Section A-Research paper
ISSN 2063-5346

Unveiling Face Detection Techniques through Mathematical Insights

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Abstract*—Face detection techniques have been expanded since the 1960s, and advances in machine learning and deep learning have revolutionized the field. Face detection algorithms are widely used in various applications, including security, surveillance and social media. TheViola–Jones object detection framework is the first to give a competitive object detection rate in real-time, introduced by authors Paul Viola and Michael Jones in 2001. However, it can be trained to detect different object classes, primarily inspired by the face detection problem. The most common features used for facial recognition include shape, color, and texture. These systems are often combined with other technologies, such as facial recognition, to improve accuracy and performance further. Face detection systems are becoming increasingly popular because they help identify people quickly and accurately. This review paper explores and reviews the basis of mathematical equations and the evaluation of various techniques and models, such as CNN-based models, their architecture and their pros and cons. In addition, facial color, gender bias, dataset bias, and facial features in low-resolution images are still a challenge that needs to be worked on.

Index Terms—*Face Detection, ANN, CNN, Deep Learning.*

I. Introduction

Face detection techniques leverage mathematical insights to accurately identify and locate human faces in images or videos. Concepts such as Haar-like features, integral images, convolutional neural networks (CNNs), intersection over union (IoU), and non-maximum suppression (NMS) play vital roles in the development of robust and efficient face detection algorithms. Researchers continue to enhance face detection capabilities by applying mathematical principles, enabling various applications in fields like biometrics, surveillance, and augmented reality.

II. An Overview of Available Face Detection Systems

This article provides the various face detection techniques in a literature survey of video and image-based face detection [1]. Also, we realized that it is mainly two steps methodology that involves face detection and face recognition [2]. To get a high recognition rate, detection plays a significant role. In recent years researchers have developed several face detection and face recognition algorithms. Here is a general mathematical briefing of some available face detection systems.

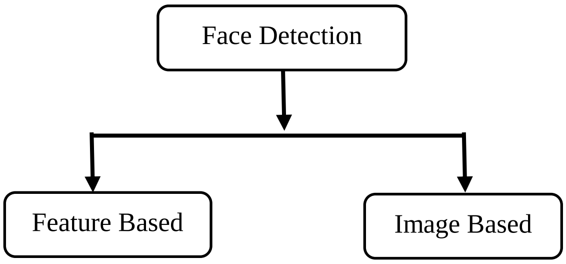

Fig. 1. Face Detection Approach

Many algorithms or methods have been previously implemented and used to detect the availability of faces and localize them within an image. Figure (1) shows the detection process in a still image or image sequence.

III. Feature-based Face Detection models

Feature-based face detection is a methodology that involves identifying specific features of a face, such as the eyes, nose, mouth, and other distinctive facial characteristics, to detect and recognize faces in images or videos [3]. This method is based on the proposal that certain features of a look are more distinguishable and unique than others, making them more reliable for face detection and recognition.

The feature-based face detection methodology generally follows the following steps:

Feature Extraction: The first step in feature-based face detection involves extracting features from the image or video frame [4]. This is typically done using image processing algorithms like edge detection, color segmentation, and shape analysis. These algorithms are designed to identify the critical features of a face, such as the eyes, nose, mouth, and other facial landmarks.

Feature Selection: Once the features have been extracted, the next step is to select the most relevant and distinctive features for face detection. This is done by applying statistical and machine-learning techniques to the extracted features [5]. For example, based on training data, a machine learning algorithm may be used to identify the features most likely present in a face.

Feature Matching: The final step in feature-based face detection involves matching the extracted features with a database of known faces or facial features [6]. This is done using algorithms such as template matching or distance-based matching.

While feature-based face detection has been widely used, it has some limitations. For example, it may not work well in cases where the lighting conditions or camera angle differ from those in the training data [7]. Additionally, it may not be able to handle faces that are partially obscured or occluded by other objects.

