



Computer-aided detection of COVID-19 from CT scans using an ensemble of CNNs and KSVM classifier

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Abstract

Corona Virus Disease-2019 (COVID-19) is a global pandemic which is spreading briskly across the globe. The gold standard for the diagnosis of COVID-19 is viral nucleic acid detection with real-time polymerase chain reaction (RT-PCR). However, the sensitivity of RT-PCR in the diagnosis of early-stage COVID-19 is less. Recent research works have shown that computed tomography (CT) scans of the chest are effective for the early diagnosis of COVID-19. Convolutional neural networks (CNNs) are proven successful for diagnosing various lung diseases from CT scans. CNNs are composed of multiple layers which represent a hierarchy of features at each level. CNNs require a big number of labeled instances for training from scratch. In medical imaging tasks like the detection of COVID-19 where there is a difficulty in acquiring a large number of labeled CT scans, pre-trained CNNs trained on a huge number of natural images can be employed for extracting features. Feature representation of each CNN varies and an ensemble of features generated from various pre-trained CNNs can increase the diagnosis capability significantly. In this paper, features extracted from an ensemble of 5 different CNNs (MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0) in combination with kernel support vector machine is used for the diagnosis of COVID-19 from CT scans. The method was tested using a public dataset and it attained an area under the receiver operating characteristic curve of 0.963, accuracy of 0.916, kappa score of 0.8305, F-score of 0.91, sensitivity of 0.917 and positive predictive value of 0.904 in the prediction of COVID-19.

Keywords COVID-19 · Computed tomography · CNN · KSVM · Computer-aided diagnosis

1 Introduction

On March 2019, the World Health Organization (WHO) has declared the Corona Virus Disease-2019 (COVID-19) a pandemic [17]. Early diagnosis and rapid isolation of the patients are crucial for effective treatment and for preventing the spread of the disease. Viral nucleic acid detection with real-time polymerase chain reaction (RT-PCR) is the gold standard for the detection of COVID-19. The availability of RT-PCR test kits is insufficient in most of the places where the

disease has spread. Moreover, RT-PCR shows less sensitivity in the early diagnosis of COVID-19 [10]. Due to the shortage of RT-PCR test kits and the likelihood of false-negative RT-PCR findings during the early diagnosis, National Health Commission of China has endorsed the diagnosis of COVID-19 using chest CT findings [4]. COVID-19 in CT scans is characterized by ground glass opacity (GGO). GGO represents an area of hazy increased lung opacity through which underlying vessels are visible [14]. Manual analysis of a large number of CT scans by the radiologists is tedious. A computer-aided diagnosis mechanism could assist radiologists in the diagnosis of COVID-19 from CT scans.

There exist a number of computer-aided studies for the diagnosis of COVID-19 from CT scans. He et al. [13] proposed a method that combines transfer learning with self-supervised learning. Anwar and Zakir [3] and Sakagianni et al. [21] also used the public dataset created by [13] for their study. Anwar and Zakir [3] used EfficientNet to diagnose COVID-19 using CT scans. The model used three different learning approaches, namely, reduce on plateau, cyclic

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and constant learning rates. Sakagianni et al. [21] used auto Machine Learning Cloud Vision platform for the prediction of COVID-19. Abraham and Nair [2] proposed a multi-CNN architecture consisting of multiple pre-trained CNNs along with correlation-based feature selection (CFS) technique and Bayesnet classifier for the classification of COVID-19 and non-COVID-19 X-ray images. Pu et al. [19] developed three classifiers based on CNN for distinguishing COVID-19 and pneumonia. Mei et al. [15] used a combination of CNN, multi-layer perceptron (MLP) and clinical information to diagnose COVID-19 from CT scans. Xu et al. [28] used a local attention classification model for classifying the infected regions into COVID-19, influenza and irrelevant to infections. Wu et al. [27] used a deep learning-based multi-view fusion model for the detection of COVID-19. In addition to CT, few works have explored the use of X-rays [12] and cough audio recordings [9] for the computer-aided diagnosis of COVID-19.

