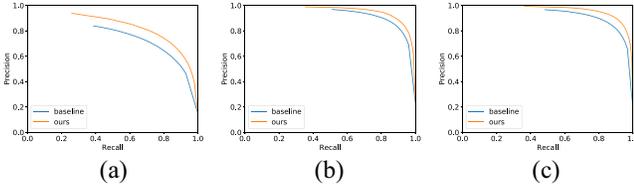


Fig. 8. Ablation study on precision–recall curves. In the above graphs, the blue curve denotes the baseline model without deploying any proposed modules, while the orange one denotes our proposed DNL network. Our proposed method obtains higher precision than the baseline, for the same recall value. (a) DUT-O. (b) ECSSD. (c) HKU-IS.

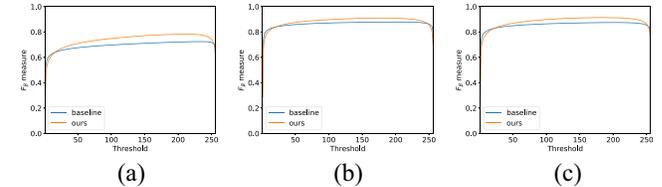


Fig. 9. Ablation study on threshold– F_β measure curves. As shown in the above, the F_β measures of our proposed method are considerably higher than those of the baseline, for most thresholds within the range of [50, 200]. (a) DUT-O. (b) ECSSD. (c) HKU-IS.

To simultaneously evaluate the efficiency and quality of our proposed method, we plot an efficiency metric and a quality metric on the same scatter diagram (shown in Fig. 7), with the efficiency metric as horizontal axis and the quality metric as vertical axis. For quality metric, larger S-measure means more accurate predictions while smaller value means lower cost for efficiency metric. Thus, the best method balancing accuracy and efficiency should be located at the upper left in an efficiency–quality scatter diagram. As shown in Fig. 7, our proposed method achieves the best tradeoff between efficiency and quality, on the scatter diagrams of Smeasure-CPU time, Smeasure-Mem, Smeasure-MAdds, and Smeasure-Params.

C. Ablation Study

This section verifies the effectiveness of the DNL module and investigates how the number of splits affects the performance of the proposed network. The baseline is built by removing all DNL modules from the proposed network. The baseline has exactly the same architecture as MobileNetV2 but has different input size. We use precision–recall curves and threshold– F_β measure curves to compare our proposed method with the baseline. To draw these curves, a list of evenly spaced thresholds is sampled. For each threshold, a tuple of precision, recall, and F_β measure is calculated, with $\beta^2 = 0.3$. Then we plot the pairs of (recall and precision) in Fig. 8, and the pairs of (threshold and F_β measure) in Fig. 9. As shown in Figs. 8 and 9, the proposed module effectively improves the prediction accuracy of the baseline on all three benchmarks.

As Table IV displays, Split-9 denotes an accelerated DNL module that divides the input feature tensor into nine sub-tensors. For Split- s ($s = 1, 3, 5, 9$), DNL modules are located after IR-3 and IR-4 shown in Fig. 5. For IR6-splits

($s = 1, 5, 10$), a DNL module is inserted after IR-6. As shown in Table IV, Split-9 surpasses the baseline by 3.9% maxF, 1.2% MAE, and 4.1% S-m on the HKU-IS dataset. The performance of Split-5 is quite close to that of Split-9. Split-9 marginally outperforms Split-1 by 0.11% maxF and 0.22% S-measure. For IR6-splits, similarly, IR6-split10 exceeds IR6-split1 by 0.9% maxF, 0.3% MAE, and 0.7% S-m. The above results suggest that DNL modules effectively improve the baseline and the splits number does not affect much of the prediction quality. Larger splits number could lead to slight improvement, since it helps to maintain better spatial coherence as discussed in Section III-B. If the splits number is larger, then the spatial size of each subregion becomes smaller. Feature vectors within the same subregion are more likely to belong to the background or the same object. In such cases, nonlocal pairwise correlations help propagate the saliency score of a feature to its adjacent features, which models spatial coherence. Compared with IR6-split1 whose DNL module is at a high level, Split-1, whose DNL modules are at the middle level, achieves better maxF, MAE, and S-m. It suggests that placing the proposed module at the middle level better improves the performance.