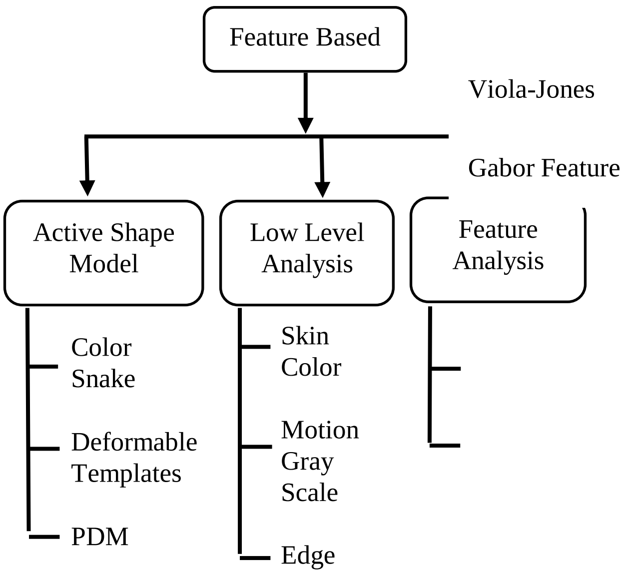

Fig. 2. Feature-based Face Detection Model Algorithms

Despite these limitations, feature-based face detection remains valuable for many applications, such as security and surveillance, image and video analysis, and biometric authentication. A few best feature-based face detection model algorithms are shown in Figure 2 and explained below.

A. Color Snake Method

Color Snakes is a face detection method that uses an active contour model, also known as a snake, to detect the outline of a face in an image [8], [9]. The technique works by optimizing the snake's position [10] and shape to match the face's color distribution. Here's how it works:

The curvature measures how much the contour deviates from a straight line at each point and is given by the formula:

$$k = (x''y' - x'y'') / (x'^2 + y'^2)^{1.5}$$

In above equation x and y are the coordinates of the snake point and x', and y' are the first derivatives of x and y. The formula gives the internal energy term

$$E\_internal = alpha * sum(k^2)$$

Where alpha is a weighting factor that controls the importance of the internal energy term.

External Energy: The external energy term measures how well the snake matches the color distribution of the face. It is defined as the negative log-likelihood of the color histogram of the image inside the snake contour [11]. The color histogram is computed in a color space such as RGB [12] or HSV and is represented as a vector of counts for each color bin. The formula gives the external energy term

$$E\_external = beta * sum(log(p))$$

Where p is the probability of the color histogram at each point inside the snake contour, [13] and beta is a weighting factor that controls the importance of the external energy term [14].

Optimization: The final step is to optimize the position and shape of the snake by minimizing the energy function. This is done using an iterative algorithm such as gradient descent [15], which updates the part of each snake point based on the gradient of the energy function. The algorithm continues until the energy function converges to a minimum, indicating [16] - [18] that the snake contour matches the color distribution of the face.

B. Deformable Templates method

The Deformable Templates method is a computer vision technique used for face detection [19] - [21], which involves fitting a deformable model to an image. This method uses a shape model to represent the face and then deforms it to fit the image [22].

The Deformable Templates method consists of the following steps.

The cost function used in the Deformable Templates method can be written as

$$E = E\_shape + E\_appearance + E\_regularization$$

Where E_shape measures the shape similarity between the model and the image, E_appearance measures the appearance similarity between the model and the image, and E_regularization is a term that encourages smoothness of the deformation.

The shape similarity term can be written as

$$E\_shape = \sum(d\_i - m\_i)^2$$

Where d_i is the distance between a landmark in the image and the corresponding landmark in the model, m_i is the mean distance between the milestones in the training set, and the sum is taken over all landmarks.

The appearance similarity term can be written as

$$E\_appearance = \sum w\_i||I\_i - T\_i(x\_i)||^2$$

Where I_i is the image patch centred on the ith landmark, T_i is the appearance template for the ith milestone, x_i is the position of the ith landmark in the deformed model, and w_i is a weight that balances the contributions of different landmarks.

The regularization term can be written as

$$E\_regularization = \alpha\sum||\nabla x\_i||^2$$

Where α is a regularization parameter that work on the amount of smoothing, and ∇x_i is the gradient of the position of the i^{th} landmark concerning the image coordinates.

The Deformable Templates method can be visualized using a diagram showing the algorithm's main steps and components. The chart typically represents the shape model, the cost function, the iterative optimization process, and the classification step.

The shape model is represented as a set of points connected by edges. The cost function is shown as a combination of shape similarity, [23] appearance similarity, and regularization terms. The iterative optimization process is shown as a loop that iteratively adjusts the positions of the points to minimize the cost function. The classification step is a thresholding [24] operation that decides whether the image contains a face based on the cost function's output [25].

C. *Skin Color based method*

A skin color-based method is a popular approach for detecting faces in images based on the assumption that human skin color falls within a specific range of color valuesb [26]. This method involves selecting a skin color model, which is used to segment the image into regions likely to contain skin pixels [27] - [29]. The skin regions are then processed to detect faces based on size, shape, and texture. The skin color-based method consists of the following steps.

