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Unimodal and Multimodal Biometric Sensing Systems: A Review

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ABSTRACT Biometric systems are used for the verification and identification of individuals using their physiological or behavioral features. These features can be categorized into unimodal and multimodal systems, in which the former have several deficiencies that reduce the accuracy of the system, such as noisy data, inter-class similarity, intra-class variation, spoofing, and non-universality. However, multimodal biometric sensing and processing systems, which make use of the detection and processing of two or more behavioral or physiological traits, have proved to improve the success rate of identification and verification significantly. This paper provides a detailed survey of the various unimodal and multimodal biometric sensing types providing their strengths and weaknesses. It discusses the stages involved in the biometric system recognition process and further discusses multimodal systems in terms of their architecture, mode of operation, and algorithms used to develop the systems. It also touches on levels and methods of fusion involved in biometric systems and gives researchers in this area a better understanding of multimodal biometric sensing and processing systems and research trends in this area. It furthermore gives room for research on how to find solutions to issues on various unimodal biometric systems.

INDEX TERMS Biometrics, identification, verification, multimodal, unimodal, sensing, and non-universality.

I. INTRODUCTION

Biometric sensing and processing systems are vital tools used for the verification and identification of individuals. Verification entails confirming that individuals are who they claim to be. The system takes and compares a biometric feature against an existing biometric profile linked to that individual seeking to obtain a match. An identification system searches for the identity of an unknown person or biometric entity by comparing the presented biometric feature with many others in an existing database. Hence, verification involves a one-to-one (1:1) search, while identification is achieved when a biometric system makes a one-to-many (1: N) search [1]–[5].

Biometric systems utilize an individual's human body characteristics which do not normally change over time, such as the face, iris, fingerprints and handprints, and identification involves the enrollment of these traits in a database for future recognition purposes, as shown in Figure 1. In addition, individuals can be verified or identified based on behavioral features, for instance signature, speech, typing rhythm and gait [6].

Biometric traits exhibit a robust connection to an individual based on his/her identity and such traits can rarely be shared or forged. Biometric systems prevent users from making false verification or identification claims, since they require the real individual to be involved in using the system [4]. Zureik and Hindle [7] point out that these live patterns, such as the face, iris, and fingerprint, etc. are used in applications such as border control, government needs, authentication on mobile phones; and time and attendance management. A biometric system provides two important functionalities, i.e. [i] verification and [ii] identification. During verification, the system checks if a claim from a user is an authentic claim [8], [9].

A typical example is a computer system where the user can claim a particular identity, such as ''name A'' by tendering an identification number that is meant to be personal. Since the system requires the biometric data of an individual and compares it with a given name in the database, it is termed 1:1 matching. Hence, the claim will be accepted as genuine when the input from the individual has an acceptable similarity with existing records from the identity that is claimed and the applicant will be called an impostor if the claim is rejected [8]. Therefore, during verification a biometric system shows that ''you are who you say you are''. In identification, on the other hand, an individual is trying to claim that he/she is one of the people registered in the database. In this functionality of

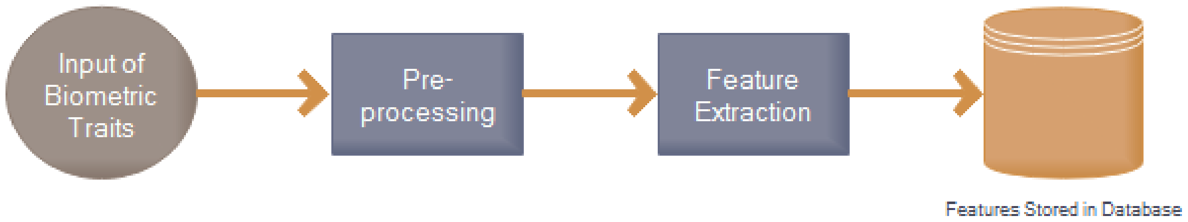

FIGURE 1. Showing the process involved in registering a biometric trait.

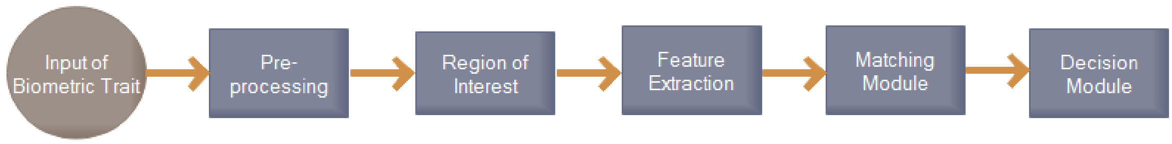

FIGURE 2. Stages Involved in a Biometric System during Recognition.

the biometric system, the individual's input is cross checked within the database to confirm his/her identity with the highest level of similarity that is subsequently produced [9].

Furthermore, a reject decision is produced when a fixed minimum threshold is not reached after it has been found that there is no familiarity between the input being checked with the templates. This signifies that the individual is an impostor. Hence, the matching in an identification process of the biometric system is 1:N. The identification system shows that an individual is "someone who is known to the system" [8], [9].

This paper gives a detailed review of both unimodal and multimodal biometric systems, highlighting the problems associated with unimodal biometric systems such as noisy data, inter class similarity, intra-class variation, spoofing and non-universality. This paper has reviewed over 200 publications with most of them being between 2011 and 2016 from IEEE Xplore, Science Direct, Springer and Google Scholar. Other sections of the paper are as follows: Section 2 describes the stages involved in a biometric system. Section 3 is an overview of the various types of biometric systems. Section 4, discusses the classification of biometric systems. Section 5, describes the different modes of involved in the biometric identification process. Section 6, discusses the various levels of fusion in multimodal biometric systems, while Section 7, highlights the different methods of fusion in multimodal biometric systems, Section 8 discusses the challenges of biometric sensing systems, thereby identifying opportunities for further research and Section 9 concludes the paper.

II. STAGES IN BIOMETRIC RECOGNITION SYSTEM

A. PRE-PROCESSING STAGE

As seen in Figure 2, stages involved in the process of a biometric system include the pre-processing stage, feature extraction stage, matching and decision stage. Pre-processing stage involves processing the biometric data acquired from the sensor with the use of a computer such that it improves the quality of the biometric data.

In biometric system, the pre-processing stage [10] plays a crucial role for identification. Furthermore, pre-processing is always used to correct distortions and to get the region of interest for feature extraction. In practice, many of the proposed methods work best when the data used has been normalized or whitened. However, the precise parameters used in pre-processing dataset are often not immediately apparent, except one possesses the needed experience working with the algorithms. Common methods for normalizing data during pre-processing are simple rescaling, per-example mean subtraction and feature standardization [10]. Xu et al. [11] proposed an approximately symmetrical face image for image pre-processing in face recognition by taking the axis-symmetrical nature of faces into consideration.

This was thereafter used to design a framework to produce an approximate axis-symmetrical virtual dictionary to enhance the accuracy of face recognition. Rehman and Saba [12] in their work proposed a neural network for document image processing. They leveraged on the fact that neural network are popular and has been successfully implemented in biometrics to perform crucial function in document layout analysis and classification. This is used to enhance the actual image for further analysis by breaking it down into smaller tasks like line removal, skew estimation and correction, base-line detection etc. Goh et al. [13] has also proposed a wavelet local binary patterns fusion as illuminated facial image pre-processing for face recognition. Han et al. [14] carried out a comparative study on illumination pre-processing in face recognition and grouped them into three main categories based on different principles; gray-level transformation, gradient or edge extraction and reflectance field estimation. Experimental results show that localization of some holistic illumination pre-processing approaches improves the performance. Reference [15] used fives steps to achieve a high quality of fingerprint image.

The steps include: normalization, Orientation Image Estimation, Frequency Image Estimation, Region Mask Generation and Filtering (Gabor Filter). Using these steps, results showed that it was possible to detect all the minutiae present in the fingerprint image which are further used for identification. Reference [16] presented four steps for the pre-processing stage in the design of a face recognition system. The steps included: Gamma correction, Difference of Gaussian (DoG) Filtering, Masking and Equalization of Variation. To remove noise in a hand written signature verification system using median filter, image binarization using Otsu binarization algorithm and cropping signature the following pre-processing steps were used normalization, re-sampling, smoothing and image enhancement [17]. To improve the performance of an automatic speech recognition system, the input speech was passed through the linear predictive analysis filter. Experiments using standard feature vectors showed that the Linear predictive filter improves robustness in speech recognition performance [18]. For an iris biometric recognition system, Lili and Mei [19] proposed a pre-processing technique by introducing an iris localization algorithm and also adopted the edge points detecting and curve fitting. Experiments on 2400 iris images from the Institute of Automation, Chinese Academy database showed that all the procedures used were valid. For a secured personal identification system based on human retina, Fatima et al. [20] proposed a pre-processing technique that extracts the vascular pattern from input retina image using wavelets and multi-layered threshold technique. In biometric online signature verification, López-García et al. [21] pre-processed the data to reduce noise and normalize the signature stroke by following these four steps; filtering, equally-spacing, location and time normalization and size normalization. For improved sensor interoperability in online biometric signature verification, Tolosana et al. [22] propose a pre-processing stage where data acquired from different devices are processed in order to normalize the signals in similar ranges.