All the above-mentioned methods which employed CT scans for the diagnosis of COVID-19 have used a single CNN for the diagnosis of COVID-19. Combination of features from multiple CNNs could produce better results than single CNNs. None of the state-of-the-art studies have explored the optimum combination of features from pre-trained CNNs along with an off-the-shelf classifier for the detection of COVID-19.

The contributions of the proposed ensemble method are listed below.

i. The proposed method explored the combination of various pre-trained CNNs to put forward a model that gives better performance than single pre-trained CNNs and transfer learning using end-to-end CNNs for the diagnosis of COVID-19 from CT scans. Based on empirical analysis, an ensemble of features generated using 5 pre-trained CNNs (MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0) is proposed in this study for the detection of COVID-19 from CT scans. Most of the state-of-the-art methods employing CT images for the detection of COVID-19 have used features from a sole CNN.

ii. The proposed technique used an off-the-shelf classifier, kernel support vector machine (KSVM), for the classification of COVID-19 from CT scans. No existing techniques have employed the combination of the above-mentioned ensemble of CNNs with KSVM for the detection of COVID-19.

2 Materials and methods

Figure 1 displays the architecture of the proposed method. The functions of various blocks of the architecture are described in the following subsections.

2.1 Feature extraction using multiple CNNs

Convolutional neural networks produce powerful feature representations for computer vision tasks. Many research works like segmentation of liver tumor [30] and diagnosis of prostate cancer [1] have proven the effectiveness of CNN in medical applications. For most of the medical diagnostic tasks, training a network from scratch is difficult due to the non-availability of sufficiently large medical datasets. Off-the-shelf features extracted using pre-trained CNNs were found successful in medical diagnosis. Using a pre-trained network is much faster than training a network from scratch. Off-the-shelf features extracted using CNN could achieve superior results even without fine-tuning [23].

Combining features extracted from an ensemble of pre-trained networks could achieve better performance than features extracted using single CNNs. The proposed method combines the features generated from the last fully connected (FC) layer of an ensemble of various CNNs. The CNNs were pre-trained on Imagenet dataset [7] which contains millions of images. The pre-trained CNNs can classify objects into 1000 different categories. The number of layers, input size and number of parameters of the above-mentioned pre-trained networks are represented in Table 1.

As the dataset contains 746 images, a feature vector of dimension 746×1000 is generated by each CNN (Activations from the last convolution layer of Darknet53 and last FC layer of other CNNs). Feature vectors produced by each CNN are concatenated to get a feature vector of size 746×5000 . Specimen features produced by the endmost convolutional layer of MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0 are displayed in Fig 2.

The five pre-trained CNNs (MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0) which achieved best performance in our study are described in the following sections.

2.1.1 MobilenetV2

The first layer of MobilenetV2 is a convolution layer that accepts input images of dimension $224 \times 224 \times 3$ [22]. The model introduced 19 Inverted Residual with Linear Bottleneck (IRB) layers which accepts a low-dimensional feature representation as input. Pointwise convolution operation is performed to increase the dimension of feature matrix to a high-dimensional one. A depth-wise convolution followed by a pointwise convolution is done subsequently.

2.1.2 Shufflenet

Shufflenet architecture introduced by Zhang et al. [31] consists of pointwise batch convolution operation and channel shuffle (CS) operation. Pointwise batch convolution reduces