This is typically done by applying a classifier trained on positive and negative examples [30], [31]. The skin color model used in the method can be represented as a probability distribution function.

$$P(Skin|RGB) = \frac{P(RGB|Skin)P(Skin)}{P(RGB)}$$

where P(Skin|RGB) is the probability of a pixel being skin given its RGB color value, P(RGB|Skin) is the probability of a skin color given the RGB color value, P(Skin) is the prior probability of a pixel being skin, and P(RGB) is the marginal probability of the RGB color value.

The skin color model is typically created using a training set of skin and non-skin images, and the probabilities are estimated using maximum likelihood or Bayesian estimation.

The skin region segmentation step can be visualized using a diagram that shows the process of classifying each pixel as skin or non-skin based on the skin color model [32].

The skin color model is represented as a probability distribution function, which is used to classify each pixel as skin or non-skin based on its RGB color value [33]. The skin regions are then extracted from the segmented image, and the face detection process is applied to these regions to identify face candidates [34]. Finally, a classifier is used to classify the face candidates as either containing a face or not.

Limitations: The skin color-based method is a simple and effective approach for detecting faces in images [35]. However, it has some limitations [36], [37], such as being sensitive to changes in lighting conditions and being prone to false positives in regions with similar color distributions to skin.

D. *Edge Detection Method*

The edge-based method for face detection is a technique that relies on detecting edges and contours in an image and then analyzing these features to determine the presence of a face [38]. This method involves several steps, including edge detection, feature extraction, and classification [39], [40].

The edge-based method can be mathematically represented using a set of image processing operations. Let I be the input image, and let E be the edge map obtained by applying an algorithm of edge detection, such as the Canny edge detector.

$$E(x,y) = Canny(I(x,y))$$

Where Canny is the edge detection algorithm.

Finally, the face candidates are classified as either containing a face or not using a classifier trained on a set of positive and negative examples. This is typically done using machine learning algorithms for example support vector machines (SVM), neural networks or decision trees.

The edge-based method can be visualized using a diagram that shows the process of detecting edges, extracting features, and classifying face candidates.

The input image is first processed using an algorithm of edge detection, such as the Canny edge detector, to obtain an edge map. The edge map is then processed using the Hough transform and Harris corner detector to extract facial features. The feature maps obtained by applying the Hough transform and Harris corner detector are then processed using algorithms such as template matching [41], Hough transforms, and classifiers to detect face candidates. Finally, a classifier is used to classify the face candidates as either containing a face or not.

Advantages: The edge-based method for face detection has several advantages, such as being robust to changes in lighting conditions [42] and facial expressions and detecting faces even in low-resolution images.

Limitations: However, it also has a few limitations, like being prone to false positives in regions with similar texture patterns to faces and being sensitive to variations in the quality of the edge map [43], [44].

E. *Viola Jones Algorithm*

The Viola-Jones algorithm [45] is a popular method for face detection that uses a combination of Haar features and a machine learning algorithm called the AdaBoost algorithm. This algorithm was proposed in 2001 [46] by Paul Viola and Michael Jones and has since become a widely used method for real-time face detection.

The Viola-Jones algorithm [47] involves several steps for face detection. Here is an overview of the process with relevant mathematical equations.

Haar-like Feature Extraction

- Haar-like features are defined as the difference of the sums of pixels within rectangular regions [48].
- A Haar-like feature is represented as follows:
- H(x, y, w, h) = sum of pixel intensities in the white region - sum of pixel intensities in the black region

- Here, (x, y) represents the top-left corner of the feature window, and (w, h) represents its width and height [49] – [51].

Integral Image Calculation

- The integral image I(x, y) represents the sum of pixel intensities from the top-left corner to the pixel (x, y).
- It is computed recursively using the following equation [52].

$$I(x,y) = I(x-1,y) + I(x,y-1) - I(x-1,y-1) + Image(x,y)$$

- Here, Image(x, y) represents the original image's pixel intensity at coordinates (x, y) [53].

Feature Selection

- The AdaBoost algorithm [54] is used to select the most discriminative Haar-like features.
- Each feature is associated with a weak classifier [55] that determines whether the region contains a face.
- The weak classifier is defined as a weighted sum of the Haar-like features.

$$f(x) = \{1 \; if \; \Sigma[\alpha\_i * H\_i(x)] >= \theta, 0 \; otherwise\}$$

- Here, α_i represents the weight of the i-th feature, H_i(x) is the i-th Haar-like feature value at location x, and θ is a threshold.