B. REGION OF INTEREST STAGE

The Region of Interest (ROI) in biometric systems is a process embedded within or a process done before moving into the feature extraction stage. The ROI is the process of highlighting key and interesting features in a biometric trait as a smaller region that will further be used as matching characteristics in a biometric system [23].

In palmprint recognition, studies reveal that fixed sizes are used to get the ROI while other studies stated that a region size is extracted which is the size of the palm itself. However, the various ROI methods are dependable on the database of choice. Hence, the database used for the different modalities of biometric systems is also a major factor that will determine the ROI extraction method to be used [24]. The region of interest techniques can be classified into four broad groups namely:

(i) Bottom-Up Feature Based Approaches: this approach aim to locate features where there is varying conditions in lighting, pose etc. and make use of them in the detection procedure. Such approach includes the Scale Invariant Feature Transform (SIFT) which is majorly used for face localization. SIFT works by putting together a scale invariant region detector and a descriptor based on the gradient distribution in the detected regions. Also similar to the SIFT method is the shape context method which shares the same idea , however it is based on edges extracted by the canny detector where the location is quantized into nine bins of a log-polar coordinate system. Furthermore, another similar method is the Histograms of Oriented Gradients (HoG) which uses overlapping local contrast normalization for improving its accuracy and it is computed on a dense grid of uniformly spread cells, proving that using a linear Support Vector Machine it is able to classify humans [25].

(ii) Top-Down Knowledge Based Approach: This approach has the ability to control the false positive situations of detection as it is majorly concerned with the object of interest. Jones and Viola [26] proposed a region of interest approach that considers existing information on an individual's motion and appearance by selecting of feature sets, scale of the training data and scales used for detection. Hence, it does not support a different technique of tracking and alignment.

(iii) Template Matching Approach: this approach uses object parts to represent the global image of the object where due to this connection, there is possibility for computation which is further used for detection. Gagan and Lalitha [27] presented a human detection idea that differentiates foreground regions and extract the boundary. The algorithm further searches for individuals within the image by matching edge features of human silhouette within the database.

(iv) Appearance-Based Approach: This approach deals with learning models from a training set of images which are further used for detection. The approach depends on machine learning and statistical analysis technique to locate unique characteristics of images containing objects. These learned characteristics which are in the form of discriminant functions are further used for detection [25]. Diaz et al. [28] proposed a novel method based on orientation entropy for incomplete fingerprint in order to extract the region of interest and using Poincare index to detect the reference point. Experiments done on the FVC 2004 database showed that the approach located the position of reference of all type of fingerprints. Saliha et al. [29] proposed a region of interest extraction method of the palm that contained its unique features. Key point localization was used to aim at locating crucial points that in order to align the hand image. The method was further based on incorporating the X-axis projection and the projection of the upper and lower edge, thereby allowing the extraction of the horizontal limits of the hand contour.

A 3D face recognition was developed by putting together the entire face with the regions of interest i.e. mouth, nose, left eye and the right eye, where Gabor filter was used to enhance the discriminant information phases and the Principal Component Analysis was applied to the data to obtain a reduced basis projection and discriminant [30].

C. FEATURE EXTRACTION STAGE

Feature extraction is also a very important stage in the identification process of biometric systems. It involves the simplification of the amount of resources which describes a large set of data. Feature extraction is mainly used to minimize the original dataset by getting some properties that can be used to classify and get patterns that are present in the input images [31]. For an offline hand written signature system, two feature extraction approaches were proposed called the static and pseudo-dynamic approaches.

The first approach involved measuring the geometrical features while in the second approach, the estimation of dynamic information of the image were tried [17]. For extraction of features in an ear biometric recognition system, Khobragade et al. [32] proposed sparse representation of ear biometrics and Ghoualmi et al. [33] proposed an invariant method of evolution and internal ear curves. A method for feature extraction called Pulse Active Ratio which is developed based on the principle of Pulse Width Modulation was implemented on the electrocardiogram signal for biometric authentication [34]. Gabor Filter, Discrete Wavelet Transform, Discrete Cosine Transform and Fast Fourier Transform were techniques used for feature extraction on a fingerprint recognition system. Experiment on the FVC 2002 database showed that DCT and FFT performed better compared to DWT and Gabor Filter [35]. Three techniques namely Wavelet Transform based Feature Extraction, Spatial Differentiation and Twin Pose Testing Scheme were used as feature extraction methods to improve the performance of a face recognition system [36].

To locate the optic disc of the retina, Radha and Lakshman [37] used the area threshold and the presence of contours was seen by means of the Hough Transform. For speech recognition system, wavelet based feature extraction method for speech data was presented. Experiment showed that the proposed feature extraction method gave high recognition rate [38]. To improve the performance of voice recognition system, Chauhan and Desai [39] proposed the Mel Frequency Cepstral Coefficients as a feature extraction method that includes wiener filter used to handle the noise in speech. To obtain iris feature from the iris image, [40] proposed an iris feature extraction method that is based on the principal texture pattern and dual tree complex wavelet transform. Also, Lahroodi and Konukseven [41] presented the application of Laplacian-of-Gaussian filters to obtain the isotropic band-pass decomposition of the normalized iris image for feature extraction. Median filter was used as a smoothing technique to remove noise in the border of the hand region in a hand geometry recognition system [42] and thereafter, the Competitive Hand valley detection was used to locate the valley points. Using high resolution approach for palmprint biometric system, features such as orientation, density, principal lines and minutiae are taken as feature extraction [43].

The Matching module stage is where the feature values are compared with the features present in the template thereby generating a matching score. An example in this module is when the facial features extracted are compared with the features present in the template database which is further computed and treated as a matching score. Also, the Decision making module is that stage where the identity of the user is either accepted or rejected based on the matching score generated in the matching module [44].

III. TYPES OF BIOMETRIC SYSTEMS

A. FINGERPRINT BIOMETRIC SYSTEM

The fingerprint is indisputably one of the most well–known biometric traits because of its uniqueness and consistency over time, since it has been used for over a century. In view of the numerous sources available for the collection of data, i.e. ten fingers, its inherent ease in acquisition and its established use and collection by law enforcement and immigration, it has been and still is very popular.

A fingerprint is caused by the friction ridges of a human finger, normally appearing as dark lines, which represent the high, peaking part of the skin as seen in Figure 3. The shallow portions of the skin are the valleys that are represented by the white spaces [45].

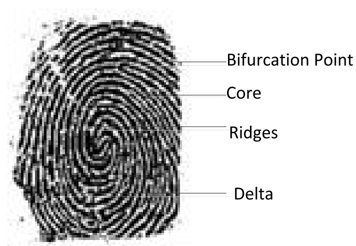

FIGURE 3. Example of a human fingerprint [46].

Human beings are able to grab and hold objects without dropping them because of the presence of the ridges and furrows; because of the space existing between them, friction is created that enables this act to be carried out. The ridges and furrows are not responsible for the uniqueness of fingerprints, rather the ''minutiae''. The minutiae are defined as the pattern created and the uniqueness of the way in which ridges end, split and join, or appear as a simple dot. The minutiae consist of bifurcations, ridge dots, ridge endings and enclosures; to ensure further uniqueness, the minutiae are further broken down into sub minutiae such as pores, crossovers and, deltas. The pores are tiny depressions within the ridge on a fingerprint, crossovers create an X pattern within the ridge of a fingerprint and deltas create a triangle-shaped pattern within the ridge of a fingerprint. Identification in fingerprint technology takes place when an individual fingerprint is compared against a known source called the fingerprint template [46], [47].

The fingerprint biometric system has four main steps which include getting the fingerprint, extraction of the features, saving of the data and comparing the data with other fingerprints in the database. The fingerprint biometric system has since its inception benefited from its level of accuracy, the fact that it is one of the most developed biometric systems, its ease of use and the small storage space required for the biometric template, thus reducing the database memory [48]. The fingerprint biometric system does have weaknesses, among others its high failure acceptance rate that can be caused by scaly or dirty skin of finger and age [49]. Fingerprint recognition has been seen as an important research topic regarding aspects such as mobile authentication. A survey of around 160 users was done by [50] and [51] and users gave a positive response to using fingerprint scanning technology for mobile phones. Oloyede Muhtahir et al. [4] also did a survey on which biometric technology system can be best used to solve the issue of staff attendance in companies. Of all the biometric technology systems, fingerprint recognition systems proved to be preferred for recording attendance. Also, an algorithm for a finger vein recognition system was developed and took less than a second to confirm an input finger-vein sample, achieving a rate of 0.07% equality on a database of 100 subjects [52].