The baseline obtains the fastest CPU inference and the lowest MAdds. As the splits number decreases, both CPU time cost and MAdds of the corresponding DNL network become larger. Because smaller splits number results in computing more pairwise similarities. Since CPU time is measured for a whole network, we need to compute *difference* between some network and the baseline to obtain the time cost of DNL modules. For examples, DNL modules in Split-9 additionally costs $399.3 - 390.6 \sim 9$ ms and $9.567 - 9.325 \sim 0.24$ B MAdds while DNL modules in Split-1 additionally takes $454.9 - 390.6 \sim 64$ ms and $10.42 - 9.325 \sim 1.1$ B MAdds

TABLE IV
EFFECTIVENESS OF THE DNL MODULE

	HKU-IS			CPUTime /secs	MAdds
	maxF	MAE	S-m		
Baseline w/o DNL	0.8745	0.0572	0.8563	0.3906	9.325B
Split-9	0.9133	0.0451	0.8974	0.3993	9.567B
Split-5	0.9133	0.0451	0.8969	0.4019	9.657B
Split-3	0.9131	0.0452	0.8967	0.4103	9.781B
Split-1	0.9121	0.0458	0.8952	0.4549	10.42B
IR6-split10	0.9125	0.0459	0.8922	0.5138	12.25B
IR6-split5	0.9069	0.0479	0.8873	0.5447	12.90B
IR6-split1	0.9036	0.0489	0.8851	1.1384	18.13B

when compared with the baseline model. Compared with Split-1, DNL modules in Split-9 speed up $7\times$ CPU time from 64 to 9 ms, and reduce $5\times$ MAdds from 1.1 to 0.24B. For IR6-splits, the difference is larger. The DNL module in IR6-split10 reduces $1.1384 - 0.5138 \sim 0.6$ s CPU time and $18.13 - 12.25 \sim 6$ B MAdds, in comparison to IR6-split1. The above results indicate that the divide-and-conquer variant of the DNL module indeed accelerates the inference. To understand the difference between positioning DNL modules at the middle level and high level, we compare Split-1 with IR6-split1. DNL modules are located at the middle level of Split-1 and the high level of IR6-split1. IR6-split1 spends more CPU time (0.7 s) and larger MAdds (7.7B) than Split-1. Thus, positioning DNL modules at a high level causes more computational cost. Because the time complexity of DNL modules is in proportion to the squared number of input channels.

V. CONCLUSION

This article introduced a novel DNL module that effectively enhances the accuracy of an IR block. A divide-and-conquer variant of DNL was proposed to further accelerate inference. Moreover, we developed a lightweight DNL-based network architecture with low memory cost, high inference speed, and competitive accuracy. The numerical results declare that our method achieves not only competitive accuracy but also state-of-the-art efficiency among deep CNN-based methods.