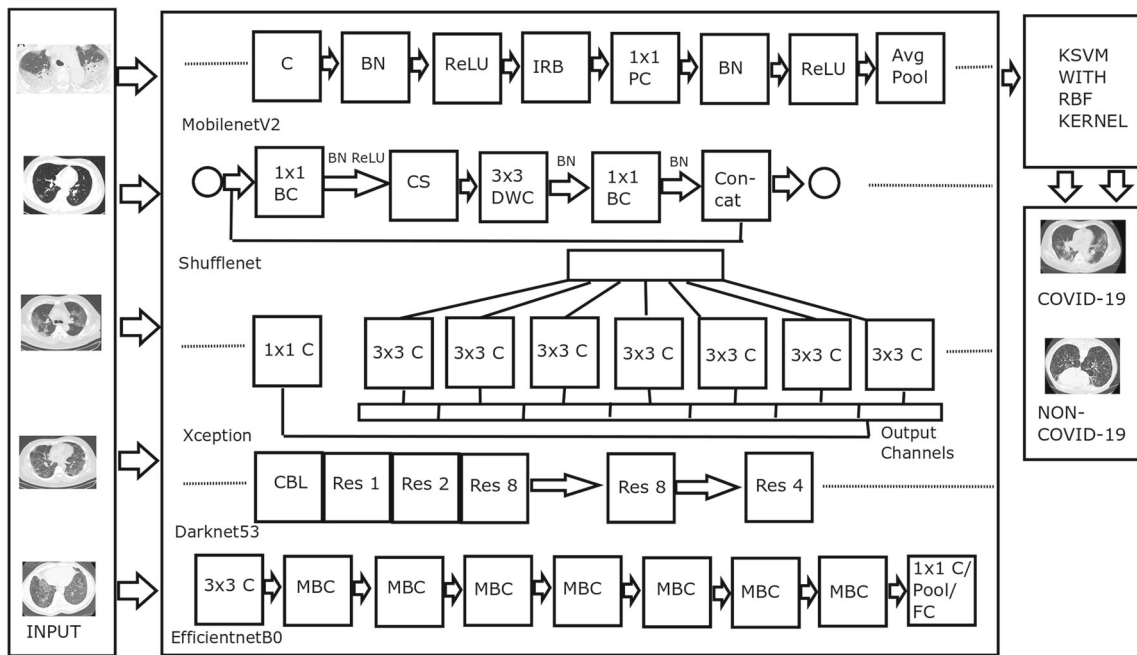


Fig. 1 Architecture of the proposed method. Abbreviations—C: Convolution, BN: Batch Normalization, ReLU: Rectified Linear Unit, IRB: Inverted Residual Block, PC: Pointwise Convolution, Avg Pool: Average Pooling, BC: Batch Convolution, CS: Channel Shuffle, DWC: Depthwise Convolution, Res: Residual

Table 1 Depth, input size and number of parameters of pre-trained CNNs

CNN	Depth	Input size	Number of parameters (In Millions)
MobilenetV2	53	224 × 224 × 3	3.5
Shufflenet	50	224 × 224 × 3	1.4
Xception	71	229 × 229 × 3	22.9
Darknet53	53	256 × 256 × 3	41
EfficientnetB0	82	224 × 224 × 3	5.3

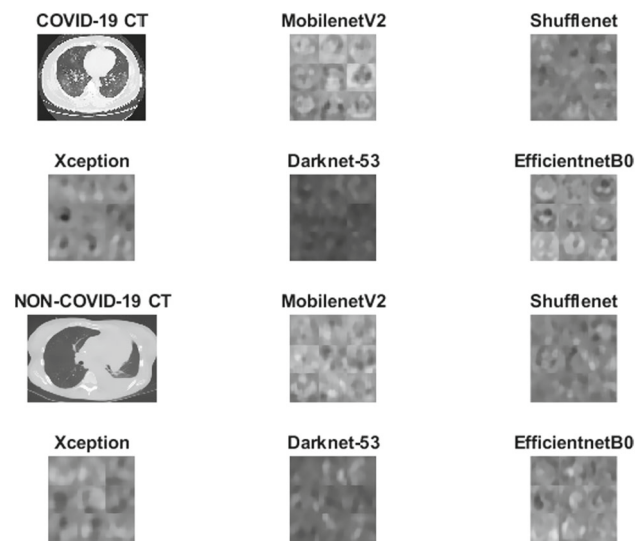


Fig. 2 Sample features. Two rows at the top represent sample features of a COVID-19 image, and the two rows at the bottom represent sample features of a non-COVID-19 CT image

the computation complexity of dense 1×1 convolution with a cost of weakened representation. Weakened representation caused by pointwise batch convolution can be overcome by using channel shuffle operation which secures input from different batches by dividing the channels in each batch into various groups.