The International Fingerprint Verification Competition, attempting to create a similar benchmark by allowing academia alongside industry to see differences in performance outcomes based on different fingerprint recognition algorithms showed that the most outstanding equal error rate (EER) results for the competition were 1.73% (2000), 0.19% (2002) 2.07% (2004) and 2.2% (2006) respectively. For privacy protection, [53] combined two different fingerprints from the same subject and the extracted minutiae were combined and stored in the database for identification and verification purposes. The system showed during experiment that a 0.04% false rejection rate was achieved, as well as a 0.1% false acceptance rate. Reference [54] developed a fingerprint recognition system where pseudo-singularity points will be detected to enhance fingerprint classification and recognition. Furthermore, a fingerprint-matching approach was proposed that was based on the embedded Hidden Markov Model approach. The fingerprint system was tested on FVC2002-DBI. Using three confidence coefficients, i.e. 99.0%, 99.5% and 99.9%, the false acceptance rate achieved was 0, 4.18% and 8.91% respectively [55]. An approach for embedding a double watermark into fingerprint images was proposed by using a discrete cosine transform algorithm where the function of the algorithm was to enhance the authentication performance based on watermark messages [56].

B. HAND GEOMETRY BIOMETRIC SYSTEM

This is a simple and very straightforward technology that takes the measurements of the human hand to verify identity as shown in Figure 4. Such measurements include shape, length and width of fingers and size of palms. This biometric system is widely used because it is easy to use, enjoys wide public acceptance and has integration capabilities [46], [57]. The shortcoming of the system is that it is not highly unique, thus limiting the system to one-to-one matches only. Other biometric features can be combined with hand recognition to improve its accuracy [58].

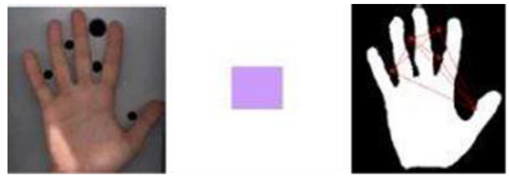

FIGURE 4. Example of the human hand used for a hand geometry biometric system, showing the shape and length of fingers and size of the palm [46].

The palm lines can be obtained using the Sobel operator, a canny edge operator, among others. Examples of the texture feature extraction methods used are Wavelet Transform, Discrete Cosine Transform and Fourier Transform [59]. The hand geometry technology is used for applications such as access control, where one is concerned about an individual trying to gain access by using someone else's card or personal identification number. The hand reader guarantees that a worker is meant to be at a particular place in a working environment and it is also used for time attendance, where the system helps in stopping employees from buddy punching, hence it improves payroll accuracy [46]. A sum-difference ordinal filter was developed for image intensities on mobile devices by [60] to select particular features of palm prints using +/− operations. A biometric recognition system using a palm print image on a mobile device was also proposed by [61]. The orthogonal line ordinal feature approach was used and it showed what was achievable as a false rejection rate (FRR) of 8.25% and false acceptance rate (FAR) of 0.01%. An Air Auth (a biometric authentication technique that uses an air gesture input to authenticate users) was designed using air hand gestures as an authentication technique to recognize individuals using a short range depth sensor that finds several unique points simultaneously [62].

A novel contactless sensing system used for multisampling hand recognition was proposed to improve the hand recognition system. Results on a database of 100 people representing up to 200 hands showed that the proposed technique performed better when compared to the single- sample approach with about 50% improvement [63]. An algorithm on a hand geometry sensing system was also developed that could distinguish the hand images from the background image. An increase in performance was observed during both the identification process and the verification process, giving percentages of 98% and 99% respectively [64]. Using the combination of principal component and linear discriminator to reduce the dimensionality of the feature vector present on a contour based hand sensing system with high level features, results showed that performance was better after the reduction of the feature levels [65]. A demonstration was done by [66] using a dynamic time warping and chain code method to develop a hand verification sensing system. The system showed that the success rate was proportional to the increase in training samples in the database. A major strength of the system is that in spite of the fact that special hardware is required, it can be integrated into other systems without difficulty; however, its disadvantages include that the system is quite expensive, and it is not valid for arthritic people, since they cannot put the hand on the scanner properly [49].

C. FACE RECOGNITION SYSTEM

Individuals are recognized and identified using the structure of the face, which is made up of peaks and valleys at different altitudes and has features located at varying latitudes and longitudes as seen in Figure 5. It is this feature that the biometric system uses to differentiate between individuals [46]. The face scan captures the face of an individual during enrollment and stores it for future verification of the individual [67]. The face recognition process has matured from using simple geometric models to using sophisticated mathematical representation and matching processes for identification [57].

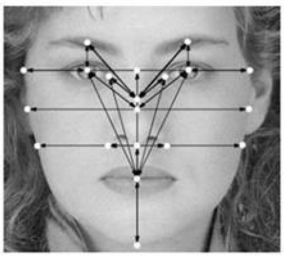

FIGURE 5. An example of the human face made up of peaks and valleys at different altitudes having features located at varying latitude and longitudes [46].

Face recognition systems have attracted much attention among various disciplines. In [68] the authors presented a face-and-eye detection scheme by combining certain features with Ad-aBoost. Promising results were achieved, showing the possibility of authentication via the face on mobile phones. The authentication rate achieved was 82% for (40×40 pixels) and the average authentication rate achieved for (80×80 pixels) was 96%. Moreover, using all available data acquired from a shot close to an individual's head, a mobile device unlock mechanism was proposed [69]. Various neural networks and support machines were evaluated for face recognition and the outcome showed the potential of this approach. A facial recognition method assisted with motion sensors that protect 2D media from attacks was proposed by [70]. The approach verified that using 450 trials in real settings, a detection rate of between 95% and 97% and false alarm rate of 2-3% could be achieved. Apple as a company also came up with an iDevice that could be locked and unlocked using a face recognition system [71]. According to [72], one of Switzerland's largest and most prestigious banks, named Pictet and Banquiers uses a 3D face scan system for the purpose of staff and personal access within the bank environment, which is said to be working effectively. A detailed model based on a graph for face identification was proposed, which was said to be comparable with other face recognition methods and obtained an accuracy of 85% [73]. Based on 3D features, a face recognition system was proposed to improve the performance of the system. For detecting facial features, the active appearance model was used and the experiment showed that classification performance was improved when compared to a traditional classification scheme [74].

A face detection system that is based on a neural network and the color of the skin was implemented. The system showed successful detection of faces on videos and photos [75]. A face recognition system using a support vector machine for detecting the face was also implemented, where elastic graph matching was used to locate the feature points of the facial image. The experiments showed the effectiveness of the face recognition system based on its result [76]. The main disadvantage of the face recognition system is that the system is not functional in the case of occlusion, where part of the face is covered and it is therefore not been able to capture the major and important part of the face. Moreover, until computers include inbuilt cameras as compulsory accessories, it is unlikely to become prominent [49], [67], [77].

D. IRIS BIOMETRIC RECOGNITION SYSTEM

Iris scan technology is one of the most reliable biometric systems developed recently for identification and verification [72]. The biometric technology system falls under the eye category because it involves the eye in identifying an individual as seen in Figure 6. The process whereby an individual is identified by the pattern of the iris is described as the iris recognition process.

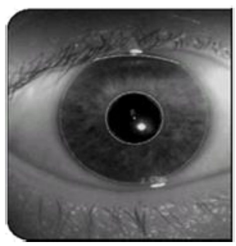

FIGURE 6. An example of the human eye used for the iris recognition system [46].

The iris is seen as the muscle in the eye that regulates the pupil size to control the supply of light rays that enter the eye [45]. According to [57], the annular region of the eye that is guarded by the sclera [white of the eye] and the pupil is called the iris. Aleksandra Babich stated that the unique pattern formed by the iris is what is used by the iris scan technology to uniquely identify an individual and that the iris pattern of an individual is also different from those of others [46]. This statement was further supported by the saying that ''even the iris of a set of twins are different'' [2]. Based on iris information iris recognition systems used at present are effective because of their speed and accuracy that make the system an evolving and widely used biometric system.

Enrollments require many images of the iris pattern, making the enrollment process rather long. When an individual's iris is scanned, a new template is produced and it is then compared with the existing templates that were produced during enrolment [46]. Most companies that have implemented iris based technology for the purpose of staff and customer identification have achieved significant, quantifiable and cost justifying benefits [78]. To improve the work done on iris recognition on phones, the idea of incorporating iris segmentation and the pupil of the eye was proposed [79]. For users wearing glasses, an iris recognition system on mobile phones that is based on corneal specular reflections was proposed [80], using a mobile phone camera to capture 400 iris images from 100 people. The experiment revealed the correct rate of the system was 99.5% for images of people not wearing glasses and 98.9% for those wearing glasses, with 0.05% EER on detected iris images. In early work on the iris recognition system, an iris sensing method based on opening of the eyes was proposed [81], where features such as eyelashes and the eyelid were removed. The length and width information generated the feature vector while for recognition, the pattern-matching method was used. To characterize the iris texture, zero crossing representation of the one-dimensional wavelet transform was used. This approach had a low recognition rate owing to the fact that it is sensitive to grey value changes [82]. To improve the iris sensing system regarding recognition, [83] proposed a scheme to fuse the Local Feature Based Classifier (LFC) and an iris blob matcher. The iris blob matcher is capable of detecting noisy images, hence assists when the LFC is not sure of its decision in recognizing iris images.

An integro-differential iris method was proposed to detect the iris boundary, the recognition system gave an accuracy of 98% when tested on a number of iris images [84]. An iris- matching technique using a class-specific weight map learned from the training images has also been proposed [85]. Experiments showed that the technique improves the recognition system as well as being effective in the detection of iris images. Furthermore, in other to improve the work done on this type of biometric system on mobile phones with regard to limited computing power, a pre-processed method was proposed. The system showed an advantage that includes better accuracy, reduced verification time and the ability to know if a user is dead or living using retina scans. High costs and much memory needed for data to be stored were indicated as disadvantages of the system [86].