REFERENCES

- [1] R. Zhao, W. Ouyang, and X. Wang, "Unsupervised salience learning for person re-identification," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2013, pp. 3586–3593.
- [2] A. P. Shon, D. B. Grimes, C. L. Baker, M. W. Hoffman, S. Zhou, and R. P. Rao, "Probabilistic gaze imitation and saliency learning in a robotic head," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2005, pp. 2865–2870.
- [3] V. Navalpakkam and L. Itti, "An integrated model of top-down and bottom-up attention for optimal object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2006, pp. 2049–2056.
- [4] H. Wu, G. Li, and X. Luo, "Weighted attentional blocks for probabilistic object tracking," *Vis. Comput.*, vol. 30, no. 2, pp. 229–243, 2014.
- [5] S. Avidan and A. Shamir, "Seam carving for content-aware image resizing," *ACM Trans. Graph.*, vol. 26, no. 3, p. 10, 2007.
- [6] M. Sandler, A. Howard, M. Zhu, A. Zhmoginov, and L.-C. Chen, "MobileNetV2: Inverted residuals and linear bottlenecks," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2018, pp. 4510–4520.
- [7] P. Zhang, D. Wang, H. Lu, H. Wang, and B. Yin, "Learning uncertain convolutional features for accurate saliency detection," in *Proc. IEEE Int. Conf. Comput. Vis.*, 2017, pp. 212–221.
- [8] X. Zhang, T. Wang, J. Qi, H. Lu, and G. Wang, "Progressive attention guided recurrent network for salient object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2018, pp. 714–722.
- [9] M.-M. Cheng, N. J. Mitra, X. Huang, P. H. Torr, and S.-M. Hu, "Global contrast based salient region detection," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 37, no. 3, pp. 569–582, Mar. 2015.
- [10] F. Perazzi, P. Krähenbühl, Y. Pritch, and A. Hornung, "Saliency filters: Contrast based filtering for salient region detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2012, pp. 733–740.
- [11] H. Jiang, J. Wang, Z. Yuan, Y. Wu, N. Zheng, and S. Li, "Salient object detection: A discriminative regional feature integration approach," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2013, pp. 2083–2090.
- [12] J. Zhang, S. Sclaroff, Z. Lin, X. Shen, B. Price, and R. Mech, "Minimum barrier salient object detection at 80 FPS," in *Proc. IEEE Int. Conf. Comput. Vis.*, 2015, pp. 1404–1412.
- [13] W.-C. Tu, S. He, Q. Yang, and S.-Y. Chien, "Real-time salient object detection with a minimum spanning tree," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2016, pp. 2334–2342.
- [14] X. Huang and Y.-J. Zhang, "300-FPS salient object detection via minimum directional contrast," *IEEE Trans. Image Process.*, vol. 26, no. 9, pp. 4243–4254, Sep. 2017.
- [15] Q. Peng, Y.-M. Cheung, X. You, and Y. Y. Tang, "A hybrid of local and global saliencies for detecting image salient region and appearance," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 1, pp. 86–97, Jan. 2017.
- [16] L. Zhang, C. Yang, H. Lu, X. Ruan, and M.-H. Yang, "Ranking saliency," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 39, no. 9, pp. 1892–1904, Sep. 2017.