Cascading Classifier

- The weak classifiers [56] are organized into a cascade of stages to reject non-face regions efficiently.
- Each stage consists of multiple weak classifiers.
- The output of each stage is determined using the following equation.

$$Stage(x) = \{1 \; if \; \Sigma[w\_i * f\_i(x)] >= \theta\_s, 0 \; otherwise\}$$

- Here, w_i represents the weight of the i-th weak classifier, f_i(x) is the output of the i-th weak classifier at location x, and θ_s is a stage threshold.

Detection

The cascade of stages is applied to the integral image.
If a region passes all stages, it is considered a face detection.

Advantages

- Fast and efficient: The algorithm is designed to perform face detection rapidly, making it suitable for real-time applications.
- Robust to lighting conditions: Viola-Jones features are effective in capturing local intensity differences, enabling face detection in varying lighting conditions [57].
- High detection accuracy: The combination of Haar features, AdaBoost, and the cascading classifier results in accurate face detection with a low false positive rate.
- Low memory footprint: The integral image representation and cascading structure minimize memory requirements, making it feasible to implement on resource-constrained devices.

Limitations

- Sensitivity to pose and occlusion: The algorithm may struggle to detect faces when they are in extreme poses or partially occluded.
- Limited to frontal faces: Viola-Jones is primarily designed for detecting frontal faces and may have reduced performance for profiles or non-frontal orientations.
- Sensitivity to scale: The algorithm may struggle with face detection at very small or very large scales, requiring additional techniques for multi-scale detection [58].
- Requires training: The algorithm relies on a training phase to select and train the classifiers, which requires a diverse and representative dataset.
- Despite these limitations, the Viola-Jones algorithm remains widely used and serves as the basis for many modern face detection approaches. Over the years, researchers have developed extensions and improvements to address some of these limitations, such as using more sophisticated features, incorporating machine learning techniques, or combining multiple algorithms for robust face detection.

F. Gabor Feature-Based Method

The Gabor filter is a commonly used feature extraction method in face detection and recognition. It is a bandpass filter tuned to detect features of different orientations and frequencies in an image [59]. The filter is defined in the spatial domain and has a complex sinusoidal waveform modulated by a Gaussian envelope. The following equation gives the Gabor filter [60].

$$g(x,y,\theta,\lambda,\psi,\sigma) = exp(-((x^\wedge 2 + y^\wedge 2)/\sigma^\wedge 2)) * cos(2\pi x/\lambda + \psi)$$

where:

- x and y sign are the spatial coordinates of the filter
- θ is the orientation of the filter
- λ is the wavelength of the filter
- ψ is the phase offset of the filter
- σ is the standard deviation of the Gaussian envelope

In face detection, the Gabor-LBP features are often used as input to a classifier, such as Support Vector Machines (SVM), to distinguish between face and non-face regions in an image [61]. The classifier is trained on positive and negative examples, where the positive samples are images containing faces, and the negative examples are non-face images.

Overall, the Gabor feature extraction method provides a robust and efficient way to capture an image's local frequency and orientation information, which is essential for face detection and recognition. The combination of Gabor filters and LBP codes further improves the method's robustness to variations in illumination and noise.

IV. Image-based Face Detection models

Image-based face detection methods refer to techniques that aim to identify and locate human faces within digital images [62], [63]. These methods utilize various computer vision and machine learning algorithms to analyze image features and distinguish facial patterns from th PCA nd. Image-based face detection methods typically eps such as preprocessing, feature extraction, and on. Preprocessing techniques may include im SVM ng, normalization, or filtering to enhance the quality of the input image [64]. Feature extraction methods extract relevant facial features, such as Haar-like features, Local Binary Patterns (LBP) [65], or Deep Convolutional Neural Networks (CNN) [66].

Finally, classification algorithms, such as Support Vector Machines (SVM), AdaBoost, or Neural Networks, are employed to determine whether a region of interest contains a face or not. Image-based face detection methods have made significant advancements in recent years, enabling robust and real-time face detection in various applications. A few best image-based face detection models are shown in Figure (3) and explained below.