E. HAND WRITTEN RECOGNITION SYSTEM

The handwriting and signatory technology that is used for smaller budgets has recently been preferred by most industries for identification and verification and has been accepted by the government, legal and commercial transactions for the purpose of authentication. As seen in Figure 7, the technology requires an individual to be in contact with a writing instrument in order to drop a signature. Dynamic signature recognition is the measurement of all the various characteristics when an individual makes a signature and these detected characteristics are what identifies an individual. Such characteristics include the speed, velocity, timing and direction of signature strokes that are all analyzed in a X, Y and Z direction [47].

FIGURE 7. Example of the hand written recognition system [46].

This type of biometric system can either be on-line or off-line handwritten signature identification. The former does not involve the physical appearance of an individual while the identification process is taking place while the latter involves the physical appearance of the individual at the point of identification [87]. Like all biometric systems, for verification or identification there must be a recognition template where users sign to create a master template, which is later compared with the signature [46]. The usage of this biometric system in mobile devices in an open way was designed following an experiment involving 20 users where average FAR and FRR of 0 and 1.2 were achieved respectively [88]. Using a database of users 11users and eight and eight mobile device users using a stylus and a finger, an evaluation was carried out and the result revealed that the most efficient EER of 0.2% and 0.3% using a stylus and fingers can be achieved respectively on Samsung Galaxy Note and an EER of 3.48% could be the worst on Asus [89]. Furthermore, an online hand signatory biometric system on touch interface based mobile devices was introduced, which can be represented by a unique feature acquired from characteristics of various analyses computed in real time [90].

A study conducted by [91] to look into various mobile acquisitions for smartphones led to a proposed signature verification system that combined score fusion with Hidden Markov Models. Results from the system showed that an EER of 4% can be achieved in random forgeries. Also, an in-depth study of linguistic profiling that identified individuals on their vocabulary in writing and typing using the short message service was also introduced [92], [93]. A hand signatory system was developed by [94] using a graph norm for fast classification and each signature graph was compared with the stored values in the database where the system showed 94% identification accuracy.

Furthermore, an off-line signature recognition system using both an artificial neural network and moment invariant method was developed [95] and the developers stated that on a set of 30 signatures, the system was 100% accurate. Using three different classifiers, namely the Hidden Markov Model, neural networks and nearest neighbor classifier [96], a hand signatory system was proposed based on angles collected from the edges of signatures for off-line signature identification. Lastly, based on the unique traits of a signature, the system is designed to confirm subjects such that if names are not signed in an even manner there will be difficulty in registering or confirming a user [97].

F. VOICE RECOGNITION BIOMETRIC SYSTEM

The voice recognition system uses an individual's voice for determining identity based on the different characteristic voice features. Figure 8 shows the system for the synthesis of the sound produced by the larynx. The Centre for Laryngeal and Voice Disorder at John Hopkins Hospital described the critical role of the larynx, which is situated in the anterior neck. During the enrollment process using voice recognition technology, a particular voice for an individual is recorded and stored in a master template and used for further verification of that particular individual [46], [98].

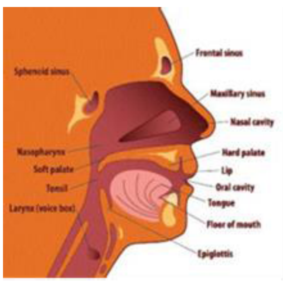

FIGURE 8. The voice recognition production system [46].

The biometric system has been widely implemented in financial institutions for the purpose of remote access telephone services [99]. Using MATLAB, a voice identification based security system was implemented as an access control key where logic 1 represents a good voice match and logic 0 indicate a mismatch. Full accuracy was shown at an allowable deviation set at 15% [100]. Using unique features known as compressed feature dynamics [CFD] that have the ability to capture the identity from speech dynamics, a speaker recognition method was proposed. The proposed approach showed that an EER of 0.5% using a total of 79 speakers can be achieved taking into consideration that each speaker mentions eight chosen passwords and also passwords from other users [101]. For real time speaker verification, an approach was proposed that showed how it was possible to bring together components of voices [99]. An EER of 15% with a total length of 2 seconds was achieved. A challenge-based speaker recognition method to protect against reply attacks on a PDA CMU dataset was proposed and the outcome showed that an EER of 0.83% could be achieved [99]. Siri, an application developed by Apple using voice recognition technology, was aimed at answering questions asked by users.

A system to know or verify a customer within a short time was developed by Barclays using speaker recognition [102]. To detect nodules in vocal folds, a larynx pathology classifier was implemented showing 90% classification accuracy. The classifier was based on linear prediction coefficients, least squares support vector machines and Daubechies discrete wavelet transform [103]. Based on cross correlation of mel frequency cepstral coefficients, a voice recognition system was developed and showed excellent performance in terms of accuracy for recognition of words [23]. To identify a speaker successfully, a voice-sensing system was developed using the multiple support vector machine and mel-frequency cepstral coefficients [104]. A major disadvantage of the voice recognition system is that an authentic voice can be recorded and used by an imposter for unauthorized identification. Also, a cold as an illness changes an individual's voice, which can make identification difficult using the voice recognition system [105].

G. GAIT RECOGNITION BIOMETRIC SYSTEM

This type of biometric recognition system identifies individuals by their posture and the way they walk through unique characteristics that are perceivable at a low resolution, hard to conceal and non – invasive [106]. The gait of an individual can be known easily in public places by the use of simple instrumentation and does not need the active attention of the individual, which is an advantage over other biometric systems. The gait recognition system can be used from a distance, making it very effective and an important biometric method in terms of security and for crime scenes [107]. The framework of the system involves detecting the subject, silhouette extraction, extraction of features, selection of features and classification [108]. As a method of extracting gait features, body part trajectories were introduced. These include the feet and head, which were normalized to appear as they are seen from a front to parallel view-point. A view intensive feature was extracted from the gait energy image and it was assumed that there would be similar and walking patters in the gait energy images that could be used for recognition [109].

A number of publications have discussed the implementation of the gait recognition system. Using various feature representations, a gait recognition system that identifies individuals through view fusion was proposed, where the fusion of various features took place and these were viewed on the Genetic Fuzzy Support Vector Machine [110]. A method called silhouette quality quantification was introduced to evaluate the sequences. It analyzes them based on one-dimensional foreground sum signal modeling [111]. Velocity Hough transform was used on a gait recognition system to establish the motion model of the thighs thereby achieving better performance on median noise immunity [112]. The gait recognition system performance is better by separating the human into components and fusing the results to form a common distance metric [113]. A model of legs to show movement was developed using biomechanics of human and pendular motion [114]. Using a population based generic walking model, a gait recognition system was developed aimed at solving the problems the system encounters such as carrying condition, surface time and movement speed [115].

A view-invariant discriminative projection technique was introduced to transform features of the gait from various views to a low dimensional feature space that has good discriminative ability [116]. To overcome the occlusion problem in gait recognition, a point cloud registration method was presented [117]. Furthermore, using principal component analysis, features of the face and gait were derived differently from a side face image and gait energy image respectively. These features were further fused and multiple discriminant analysis was used to attain the synthetic features. Results showed better performance when compared to individual biometric features [118].

H. PALM VEIN RECOGNITION SYSTEM

This biometric system operates by identifying individuals based on vein patterns that are formed by vast blood vessel networks the skin, reducing the possibility of external distortion and making them difficult to forge [119]. The system makes use of an infrared beam applied to an individual's hand as it is placed over a sensor. Black lines are returned, indicating the veins in the palm, which are compared with an existing vein pattern to confirm the identity of the individual [120].The vein pattern is detectable in living humans and is seen to be unique as it develops before birth and does not change throughout one's life time. Near infrared (NIR) light is used to capture the finger vein image because the hemoglobin in the vein absorbs the NIR light making the vein pattern in fingers appear as shadows [121].

The processes involved in a palm vein recognition system include image acquisition, preprocessing, feature extraction and matching. Significant research has been done on the palm vein recognition system. A palm vein recognition system was developed by investigating two infrared imaging technologies, which were used for biometric purposes [122]. An approach to extract vein minutiae and transform them into a fixed length was followed in developing a palm vein recognition system. It achieved a uniqueness rate of 90% with considerable effective key length [123]. A palm vein recognition system that showed good results in personal authentication and detection of life was developed in three phases namely infrared palm image capture, detection of region of interest and extraction of palm by multi scale filtering and matching [124].

I. EAR BIOMETRICS SYSTEM

Studies have revealed that the appearance and shape of the human ear as seen in Figure 9, give its unique features that change little during a lifetime; similar to facial images, the ear images can also be acquired [125]. The system has three main phases, namely acquisition of the ear images, segmentation of the images and recognition. The first phase can be acquired by using a camera, the second phase is a way of distinguishing the image of the ear from the image background, while the third phase is matching the image with another in an existing database of ear images [126].

FIGURE 9. Showing the shape of the Human ear.