- [17] G. Li and Y. Yu, "Visual saliency based on multiscale deep features," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2015, pp. 5455–5463.
- [18] L. Wang, H. Lu, X. Ruan, and M.-H. Yang, "Deep networks for saliency detection via local estimation and global search," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2015, pp. 3183–3192.
- [19] G. Li and Y. Yu, "Contrast-oriented deep neural networks for salient object detection," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 29, no. 12, pp. 6038–6051, Mar. 2018.
- [20] X. Li *et al.*, "DeepSaliency: Multi-task deep neural network model for salient object detection," *IEEE Trans. Image Process.*, vol. 25, no. 8, pp. 3919–3930, Jun. 2016.
- [21] N. Liu and J. Han, "DHSNet: Deep hierarchical saliency network for salient object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2016, pp. 678–686.
- [22] Z. Luo, A. K. Mishra, A. Achkar, J. A. Eichel, S. Li, and P.-M. Jodoin, "Non-local deep features for salient object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2017, pp. 6609–6617.
- [23] L. Wang, L. Wang, H. Lu, P. Zhang, and X. Ruan, "Salient object detection with recurrent fully convolutional networks," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 41, no. 7, pp. 1734–1746, Jul. 2019.
- [24] M. Sun, Z. Zhou, Q. Hu, Z. Wang, and J. Jiang, "SG-FCN: A motion and memory-based deep learning model for video saliency detection," *IEEE Trans. Cybern.*, vol. 49, no. 8, pp. 2900–2911, Sep. 2018.
- [25] H. Li, G. Li, and Y. Yu, "ROSA: Robust salient object detection against adversarial attacks," *IEEE Trans. Cybern.*, early access, doi: 10.1109/TCYB.2019.2914099.
- [26] Y. Qin, M. Feng, H. Lu, and G. W. Cottrell, "Hierarchical cellular automata for visual saliency," *Int. J. Comput. Vis.*, vol. 126, no. 7, pp. 751–770, 2018.
- [27] S. Chen, X. Tan, B. Wang, and X. Hu, "Reverse attention for salient object detection," in *Proc. Eur. Conf. Comput. Vis.*, 2018, pp. 236–252.
- [28] G. Li, Y. Xie, T. Wei, K. Wang, and L. Lin, "Flow guided recurrent neural encoder for video salient object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit. (CVPR)*, Jun. 2018, pp. 3243–3252.
- [29] H. Li, G. Chen, G. Li, and Y. Yu, "Motion guided attention for video salient object detection," in *Proc. IEEE Int. Conf. Comput. Vis. (ICCV)*, Oct. 2019, p. 125.
- [30] Y. Zeng, M. Feng, H. Lu, G. Yang, and A. Borji, "An unsupervised game-theoretic approach to saliency detection," *IEEE Trans. Image Process.*, vol. 27, no. 9, pp. 4545–4554, Sep. 2018.
- [31] L. Zhang, J. Ai, B. Jiang, H. Lu, and X. Li, "Saliency detection via absorbing Markov chain with learnt transition probability," *IEEE Trans. Image Process.*, vol. 27, no. 2, pp. 987–998, Feb. 2018.
- [32] Q. Hou, M.-M. Cheng, X. Hu, A. Borji, Z. Tu, and P. Torr, "Deeply supervised salient object detection with short connections," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 41, no. 4, pp. 815–828, Apr. 2019.
- [33] T. Wang *et al.*, "Detect globally, refine locally: A novel approach to saliency detection," in *Proc. IEEE/CVF Conf. Comput. Vis. Pattern Recognit.*, Jun. 2018, pp. 3127–3135.