2.1.3 Xception

Xception [6] is a pre-trained CNN model based on Inception, where stacks of depthwise separable convolution layers with residual connections substitute inception modules. A depthwise separable convolution is composed of a depthwise convolution which is a spatial convolution operation done separately over each input channel, followed by a 1×1 convolution operation. The Xception architecture consists of 36 convolutional layers which are grouped into 14 modules, all of which except the first and last modules have linear residual connections among them.

2.1.4 Darknet53

The basic building block of Darknet53 is CBL (Convolution, Batch normalization, Leaky ReLU) layer [20]. Darknet53 is a pre-trained CNN mainly composed of a series of 1×1 and 3×3 convolutional layers. The network consists of 5 residual layers which are used to solve the gradient vanishing problem. The residual layers are indicated as Res n , where n is the number of residual blocks in a residual layer. The different values of n are 1, 2, 4 and 8.

2.1.5 EfficientnetB0

The main building block for EfficientNetB0 is the Mobile inverted Bottleneck MBC to which squeeze and excitation optimization is added [24]. MBC blocks consist of a layer that performs expansion followed by compression of the channels. Direct connections are used among bottlenecks which connect much lesser channels compared to expansion layers.

2.2 KSVM

Support vector machine (SVM) proposed by Vapnik et al. [25] is a classifier that determines the optimum hyperplane which separates the positive and negative instances of a training data. A training data of n observations can be defined as

$$T = \{(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)\} \quad (1)$$

where $x_i = x_1, x_2, \dots, x_n$ is an instance of training data and $y_i \in \{\pm 1\}$ is the corresponding label.

A hyperplane in the feature space can be represented as

$$w^T x + b = 0 \quad (2)$$

where w represents the weight matrix and b is the bias term. Distance of an instance x_i from the hyperplane plane (w, b) is defined as

$$d(w, b; x_i) = \frac{w \cdot x_i + b}{\|w\|} \quad (3)$$

SVM model proposes a maximum margin separating $w \cdot x_i + b = 1$ and $w \cdot x_i + b = -1$, which can be obtained by solving the optimization problem

$$\min \frac{1}{2} \|w\|^2 \quad (4)$$

conditional on

$$y_i (w^T \cdot x_i + b) \geq 1, \quad i = 1, 2, \dots, n \quad (5)$$

By introducing a mapping function δ , the vector x in the original low-dimensional space can be transformed into $\delta(x)$ of high-dimensional space. A kernel function is described as

$$K(x_i, x_j) = \delta^T(x_i) \delta(x_j) \quad (6)$$

The optimization problem defined in Eq. 4 becomes

$$\min \frac{1}{2} w^T w + C \sum_{i=1}^n \epsilon_n \quad (7)$$

conditional on

$y_i (w^T \delta(x_i) + b) \geq 1 - \epsilon_i, \quad \epsilon_i \geq 0, \quad i = 1, 2, \dots, n$
where C is a regularization parameter and ϵ is a slack variable used to solve overfitting.

The optimization problem in Eq. 7 can be solved in dual form as given below.

$$\min_{\theta} \frac{1}{2} \theta^T M \theta - e^T \theta \quad (8)$$

conditional on

$$y^{\theta} = 0, \quad 0 \leq \theta_i \leq C, \quad i = 1, 2, \dots, n,$$

where θ_i represents the weight of x_i and

$$M_{i,j} = y_i y_j K(x_i, x_j), \text{ a matrix of dimension } n \times n.$$

The proposed method uses RBF kernel in association with KSVM classifier [5]. RBF kernel is described as

$$K(x_i, x_j) = e^{-\beta \|x_i - x_j\|^2} \quad (9)$$

where $\beta = \frac{1}{2\rho^2}$ and ρ is a free parameter. The decision function for the KSVM is specified as

$$y(x) = \text{sign} \left(\sum_{i=1}^n \theta_i y_i K(x_i, x) + b \right) \quad (10)$$

3 Results and discussion

A publicly available dataset consisting of 349 CT scans diagnosed with COVID-19 and 397 CT scans confirmed as non-COVID was used for the study [33]. The area under the receiver operating characteristic curve (AUROC), accuracy, kappa score, positive predictive value (PPV), sensitivity and F-score were used as the performance metrics. MATLAB 2020b with default parameter settings was used for feature extraction using the CNNs. The classification was performed using LibSVM package of Weka 3.6. Parameter settings of the classifier are given in Table 2.