Nippon Electric Company (NEC) recently introduced an ear based biometric system for identification that uses the vibration of sound determined by the shape of an individual's ear which is said to be unique for each individual. The system consists of an earphone with a built-in microphone to acquire sounds as they vibrate within the ear. A method to locate the boundary of the ear was presented by making use of the edge regions as convex curved. Because of occlusion the method showed quite a high rate of false positive matching [127].

An ear recognition system was implemented for 2D intensity images, had 660 images from six people. It is reported that the rate of recognition for registered people was high and that the rejection rate was very low [128]. Using a local surface shape descriptor, 3D ear recognition was presented that showed a 90% recognition rate [129]. A 3D ear recognition system was proposed using local surface patch representation computed at feature points. A Uniform Crime Report (UCR) dataset of subjects with images in different poses was used and a recognition rate of 96.4% was achieved [130].A method using the distance transform that is generated from the binary image was implemented to detect the ear. By using three techniques namely weighted Bayesian, Bayesian and Borda, 2-D images of 28 subjects, an ear recognition system was developed that showed 93% recognition accuracy [131]. By using a local surface shape descriptor, a 3D ear recognition was presented. As an experiment on the system, 20 images from 10 subjects were used and a recognition rate of 100% was achieved [132]. Ear recognition based on geometric feature extraction obtained from 2D images was proposed, and showed a high percentage recognition rate [133].

J. PALMPRINT BIOMETRICS SYSTEM

The palmprint biometric system is a relatively new biometric when compared to other biometric systems such as face, fingerprint and iris recognition systems. As seen in Figure 10, the palmprint has unique and reliable characteristics with high usability. Just like the fingerprint, the palmprint has got unique features such as delta points, principal lines, minutiae features, wrinkles, ridges etc. However, it has got a wider surface area when compared to the fingerprint and hand geometry; hence it is expected to produce unique characteristic traits that have the ability to be reliable when used for identification [134].

The palmprint has got principal lines divided into three regions namely the Interdigital region, Thenar region and

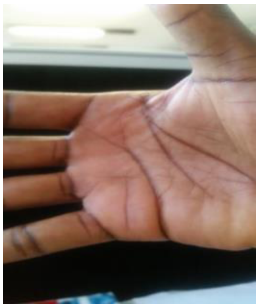

FIGURE 10. An example of the human palmprint.

Hypothenar region. The Interdigital region is seen above the heart line, the Thenar region is seen just below the life line and the Hypothenar is seen between the heart and life line [135]. A main issue that reduces the performance of the palmprint recognition system is the deformation of images brought up during image acquisition. In an attempt to solve this issue, researchers suggested that the palmprint recognition methods should be designed with contact acquisition devices such as pegs. This involves the use of huge devices that will limit the usability of the recognition system on smart mobile devices and can also cause hygienic concerns. Hence, such method constrains the position, stretch and rotation of the palm, thereby still leaving room for improvement in solving this issue. To finally overcome these problems, contactless palmprint recognition was looked upon by researchers, in which the capturing of the palmprint are done without getting in touch with any part of the devices [136]. It is seen from research that the palmprint employs low and high resolution images. Where low resolution images ($<$150 dpi) are majorly suitable for commercial applications such as gaining access control, the high resolution images ($>$ 400 dpi) are more suitable for applications such as criminal detection [137]. Isnanto et al. [134] developed a palmprint recognition system that is based on principle lines feature using Euclidean distance and neural network. To generate input images the system consisted of a webcam embedded with complete software where the principle lines were detected as feature extraction. On a database of 90 palmprint images obtained from 30 people, experiment results showed 90% successful recognition rate. Dai and Zhou [138] proposed the high resolution approach in developing a palm recognition system where various features were extracted, such as orientation, density, minutiae. Radon-Transform-Based Orientation was used for the orientation extraction; Gabor filter was used for the ridges enhancement based on the local ridge direction and density; and the Support Vector Machine was used as the fusion method for the recognition system. Chlaoua et. al. [139] proposed a palm recognition system in which the image is captured under several wave lights and the number of bands is reduced using a clustering process. Gabor filter is used as a technique to extract the features. Experiment is done on a hyper-spectral palmprint database of 300 people, and results showed that the system achieved good identification rate.

Other biometric systems include odour, keystroke and retinal eye scan. The odour of individuals is unique as it contains chemical compositions that can be used for identification. However, it is not certain if the invariance in the body odour can be detected if there is the presence of deodorant or chemical composition of the surrounding environment [140]. Keystroke is the manner in which every individual types on a keyboard in a particular pattern, and it is believed that this behavioural biometric can offer enough information that can assist in identification and verification; however it is not seen as a unique trait to every individual [141]. Retinal scan system involves the retina vasculature which is unique amongst individual and each eye as it is very difficult to replicate or change. The system requires an individual or person to focus the eye on a scanner which leads to a conscious effort. Hence, the system could cause some medical complication such as hypertension and this does not allow the full acceptance of the biometric system by the public [142].

IV. CLASSIFICATION OF BIOMETRIC SYSTEMS

A. UNIMODAL BIOMETRIC SYSTEM

A unimodal (or single) biometric system is a system that uses a single biometric trait [143], [144], or one source of information for verification or identification [145]. Unimodal systems have said to have improved steadily in accuracy and reliability; however, they often suffer from problems in the enrollment process because of non-universal biometric traits, spoofing and lack of accuracy due to noisy data as stated earlier. Furthermore, unimodal biometric systems achieve less desired performances in real world applications. Hence, a method to solve these issues is making use of a multimodal biometric authentication system [146]. The problems associated with unimodal biometric systems are discussed further. Table 1 shows the performance of the various biometric sensing systems.

1) NOISY DATA

Noise is normally present within biometric data when sensors are not properly maintained. A typical example is the presence of dirt on the sensor of a fingerprint scanner, which leads to a noisy fingerprint. Failure to produce the correct voice during enrollment is also a form of noisy data. Furthermore, not being able to focus a camera properly can lead images of the face and iris that are not very clear [146], [147].

2) NON-UNIVERSALITY

A biometric system is said to be universal if all users are able to present a biometric trait for identification. However, not all biometric traits are universal. It has been revealed that about 2 % of a population are not likely to get a good quality fingerprint, i.e. there are individuals with disabilities and other factors that hinder a smooth registration process, meaning that such individuals cannot be included successfully in the database of the system [146], [147].

TABLE 1. Performance of the various biometric sensing systems.

Factors	Biometric Sensing Systems									
	Finger print	Face	Hand Geometry	Iris	Voice	Hand Signatory	Gait	Ear	Palm Vein	Palmprint
Accuracy	High	Low	Medium	High	Medium	Medium	High	High	High	High
Ease of Use	High	Medium	High	Medium	High	High	Medium	Medium	Medium	Medium
Cost	Low	Medium	Medium	High	High	Low	High	High	High	High
Privacy	High	High	Medium	High	High	High	High	Low	Low	Medium
Distinctiveness	High	Low	Medium	High	Low	Medium	Medium	High	High	High
Error Causing Factor	Age	Occlusion	Injury	Eye Angle	Illness	Inconsist ency	Weight Gain	Pose	Illness	Age
Barrier to Universality	Worn Ridges	Plastic Surgery	Hand Impairment	Visual Impairment	Speech Impairment	Forging	Drunken ness	Lighting Conditio ns	Ageing	Worn prints

3) LACK OF INDIVIDUALITY
Traits obtained from a biometric system, such as the face recognition system that deals with facial images, may be quite similar. A typical example is the case of identical twins or father and son. This causes an increase in false match rate that is due to the issue of uniqueness [146], [147].

4) SUSCEPTIBILITY TO CIRCUMVENTION
It is possible to impersonate an individual's trait by an impostor using spoofed traits, such as designing bogus fingers by using fingerprints and using them to wrongfully gain access to a biometric system [72], [73]. Due to these issues of unimodal biometric systems, the error rates in the systems are quite high, making them unacceptable for introduction in security applications. These issues can be addressed by using multimodal biometric systems.

B. MULTIMODAL BIOMETRIC SYSTEM
This system can be defined as one that combines the outcome obtained from more than one biometric feature for the purpose of identification. Unlike a unimodal biometric system that may result in non-universality, a multimodal system uses multiple biometric modalities that can result in highly accurate and secure biometric identification system [148]–[150]. A typical example is the issue of worn fingerprints that may result in error. In a multimodal biometric system such error or failure may not seriously affect an individual because other biometric technology systems are employed. Hence, the failure to enroll rate is reduced in a multimodal system, which is one of its major advantages [151].

Quite a lot of research has been done on multimodal biometric systems: face and voice were fused by using the hyperbolic tangent [tanh] by normalizing and weighing the geometric average [152]. Ross and Jain [44] used linear discriminant-based methods, the sum rule and decision tree to combine face, fingerprint and hand geometry biometrics. The authors reported that the sum rule performed better than the others. Several fusion strategies were taken into consideration, such as the tree classifier, support vector machines and multi-layer perception for voice and face biometrics [153]. Finally, a multimodal biometric system was proposed by combining the ridge-based matching of the fingerprint and Eigen face from the face [154]. Table 2 shows related work on multimodal systems, indicating the type of systems fused together and the algorithm used [155]. At the first module [sensor module] before the raw biometric data of the user can be recorded, it is necessary to incorporate the biometric sensor with a suitable user interface (see Figure 11). Thereafter, the raw biometric data are acquired and transferred further for extraction of features. During this process, the acquired biometric data are accessed based on their quality for further processing. Hence, a digital representation of the traits is generated which is given as an input to the matching module for further comparison.