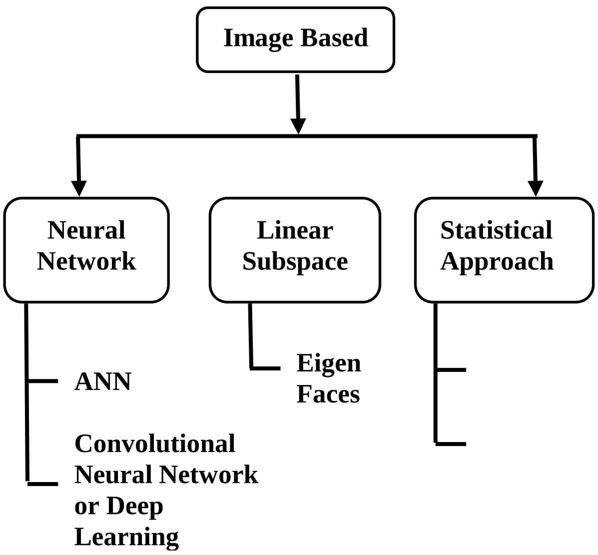

Fig 3. Image-based Face Detection Model Algorithms

A. Artificial Neural Network

In face detection, ANNs can achieve high accuracy and robustness to lighting, pose, and occlusion variations. However, ANNs [67] can be computationally expensive and require much training data to perform well.

The structure of an ANN consists of layers of interconnected neurons. The first layer is the input layer, where each neuron represents a feature of the input image. The last layer of the output layer, which contains a single neuron that outputs a value between 0 and 1, representing the probability that the input image includes a face. The intermediate next upcoming layers are called hidden layers, and each neuron in a hidden layer performs a non-linear transformation of its inputs to produce an output that is then fed to the next layer.

The weights between the neurons in an ANN are initially randomly assigned. The network is trained using a supervised learning algorithm, such as backpropagation, to adjust the weights based on the difference between the network's output and the expected output. As shown in Figure (4), during training, the network is presented with a set of labelled images, each labelled as either containing a face or not. The network output is compared to the labelled output, and the weights are adjusted to minimize the difference between them. This process is repeated until the network's output matches the labelled output for a sufficiently large number of images.

The input features for face detection can be extracted using various techniques, such as the Haar-like features used in the Viola-Jones algorithm. These features are computed by subtracting the sum of the pixel values in one rectangular region from the sum in another rectangular area. The resulting value is then compared to a threshold to determine whether the feature is present in the input image as shown in figure (4).

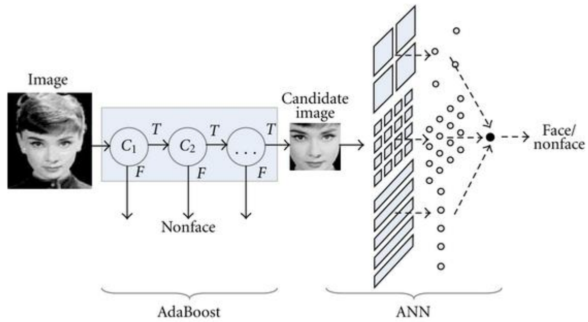

Figure 4. The process of detecting faces of ABANN [68]

The activation function of each neuron in an ANN determines its output based on the weighted sum of its inputs. A commonly used activation function in ANNs for face detection is the Rectified Linear Unit (ReLU), which computes the output as the maximum of the input and zero.
Once an ANN has been trained, it can classify new images as containing a face [69]. The input image is first important preprocessed to extract the all features using the same technique as during training. The parts are then fed into the network, and the output of the output layer is used to determine whether the input image contains a face.

In summary, ANNs are powerful machine-learning algorithms for face detection that can learn to distinguish between face and non-face regions in an image based on a set of input features. The network's weights are adjusted during training to minimize the difference between the network's output and the expected output for a group of labelled images. Once trained, the network can classify new images as containing a face.

B. Convolutional Neural Network

Convolutional Neural Networks (CNNs) are a type of Deep Learning algorithm that has revolutionized the field of computer vision, including face detection, as shown in Figure (5). CNNs [70], are designed to automatically learn hierarchical representations of features from the input images without explicit feature engineering.