- [34] J.-J. Liu, Q. Hou, M.-M. Cheng, J. Feng, and J. Jiang, "A simple pooling-based design for real-time salient object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2019, pp. 3917–3926.
- [35] J. Ngiam, Z. Chen, D. Chia, P. W. Koh, Q. V. Le, and A. Y. Ng, "Tiled convolutional neural networks," in *Proc. Adv. Neural Inf. Process. Syst.*, 2010, pp. 1279–1287.
- [36] S. Han, J. Pool, J. Tran, and W. J. Dally, "Learning both weights and connections for efficient neural network," in *Proc. Adv. Neural Inf. Process. Syst.*, 2015, pp. 1135–1143.
- [37] B. Liu, M. Wang, H. Foroosh, M. Tappen, and M. Pensky, "Sparse convolutional neural networks," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2015, pp. 806–814.
- [38] V. Sindhwani, T. Sainath, and S. Kumar, "Structured transforms for small-footprint deep learning," in *Proc. Adv. Neural Inf. Process. Syst.*, 2015, pp. 3088–3096.
- [39] M. Rastegari, V. Ordonez, J. Redmon, and A. Farhadi, "XNOR-Net: ImageNet classification using binary convolutional neural networks," in *Proc. Eur. Conf. Comput. Vis.*, 2016, pp. 525–542.
- [40] X. Zhang, J. Zou, K. He, and J. Sun, "Accelerating very deep convolutional neural networks for classification and detection," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 38, no. 10, pp. 1943–1955, Oct. 2016.
- [41] M. Wang, B. Liu, and H. Foroosh, "Factorized convolutional neural networks," in *Proc. IEEE Int. Conf. Comput. Vis. Workshops*, 2017, pp. 545–553.
- [42] Y. He, X. Zhang, and J. Sun, "Channel pruning for accelerating very deep neural networks," in *Proc. IEEE Int. Conf. Comput. Vis.*, vol. 2, 2017, pp. 1398–1406.
- [43] X. Zhang, X. Zhou, M. Lin, and J. Sun, "ShuffleNet: An extremely efficient convolutional neural network for mobile devices," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2018, pp. 6848–6856.
- [44] P. W. Battaglia, R. Pascanu, M. Lai, D. J. Rezende, and K. Kavukcuoglu, "Interaction networks for learning about objects, relations and physics," in *Proc. Adv. Neural Inf. Process. Syst.*, 2016, pp. 4502–4510.
- [45] A. Buades, B. Coll, and J.-M. Morel, "A non-local algorithm for image denoising," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, vol. 2, 2005, pp. 60–65.
- [46] X. He, S. Yang, G. Li, H. Li, H. Chang, and Y. Yu, "Non-local context encoder: Robust biomedical image segmentation against adversarial attacks," in *Proc. AAAI Conf. Artif. Intell. (AAAI)*, Jan. 2019, pp. 8417–8424.
- [47] A. A. Efros and T. K. Leung, "Texture synthesis by non-parametric sampling," in *Proc. IEEE Int. Conf. Comput. Vis.*, 1999, p. 1033.
- [48] P. Krähenbühl and V. Koltun, "Efficient inference in fully connected CRFs with Gaussian edge potentials," in *Proc. Adv. Neural Inf. Process. Syst.*, 2011, pp. 109–117.
- [49] A. Santoro *et al.*, "A simple neural network module for relational reasoning," in *Proc. Adv. Neural Inf. Process. Syst.*, 2017, pp. 4967–4976.
- [50] A. Vaswani *et al.*, "Attention is all you need," in *Proc. Adv. Neural Inf. Process. Syst.*, 2017, pp. 5998–6008.
- [51] X. Wang, R. Girshick, A. Gupta, and K. He, "Non-local neural networks," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2018, pp. 7794–7803.
- [52] N. Watters, D. Zoran, T. Weber, P. Battaglia, R. Pascanu, and A. Tacchetti, "Visual interaction networks: Learning a physics simulator from video," in *Proc. Adv. Neural Inf. Process. Syst.*, 2017, pp. 4539–4547.
- [53] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian, "Image denoising by sparse 3-D transform-domain collaborative filtering," *IEEE Trans. Image Process.*, vol. 16, no. 8, pp. 2080–2095, Aug. 2007.
- [54] G. Li, X. He, W. Zhang, H. Chang, L. Dong, and L. Lin, "Non-locally enhanced encoder-decoder network for single image de-raining," in *Proc. ACM Multimedia Conf. Multimedia Conf.*, 2018, pp. 1056–1064.
- [55] L.-C. Chen, Y. Zhu, G. Papandreou, F. Schroff, and H. Adam, "Encoder-decoder with atrous separable convolution for semantic image segmentation," in *Proc. Eur. Conf. Comput. Vis.*, 2018, pp. 801–818.
- [56] C. Yang, L. Zhang, H. Lu, X. Ruan, and M.-H. Yang, "Saliency detection via graph-based manifold ranking," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2013, pp. 3166–3173.
- [57] Q. Yan, L. Xu, J. Shi, and J. Jia, "Hierarchical saliency detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2013, pp. 1155–1162.
- [58] G. Li and Y. Yu, "Visual saliency detection based on multiscale deep CNN features," *IEEE Trans. Image Process.*, vol. 25, no. 11, pp. 5012–5024, Sep. 2016.
- [59] Y. Li, X. Hou, C. Koch, J. M. Rehg, and A. L. Yuille, "The secrets of salient object segmentation," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2014, pp. 280–287.