At the matching level, the extracted features are compared with templates in the database to achieve a match score that is determined by the data quality, and lastly, the decision-making module is informed whether a user is real or an intruder based on the match scores [156]–[158].

V. MODE OF BIOMETRIC IDENTIFICATION
The modes of biometric identification can be in two forms, i.e. Open set identification and Closed set identification which are further described thus:

A. OPEN SET IDENTIFICATION
This type of identification occurs when there is no possibility that the subject presented to the biometric system

TABLE 2. Showing related works in the area of multimodal biometric system and algorithms used.

Researcher[s]	Year	Multibiometric Properties	Algorithm Used
Singhal, D., et al.[158]	2014	Iris and face	Normalization of all features in one domain
Ching, H.C. et al [160]	2003	Fingerprint and online signature	Hidden Markov Model of temporal functions was applied.
Kowtko, M.A.[161]	2014	Fingerprint, hand geometry and voice	Threshold settings are chosen approximately for each individual to improve the system using sum rule based match score level fusion.
Manjunathswamy,B.E. et al. [162]	2015	Fingerprint and face	Normalization techniques [z-score, tanh, two quadrics] and fusion techniques [max score, match weighing] was used.
Zhou X., et al. [163]	2006	Video gait and face	A model based on likelihood ratio is presented deriving the fisher measurement of the system at the sensor fusion level and matched with score Gaussian distribution.
Ghate, M.D.J. et. al. [164]	2015	Fingerprint and face	Neyman-Pearson based methodology was used by combining match scores provided by various biometric matchers.
Hu, X. et. al [165]	2015	Face recognition [video based] framework using 3D face modeling technique	Combining the facial mark matching and commercial face recognition using a fusion scheme to improve the productivity of the system.
Oravec, M. [166]	2014	Face and iris images	The algorithm used was able to detect an individual's face, eyes and other parts of the face.
Wang et. al. [167]	2006	Signature and iris	The final authentication performance was improved by combining the feature and decision level fusion.

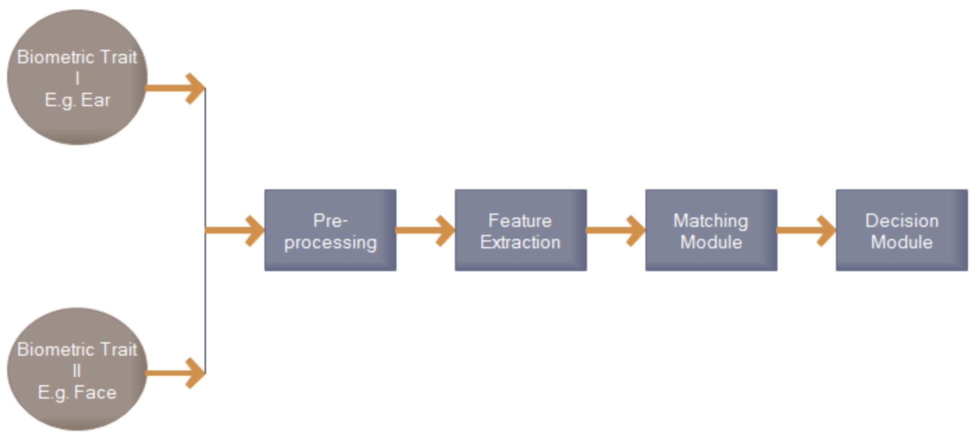

FIGURE 11. Process Involved in a Multimodal Biometric System [159].

has previously been enrolled in the database [168]. An example is the case of a watch list identification from surveillance cameras which involves a continuous check of a list of people as against streaming videos. The open set identification is a situation where the person of interest is not enrolled in the biometric database, in which case the biometric system may return an empty candidate list [169].

This biometric identification mode is of two processes i.e. firstly identify the unknown individual (probe) and decide if the individual should be accepted or rejected; secondly if the probe is on the watchlist, the individual is recognized and added to the biometric database [170]. In a recognition situation, when the unknown individual is presented to the biometric system, it is compared to each individual in the database and computes the similarity. Hence, in an open set identification, the system may not recognize the unknown individual and the first objective is to detect if the unknown individual is present in the database and further obtain its true identification. The following metrics can be used in the open set identification mode:

1) FALSE ACCEPTANCE RATE

This can be described as the rate of accepting an unauthorized individual as a legitimate user, i.e. the system allowing an impostor to have rights in the system. Furthermore, during similarity scaling, if an individual is really an imposter and the threshold has a high matching score, he is seen as a legitimate user and this brings about false acceptance. The FAR is the ratio of falsely accepted users to the total number of impostor users as described as follows [9]:

$$\mathrm{FAR} = \sum_{t=T}^{\max T} FA(t) \Bigg/ \sum_{t=0}^{\infty} AI(t) \tag{1}$$

where T = threshold value, FA = number of falsely accepted users and AI = number of all imposter authentication attempts.

2) FALSE REJection RATE

The FRR quantifies the rejection of authorized individuals, during similarity scaling; it is possible that the user is legitimate but seen as an imposter if the matching score is lower than the threshold. It is the ratio of the number of rejected authorized users to the total number of authorized users [9].

$$\mathrm{FRR} = \sum_{t=T}^{T} RA(t) \Bigg/ \sum_{t=0}^{\infty} AG(t) \tag{2}$$

where T = threshold value, RA = number of rejected authorized users and AG = total number of all genuine verification attempts.

3) FAILURE TO ENROLL

This happens when the biometric system fails to recognize an enrolled user at the point of identification because the user fails to produce the required biometric trait. It is described as the ratio of the number of unrecognized authorized users to the total number of authorized user [9].

$$\mathrm{FTE} = \sum_{t=T}^{T} UA(t) \Bigg/ \sum_{t=0}^{\infty} AU(t) \tag{3}$$

where T = threshold value, UA = unrecognized authorized users and AU = total number of authorized users.

4) FAILURE TO ACQUIRE/FAILURE TO CAPTURE

Failure to acquire occurs when the biometric trait of an individual is present but cannot be captured because of mishandling of the system. It is the probability of the sensor not recognizing a biometric characteristic.

5) GENUINE ACCEPTANCE RATE

For a legitimate user, there are two possibilities i.e. accept or reject. Acceptance will cause genuine acceptance and rejection will cause false rejection.

6) CROSSOVER ERROR RATE/ EQUAL ERROR RATE

The EER indicates when the number of false rejection and false acceptance errors are equal. Balance between FAR and FRR is noticed, i.e. if either is increased the other will decrease [150], [155], [156].

B. CLOSED-SET IDENTIFICATION

This type of biometric identification occurs when there is the possibility that the subject presented to the biometric system has previously been enrolled on the system. It is also a biometric task where an unknown individual is known to be present in the database and the identity of such is been determined [169]. Furthermore, the closed set identification deals with the situation where the person of interest is likely to be present in the biometric database and in such case the biometric system does not return an empty candidate list [170].

VI. LEVELS OF FUSION IN MULTIMODAL BIOMETRIC SYSTEM

When we employ the data from any of the modules discussed i.e. sensor, feature, matching and decision-making module; they can be fused in more than one biometric system and called "fusion". The different levels of fusion are therefore sensor, feature, matching score and decision level fusion [158], [171].

A. SENSOR LEVEL FUSION

This comprises bringing together different sensors' raw data, e.g. from the fingerprint sensor, video camera, etc. Raw information is extracted from the multiple sensors and combined at the very first level of fusion [sensor] to produce raw fused information [156]–[158].