A 10-fold cross-validation (CV) was performed on the dataset, and the average results of 10-fold were taken into account. Using the same training and test set will give more accurate results when the performance of different models is

Table 2 Parameter Settings

Parameter	Value
Cost	4.5
Degree	3
eps	0.001
Kernel	Radial Basis Function (RBF)
Loss	0.1

		Confusion Matrix		
Target Class	Covid	320	29	0.917
	Non-Covid	34	363	0.914
		Covid	Non-Covid	
		0.904	0.926	0.916
		Output Class		

Fig. 3 Confusion matrix of COVID-19 vs. non-COVID-19 classification. The diagonal element at the bottom shown in green color corresponds to accuracy. Rightmost column values represent sensitivity and bottom-most row elements represent PPV

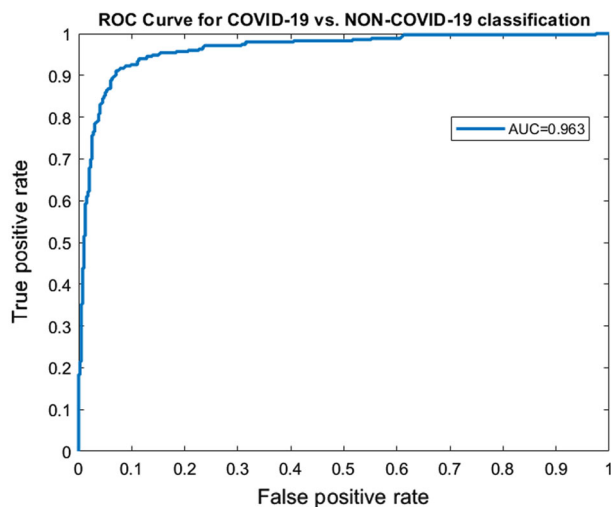


Fig. 4 ROC curves corresponding to COVID-19 vs. non-COVID-19 classification

compared. A seed value of 1 was used for generating the folds of 10-fold cross-validation so that the same data partitions were created for each of the experiments. All experiments were performed on the same training and test sets so that the results are comparable. The proposed method achieved an accuracy of 91.6% and AUROC of 0.963. Figure 3 represents the confusion matrix of the proposed method. Figure

4 displays the AUROC achieved by the proposed method. The p value based on Chi-square statistic was computed to determine the statistical significance of the proposed method. Level of significance was set at 0.05. The p value achieved was less than 0.00001, significant at $p < 0.05$.

Two more types of validation were performed to ensure the performance of the method further. Partitions were created using different seed values from 1 to 10 and repeated the experiments 10 times. Ten-fold CV was performed using the training sets and test sets created using each seed value. The average PPV, sensitivity, F-score, kappa score, AUROC and accuracy achieved on repeating the experiments 10 times were 0.9033, 0.9194, 0.9112, 0.8319, 0.9622 and 0.9155, respectively. We also performed validation by dividing the data into a 70% training set and a 30% test set. This type of validation achieved a PPV, sensitivity, F-score, kappa score, AUROC and accuracy of 0.933, 0.866, 0.898, 0.959 and 0.9018, respectively. The results achieved using the three types of validation were comparable.

Table 3 represents the results achieved using various combinations of pre-trained CNNs. Ensemble of 4 pre-trained CNNs consisting of Darknet53, Shufflenet, Xception and EfficientnetB0 also achieved an AUROC of 0.963. However, the proposed 5 CNNs achieved a slightly better accuracy, sensitivity, kappa score and F-score. The combinations of various 4 CNNs selected from the 5 networks of the proposed ensemble also achieved good performance, but slightly lower than the proposed architecture. The results show that ensemble of CNNs, selected based on empirical analysis, could perform better than single CNNs.