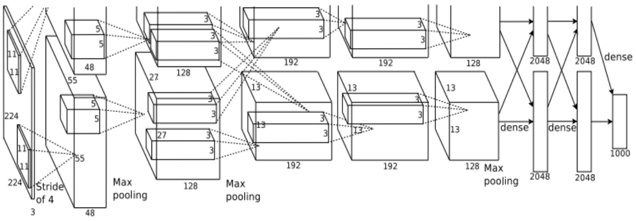

Figure 5. An illustration of the architecture of CNN [71]

Let's consider a simple example of a CNN with one convolutional layer and one fully connected layer. Let X be the input image, with dimensions W x H x D, where W is the width, H is the height, and D is the number of color channels (usually 3 for RGB images) [72]. We will use a single convolutional filter with dimensions F x F x D, where F is the size of the filter. The output of the laye of convolutional is a feature map, Z, with dimensions (W-F+1) x (H-F+1) x 1. The outcome of the pooling layer is a downsampled feature map, P, with dimensions (W-F+1)/S x (H-F+1)/S x 1, where S is the stride of the pooling operation. Finally, the output of the fully connected layer is a vector of probabilities, Y, with dimensions 1 x 2, representing the probabilities of the input image containing a face or not incorporating a face.
The convolution operation can be defined mathematically as follows.

$$Z(i,j) = relu(sum(sum(sum(X(i{:}i+F-1, j{:}j+F-1, :).*W)))) + b$$

Where Z(i,j) is the activation at position (i,j) in the feature map, relu is the rectified linear unit activation function, X(i:i+F-1,j:j+F-1, is the input window at position (i,j), W is the convolutional filter, and b is the bias term. The relu function sets negative values to zero while preserving positive values.

The pooling operation can be defined mathematically as follows

$$P(i,j) = max(Z(iS{:}iS+F-1, jS{:}jS+F-1))$$

Where P(i,j) is the activation at position (i,j) in the downsampled feature map, and max is the maximum pooling operation.
The output of the fully connected layer can be defined mathematically as follows.

$$Y = softmax(W * P + b)$$

Where Y is the vector of probabilities, softmax is the softmax activation function, W is the weight matrix, P is the input vector, and b is the bias vector.

The CNN is trained [73] using backpropagation and the cross-entropy loss function to minimize the difference between the network's output and the expected output. During training, the weights are adjusted iteratively to reduce the loss. Once trained, the web can classify new images as containing a face.

In summary of CNN, CNNs are a robust Deep Learning algorithm for face detection that can automatically learn hierarchical representations of features from the input images [74]. The network's architecture is designed to extract local features from the input image using convolutional filters and to learn shared parameters across different regions of the input image.

V. Overall Limitations and Discussion

Face detection techniques have made significant advancements in recent years but still have some limitations. Here are some common limitations of face detection techniques as of the current study and research knowledge cutoff in September 2021.

Variability in pose and viewpoint: Face detection algorithms struggle when faces are captured at extreme angles or in non-frontal poses. Recognizing faces in profile views or with severe occlusions (such as partial face coverings) can be challenging.

Occlusion: When a face is partially or fully covered by objects like sunglasses, masks, or hands, face detection algorithms may fail to accurately detect the face or may mistake the occluding object as part of the face.

Lighting conditions: Poor lighting conditions, extreme shadows, or strong highlights can affect the accuracy of face detection algorithms. Low-light environments or overexposed images may make it difficult to detect faces reliably.

Scale and resolution: Faces can appear at different scales in an image, and face detection algorithms need to be robust to variations in size and resolution. Detecting small faces or faces in images with low resolution remains a challenge.

Ethnicity and gender bias: Some face detection algorithms have shown biases towards certain ethnicities or genders. This bias can result in lower accuracy or misidentification for specific demographic groups.

Dataset bias: Face detection algorithms heavily rely on training data, and if the training dataset is not diverse or representative enough, the algorithm's performance can be limited. Lack of diverse data can lead to biased results or reduced accuracy across different populations.

Computational requirements: Many face detection techniques require substantial computational resources, making real-time or high-speed face detection challenging on devices with limited processing power.

It's important to note that the field of face detection is continuously evolving, and new research and advancements may address some of these limitations.

VI. CONCLUSION AND FUTURE WORK

In conclusion, when comparing the most relevant and latest face detection methods, it is evident that deep learning-based approaches, such as Convolutional Neural Networks (CNNs) and their variants, have emerged as state-of-the-art techniques. These methods leverage the power of deep learning to learn discriminative features and exhibit robustness to variations in pose, lighting conditions, and occlusions. Among these methods, Single Shot MultiBox Detectors (SSD) and Multi-task Cascaded Convolutional Networks (MTCNN) have garnered attention for their high accuracy, real-time performance, and ability to handle challenging scenarios.

However, future work should focus on improving occlusion handling, enhancing real-time performance for resource-constrained devices, addressing privacy and ethical considerations, improving robustness to environmental factors, and diversifying training datasets to ensure fairness and representativeness across different populations. By addressing these challenges and exploring these research directions, face detection technology can continue to advance and contribute to developing more sophisticated computer vision systems.

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