Sensor level fusion can take place when the multiple traits are scenarios of the same biometric trait acquired from multiple sensors or multiple values of the same biometric cues acquired from a single sensor [see Figure 12]. An example is the presentation of images containing various fingerprints to become a full fingerprint image. Other examples include facial images taken from various cameras put together to become a 3D model of a face [172], [173]. Sensor level fusion is grouped into three classes, namely: [i] Single sensor-multiple instances where multiple instances obtained from a single sensor are integrated to acquire the information in a trustworthy and descriptive mode. Averaging, weighted summation and mosaic construction are methods used to accomplish this fusion. During averaging, the multiple instances derived are combined to reduce the noise, merge and prioritize the multiple instances; weighted summation is used to handle the problem of pose variation,

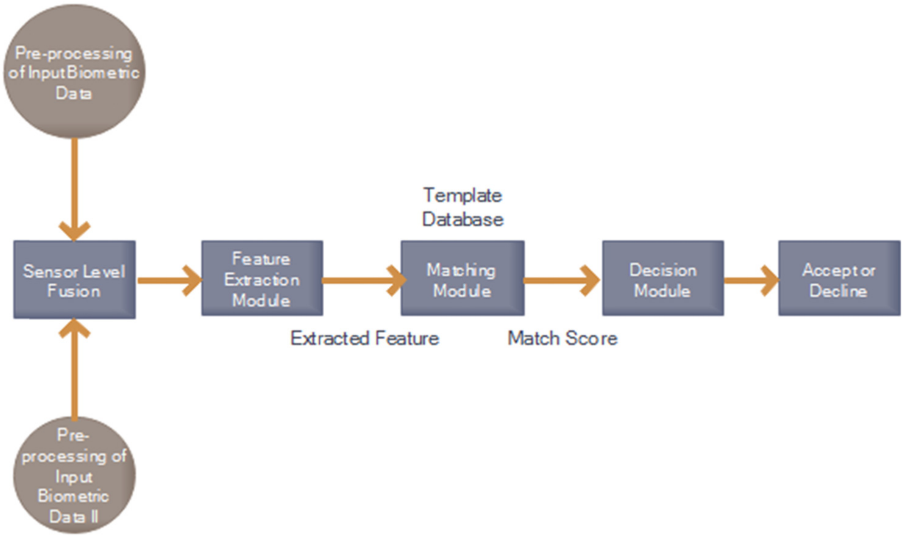

FIGURE 12. Fusion of Two Biometric Traits at the Sensor Level [159].

mosaic construction is used [174]. [ii] Intra-class multiple sensors: where multiple instances obtained from various sensors are put together to detail the information location of a similar sensor or variability of different sensors [174], [175] and [iii] Inter-class multiple sensors, less study has been undertaken of this sensor fusion mode. An example in this category is fusion involving the print of the palm and the images of the palm vein; this generated 95% recognition accuracy using the Shift Invariant Fourier Transform [SIFT] features that are extracted from the fused and matched image [176].

B. FEATURE LEVEL FUSION

This involves integrating the various feature sets acquired from different biometric types into a single vector. At this level of fusion, signals from various biometric channels [such as a microphone or camera] are firstly preprocessed and feature vectors are deduced independently; by using a specific fusion algorithm the feature vectors are combined to form a composite feature vector, which is then further used for the classification process [see Figure 13]. The feature level contains information that assists with processing raw biometric data and hence, is believed to be more effective

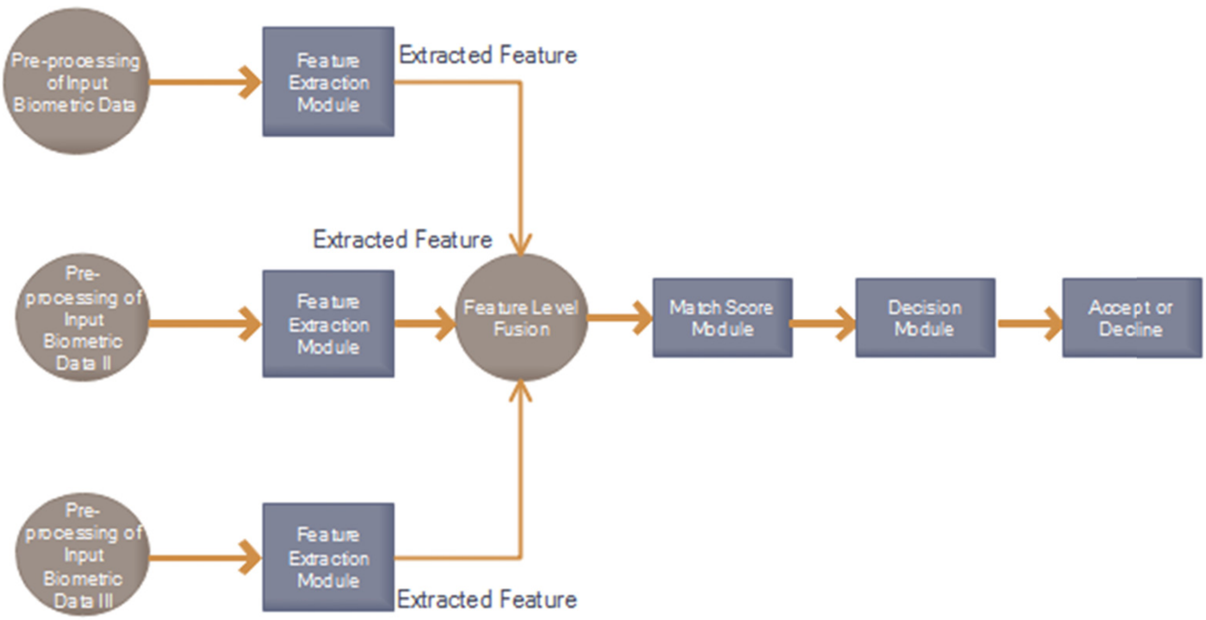

FIGURE 13. Process Involved during Fusion at the Feature Level [159].

when compared with fusion at the score level and decision level [176].

The process involved in feature level fusion occurs in two stages, i.e. normalization of a feature and selection of a feature. The normalization of feature involves using schemes like the min max technique and media scheming to amend the location and scale of feature values. Using this scheme, face and hand recognition has been deployed at this level of fusion [137], [177], [178]. Other research used scale invariant feature transform in collecting features from the normalized ear and fingerprint. For improvement of the matching performance with regards to accepting more authentic as real accept, the feature selection is done to decrease the dimensionality of a new feature vector. Algorithms that deal with feature selection include sequential forward selection, sequential backward selection and partition about Medoids.

In practice, feature level fusion is sometimes hard to accomplish as there may be incompatibility of feature sets to be combined and the joint feature set of different biometric sources may not be linear [178]. If the feature vectors have the same traits, e.g. various fingerprint impressions of an individual's finger, a mono resultant feature vector can be derived as a weighted average of the individual feature vectors. On the other hand, when the feature vectors have different traits, e.g. face and fingerprint, they can be concatenated to become a single feature vector [179], [180]. Correlated feature values are built up by various biometric algorithms selecting the main set of features used to improve the recognition accuracy. This is seen as a major advantage of the feature level fusion [178].

C. MATCHING SCORE LEVEL FUSION

This involves the joining of identical scores produced by a matching module for each input feature and template biometric feature vector within the database [see Figure 14]. The feature levels are processed separately rather than combining them and an individual matching score is derived, depending on the accuracy of each biometric channel composite matching score that can be achieved by fusing the matching level that is further sent to the decision level [44], [181], [182].

The matching score level fusion can also be called measurement level fusion. The matched score output produced by the biometric matchers gives the necessary information about the pattern input and the representation of the feature vector. The matching score can be derived by two different approaches based on the processing of the match score i.e. by classifying or combining the feature vector. Following the classifying approach, a feature vector is designed using the matching scores output by the singular matcher, which is further classified into either "Accept class" or "Reject class" [146]. Following the combination approach, the scores of individual matching are linked to become a singular scalar score that is used to reach the end decision. The scores must be converted to a common domain to ensure a sensible combination of scores from the various modalities. Many researchers have introduced different normalization methods to solve the dissimilarities in match score generated by multiple modalities [155]. The matching scores contain enough data to make real and impostor cases very clear. Hence, the process can be affected by some factors which further reduce the performance of the biometric system [183]. For example, the fact that the matching scores could be in dissimilar scale or dissimilar probability distribution, means that the scores generated by individual matchers may not be similar.

Three fusion schemes have been proposed as a way to solve this issue, i.e. density-based schemes, classifier-based schemes and transformation-based schemes [184]. The density-based scheme is derived from the estimation of score distribution and its applicability to common models such as the Naïve Bayesian and Gaussian Mixture Model [185]. When using the classifier-based scheme, classifiers are

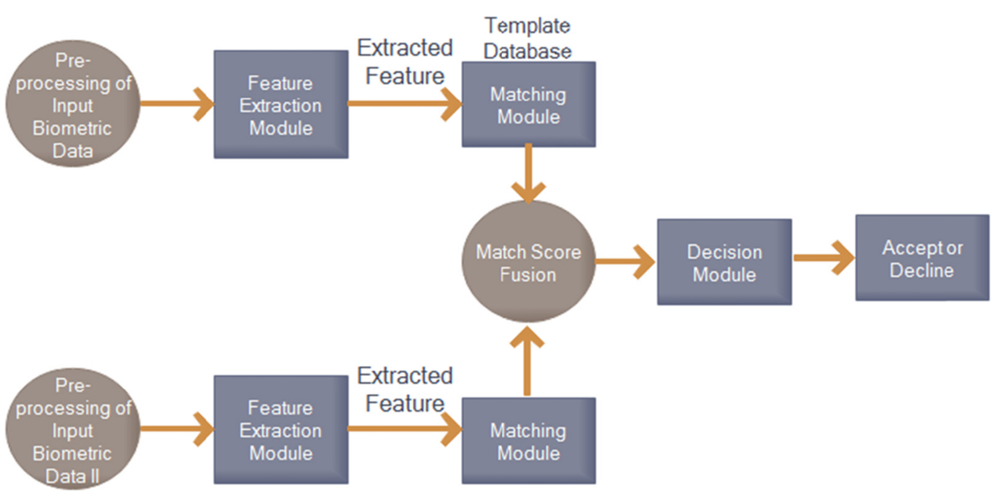

FIGURE 14. Process of Fusion at the Matching Score Level [159].

constructed to point out real and impostor scores derived from multiple matchers being treated as feature vector [16]. Lastly, a transformation-based scheme is usually applied for the score normalization processes. This task is key in making sure there are agreeable conditions between various score variables by changing the position and scale parameters of the underlying match score distribution, with sum rule, min rule. etc. as techniques being applied in this scheme [16], [185].