Pre-trained networks can be used in two different ways for the classification task. In the proposed method, the pre-trained CNNs serve as a feature extractor, where the activations of a layer are used as features to train an off-the-shelf classifier like KSVM. Pre-trained CNNs can also be used for transfer learning where the layers of the pre-trained network are fine-tuned using the data at hand. Table 4 illustrates the performance of transfer learning using MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0 with the proposed method. Number of epochs, mini batch size and learning rate were set as 5, 8 and 0.0001, respectively. The proposed method achieved better accuracy and kappa score than transfer learning using pre-trained CNNs. The execution time in minutes of transfer learning using MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0 was 146.52, 70.08, 312.78, 657.35 and 298.99, respectively, whereas the proposed method took only 10.79 minutes for 10-fold CV. The time required for feature extraction and classification of a single instance was 24.315 seconds.

We selected KSVM as the classifier empirically, after experimenting with other major classifiers. The results attained using various major classifiers along with the proposed ensemble of CNNs are shown in Table 5. Even though

Table 3 Performance of various CNNs and ensemble of CNNs in combination with KSVM

Network	PPV	Sensitivity	F-Score	Kappa score	AUROC	Accuracy
MobilenetV2+Shufflenet+Xception+Darknet53+EfficientnetB0	0.904	0.917	0.91	0.8305	0.963	0.916
MobilenetV2+Shufflenet+Xception+Darknet53+Alexnet	0.892	0.90	0.896	0.8036	0.958	0.902
MobilenetV2+Shufflenet+Xception+Darknet53+Densenet201	0.892	0.897	0.894	0.8009	0.958	0.901
Darknet+Shufflenet+Xception+EfficientnetB0	0.906	0.911	0.909	0.8278	0.963	0.914
MobilenetV2+Darknet+Xception+EfficientnetB0	0.90	0.90	0.90	0.8116	0.96	0.906
MobilenetV2+Shufflenet+Xception+EfficientnetB0	0.905	0.903	0.904	0.8196	0.962	0.910
MobilenetV2+Shufflenet+Xception+Darknet53	0.892	0.9	0.896	0.8036	0.959	0.902
Alexnet+Googlenet+Resnet101	0.863	0.868	0.866	0.747	0.943	0.874
Efficientnet+Shufflenet+MobilenetV2	0.904	0.891	0.898	0.8087	0.957	0.905
Darknet53+Shufflenet+MobilenetV2	0.887	0.897	0.892	0.7955	0.953	0.898
Darknet53+Shufflenet+Xception	0.884	0.897	0.89	0.7929	0.956	0.897
MobilenetV2+Shufflenet+Xception	0.886	0.871	0.879	0.773	0.956	0.887
MobilenetV2+Darknet53+Xception	0.881	0.888	0.884	0.7821	0.954	0.891
MobilenetV2+Shufflenet	0.87	0.883	0.876	0.766	0.883	0.883
MobilenetV2+Darknet53	0.871	0.888	0.879	0.7714	0.886	0.886
Xception	0.831	0.848	0.84	0.6962	0.916	0.849
Darknet53	0.85	0.845	0.848	0.7145	0.93	0.857
MobilenetV2	0.84	0.857	0.848	0.7123	0.926	0.857
Shufflenet	0.839	0.865	0.852	0.7148	0.926	0.858
Alexnet	0.826	0.805	0.816	0.6576	0.909	0.830
Googlenet	0.813	0.811	0.812	0.6473	0.904	0.824
Resnet101	0.844	0.868	0.856	0.7259	0.928	0.863
Densenet201	0.845	0.857	0.85	0.7176	0.93	0.859
EfficientnetB0	0.87	0.86	0.865	0.7468	0.948	0.873
Resnet18	0.843	0.828	0.835	0.7339	0.925	0.847

Performance of the proposed method (Ensemble of CNNs+KSVM) is represented in bold

Table 4 Comparison of the performance of proposed method with transfer learning

Network	PPV	Sensitivity	F-Score	Kappa score	AUROC	Accuracy
Proposed	0.904	0.917	0.91	0.8305	0.963	0.916
Xception	0.9398	0.8241	0.8782	0.7571	0.9590	0.8780
MobilenetV2	0.889	0.874	0.882	0.687	0.923	0.843
Shufflenet	0.796	0.883	0.837	0.679	0.927	0.839
Darknet53	0.777	0.937	0.849	0.692	0.943	0.845
EfficientnetB0	0.9427	0.8246	0.8797	0.7598	0.9659	0.879

Performance of the proposed method is indicated in bold

all the classifiers produced statistically significant results at $p < 0.05$, their performance was considerably less compared to KSVM.