- [60] L. Wang *et al.*, "Learning to detect salient objects with image-level supervision," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit. (CVPR)*, Jul. 2017, pp. 3796–3805.
- [61] R. Achanta, S. Hemami, F. Estrada, and S. Susstrunk, "Frequency-tuned salient region detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2009, pp. 1597–1604.
- [62] D.-P. Fan, M.-M. Cheng, Y. Liu, T. Li, and A. Borji, "Structure-measure: A new way to evaluate foreground maps," in *Proc. IEEE Int. Conf. Comput. Vis.*, 2017, pp. 4558–4567.
- [63] G. Li and Y. Yu, "Deep contrast learning for salient object detection," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, 2016, pp. 478–487.
- [64] L. Wang, L. Wang, H. Lu, P. Zhang, and X. Ruan, "Saliency detection with recurrent fully convolutional networks," in *Proc. Eur. Conf. Comput. Vis.*, 2016, pp. 825–841.



Haofeng Li received the B.S. degree from the School of Data and Computer Science, Sun Yat-sen University, Guangzhou, China, in 2015. He is currently pursuing the Ph.D. degree with the Department of Computer Science, University of Hong Kong, Hong Kong.

His current research interests include computer vision, image processing, and deep learning.

Mr. Li is a recipient of the Hong Kong Ph.D. Fellowship.



Guanbin Li (Member, IEEE) received the Ph.D. degree from the University of Hong Kong, Hong Kong, in 2016.

He is currently an Associate Professor with the School of Data and Computer Science, Sun Yat-sen University, Guangzhou, China. He has authored and coauthored more than 50 papers in top-tier academic journals and conferences. His current research interests include computer vision, image processing, and deep learning.

Dr. Li was a recipient of the Hong Kong Ph.D. Fellowship and the Best Paper Nomination Award at IEEE ICCV2019. He serves as an Area Chair for the conference of VISAPP. He has been serving as a Reviewer for numerous academic journals and conferences, such as the IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, the IEEE TRANSACTIONS ON IMAGE PROCESSING, the IEEE TRANSACTIONS ON MULTIMEDIA, the IEEE TRANSACTIONS ON CYBERNETICS, CVPR, ICCV, and AAAI.



Binbin Yang is currently pursuing the B.S. degree with the School of Data and Computer Science, Sun Yat-sen University, Guangzhou, China.

His current research interests include computer vision, image processing, and deep learning.



Guanqi Chen is currently pursuing the B.S. degree with the School of Data and Computer Science, Sun Yat-sen University, Guangzhou, China.

His current research interests include computer vision and image/video processing.



Liang Lin (Senior Member, IEEE) received the Ph.D. degree from Beijing Institute of Technology, Beijing, China, in 2008.

He is a Full Professor with Sun Yat-sen University, Guangzhou, China. He is the Excellent Young Scientist with the National Natural Science Foundation of China, Beijing, China. From 2008 to 2010, he was a Postdoctoral Fellow with the University of California at Los Angeles, Los Angeles, CA, USA. From 2014 to 2015, he was a Senior Visiting Scholar with Hong Kong Polytechnic

University, Hong Kong, and the Chinese University of Hong Kong, Hong Kong. He has authored and coauthored more than 100 papers in top-tier academic journals and conferences. He currently leads the SenseTime Research and Development teams to develop cutting-edge and deliverable solutions on computer vision, data analysis and mining, and intelligent robotic systems.

Prof. Lin was a recipient of the Best Paper Runners-Up Award at ACM NPAR 2010, the Google Faculty Award in 2012, the Best Paper Diamond Award at IEEE ICME 2017, and the Hong Kong Scholars Award in 2014. He has been serving as an Associate Editor for the IEEE TRANSACTIONS HUMAN-MACHINE SYSTEMS and *The Visual Computer and Neurocomputing*. He served as the Area/Session Chair for numerous conferences, including ICME, ACCV, and ICMR. He is a fellow of IET.



Yizhou Yu (Fellow, IEEE) received the Ph.D. degree from the University of California at Berkeley, Berkeley, CA, USA, in 2000.

He is a Professor with the University of Hong Kong, Hong Kong. He was a Faculty Member with the University of Illinois at Urbana-Champaign, Champaign, IL, USA, for 12 years. His current research interests include computer vision, deep learning, biomedical data analysis, computational visual media, and geometric computing.

Prof. Yu was a recipient of the 2002 U.S. National Science Foundation CAREER Award, the 2007 NNSF China Overseas Distinguished Young Investigator Award, and the ACCV 2018 Best Application Paper Award. He has served on the editorial board for *IET Computer Vision*, *The Visual Computer*, and the IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS. He has also served on the program committee of many leading international conferences, including SIGGRAPH, SIGGRAPH Asia, and International Conference on Computer Vision.