Majority of the state-of-the-art techniques have used the public dataset used by the proposed method. Few other methods have used private datasets acquired from various

Table 5 Performance of different classifiers when used along with the proposed ensemble of CNNs

Classifier	PPV	Sensitivity	F-Score	Kappa score	AUROC	Accuracy
KSVM	0.904	0.917	0.91	0.8305	0.963	0.916
AdaBoostM1	0.691	0.691	0.691	0.4185	0.79	0.710
Random Forest	0.805	0.768	0.786	0.6059	0.89	0.804
Naive Bayes	0.729	0.639	0.681	0.433	0.801	0.7198
KNN	0.71	0.756	0.732	0.4825	0.7776	0.741
Bayesnet	0.726	0.668	0.696	0.4481	0.808	0.727

Results achieved using KSVM are indicated in bold

Table 6 Performance achieved by different methods

Method	Dataset	PPV	Sensitivity	F-Score	Kappa score	AUROC	Accuracy
Proposed	He et al. [33]	0.904	0.917	0.91	0.8305	0.963	0.916
He et al. [13]	He et al. [33]	–	–	0.85	–	0.94	0.86
Sakagianni et al. [21]	He et al. [33]	0.8831	0.8831	–	–	–	–
Anwar and Zakir [3]	He et al. [33]	–	–	–	–	0.90	0.90
Wu et al. [27]	Private	–	0.811	–	–	0.819	0.76
Pu et al. [19]	Private	–	–	–	–	0.70	–
Xu et al. [28]	Private	0.813	0.867	0.839	–	–	0.867
Mei et al. [15]	Private	–	0.843	–	–	0.92	–
Polsinelli et al. [18]	He et al. [33]	0.8501	0.8755	0.8620	–	–	0.8503
Wang et al. [26]	Private	–	0.974	–	–	0.991	–
Di et al. [8]	Private	0.9065	0.9327	–	–	–	0.8979
Gao et al. [11]	Private	–	0.8914	–	–	0.9755	0.9599
Zhang et al. [32]	Private	–	0.9444	–	–	–	0.9403
Yener and Oktay [29]	Kaggle, He et al. [33]	0.90	0.94	0.92	–	0.91	0.91
Ouyang et al. [16]	Private	–	0.869	0.820	–	0.944	0.875

Performance attained by the proposed method (ensemble of CNNs+KSVM) is shown in bold

hospitals. The results of different state-of-the-art methods are compared in Table 6. Methods by He et al. [13], Anwar and Zakir [3], Sakagianni et al. [21], Polsinelli et al. [18] and Yener and Oktay [29] employed the public dataset used in the proposed method. The proposed method and the method by Anwar and Zakir [3] used cross-validation, whereas the other methods which used the public dataset validated the performance using hold-out data. The proposed method achieved better results than the other methods that used the same dataset. The methods by Wu et al. [27], Pu et al. [19], Xu et al. [28], Mei et al. [15], Wang et al. [26], Di et al. [8], Gao et al. [11], Zhang et al. [32] and Ouyang et al. [16] were validated on other datasets which are not publicly available.

4 Conclusion

The experimental analysis performed in this work shows the effectiveness of ensemble of features extracted using MobilenetV2, Shufflenet, Xception, Darknet53 and EfficientnetB0 in predicting COVID-19 from CT scans. Features

extracted using the aforementioned CNNs in combination with KSVM classifier achieved significant performance in the classification of COVID-19 vs. non-COVID-19. There can be combinations of CNNs that could provide better results. We leave it to the readers to experiment with more combinations of pre-trained CNNs to come up with improved results. A multi-class classification of CT scans into COVID-19, normal, viral pneumonia and bacterial pneumonia using an ensemble of CNNs is proposed as future research work.

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