D. DECISION LEVEL FUSION

On decision level, the joining of different information from multiple biometric modalities happens when the individual system makes an individualistic decision about the identity of the user of a claimed identity. Here, each biometric type is pre-classified individually and the final classification is based on the fusion of the outputs of the various modalities [see Figure 15]. Furthermore, a decision is given for each biometric type at a later stage which reduces the reason for improving the system accuracy through the fusion process [159]. This fusion level makes use of the final output of the individual modalities with methods such as 'AND' or 'OR' making it the simplest form of fusion [155]. The Dempster-Shafer Theory of Evidence, Behavior Knowledge Space and Bayesian decision fusion are other methods used at this level of fusion.

VII. METHODS OF FUSION

This section gives an overview of the various fusion methods used in multimodal biometric systems. Fusion methods can be divided into three categories namely: Classification-based method, Estimation-based method and Rule-based method

A. RULE-BASED FUSION METHOD

Studies have revealed that a theoretical framework has been developed for merging the evidence collected from various classifiers using methods such as sum, product, max and min rules. These methods are also called unsupervised methods of fusion as there is no training process because learning rules are most suitable for physical applications that work for pre-decided target marks. Based on this theory, the posterior probabilities obtained from matching scores of real or fake identities can be fused using sum, product, max and min rules. Hence, if $\vec{x}_i$ is the feature vector of the input pattern X, the output will be the posterior probability i.e. $P[wj|\vec{x}_i]$, where wj is the class given to the feature vector $\vec{x}_i$ [186].

1) SUM RULE

This is seen as one of the most effective rules as it eliminates the issue of noise that could lead to difficulty during classification. In the sum rule, to obtain the final score, transformed scores of every class are added together to obtain the final score. For example, one can assume the input pattern is delegated to class a such that

$$a = argmax_j \sum_{i=1}^{R} PW_j|\vec{X}_i \tag{4}$$

2) PRODUCT RULE

This rule yields fewer results compared to the sum rule, as it is based on the statistical independence of the feature vectors. Hence, the input class delegated to class a is given by

$$a = argmax_j \prod_{i=1}^{R} PW_j|\vec{X}_i \tag{5}$$

3) MAX RULE

Here, the max rule approximates the average of the posterior probability by the maximum value of the input pattern, thus,

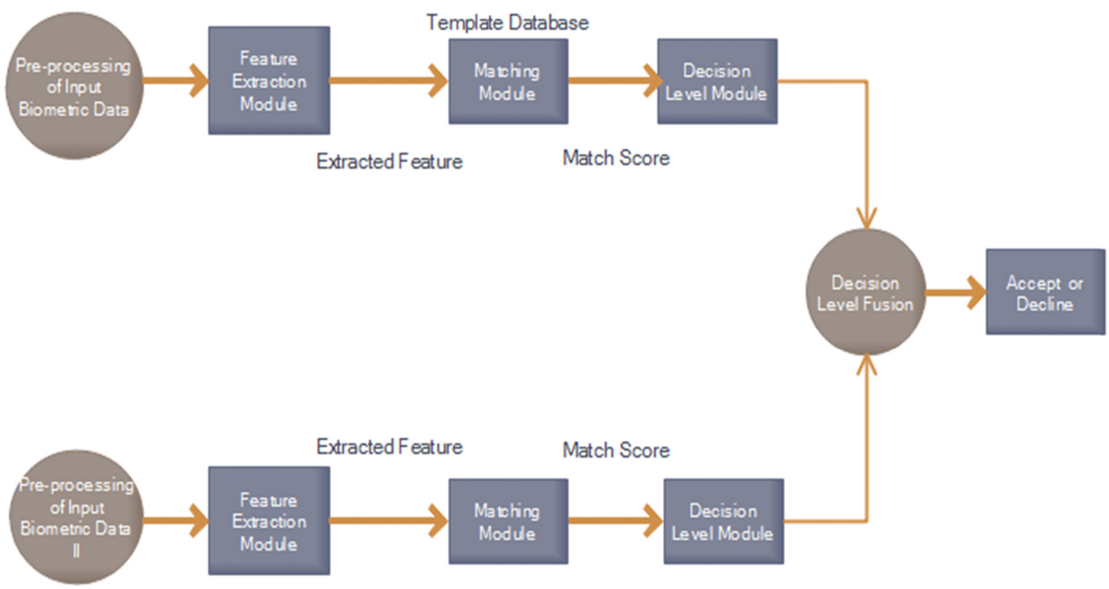

FIGURE 15. Process of Fusion at the Decision Level [159].

TABLE 3. Showing related works done using the Rule base fusion method.

Method of Fusion	Research Work	Fusion Level	Biometric Modalities
Linear Weighted Fusion	Xu et. al. [187]	Feature	Face and Ear
	Yazdanpanah et. al. [190]	Decision	Face, Ear and Gait
Majority Voting Rule	Chaw. P [188]	Feature	Face and Fingerprint
	Yu et. al. [191]	Decision	Palm and Fingerprint
Custom Defined Rule	Saleh et. al. [192]	Feature	Iris and Signature
	Yao et. al. [189]	Feature	Face and Palmprint

the input pattern designated to class a is given by

$$a = argmax_j max PW_j|\vec{X}_i \tag{6}$$

4) MIN RULE

In the min rule, a minimum posterior probability is collected from of all classes. Thus, the input pattern designated to class a is such that

$$a = argmax_j \min PW_j|\vec{X}_i \tag{7}$$

Other strategies of the Rule Based fusion methods are linear weighted fusion, Majority voting Rule and Custom defined Rule. Linear weighted fusion is a method that combines the information derived from various biometric modalities in a linear form using normalized weights. Based on literature, weight normalization can be done using various techniques such as decimal scaling, z score methods, tan h estimators and min-max [187]. Majority voting rule is a method that combines information where all the weights are equal. In this method, at the final decision is where most of the classifier reaches a similar decision [188]. Lastly, the custom defined rule method does not use the statistical approach unlike the previous rules mentioned, instead a production rule based approach is used where each input is defined within its context of use, that is further determined based on the previously recognized input events and dialog state belonging to the same user turn [189]. Table 3 shows some research works that have adopted the rule-based fusion method.

B. CLASSIFICATION BASED FUSION METHOD

This type of fusion method includes a range of classification techniques that are used to classify the multimodal observation into one of the pre-defined classes. The following which will be discussed are methods involved in this category. These are: Bayesian inference, Dempster-Shafer theory, neural networks, dynamic Bayesian networks, maximum entropy model and support vector machine.

1) BAYESIAN INFERENCE

This is also known as the classical sensor fusion method due to the fact that it has been widely used and made as reference for other methods. It can be applied both at the feature level and also the decision level where observations derived from various classifiers are combined and an inference of the joint probability of a decision is obtained [193]. The Bayesian inference fusion method can be described as: Assume we fuse the feature vectors or the decisions (d_1, d_2, d3…d_n) obtained from n various modalities. Then if these modalities are statistically independent, the joint probability of a hypothesis H as regard the fused feature vectors can be given as [194]:

$$P(H|d_1 d_2 d_3 \ldots d_n) = \frac{1}{N} \prod_{k=1}^{n} P(d_k|H)^{wk} \tag{8}$$

where N is used to normalize the posterior probability estimate $P(H|d_1 d_2 d_3 \ldots d_n)$ and the term wk is the weight of the kth modality. The Bayesian inference method has the ability to allow for any previous knowledge about the likelihood of the hypothesis to be utilized in the inference process.

2) DEMPSTER-SHAFER THEORY

This is a method of fusion that uses belief and plausibility values to represent the evidence and corresponding uncertainty [195]. The method is based on a concept known as the frame of discernment that consists of a set of the entire available mutually exclusive hypothesis. The hypothesis is characterized by belief and plausibility, where the degree of belief means that at the lower bound, there is the possibility that the hypothesis is identified as true and the plausibility represents the upper bound of the possibility that the hypothesis can be true [196]. Probability is assigned to every hypothesis $H \epsilon P$ (Θ) using a belief mass function m: $P(\Theta) \rightarrow [0, 1]$.

The Dempster-Shafer theory combination rule is used when there is the presence of multiple independent modalities i.e. the mass of hypothesis H based on two modalities I_i and I_j can be described mathematically as [194]:

$$(mi \oplus mj)(H) = \frac{\sum_{Ii \cap Ij = H} mi\,(Ii)\, mj(ij)}{1 - \sum_{Ii \cap Ij = \emptyset} mi\,(Ii)\, mj(ij)} \tag{9}$$

The method has been seen as one that can handle mutually inclusive hypothesis; hence it suffers from the combinatorial explosion when the number of frames of discernment is large [196].

TABLE 4. Showing related works done using the Classification based fusion method.

Method of Fusion	Research Work	Fusion Level	Biometric Modalities
Bayesian Inference	Tong et. al [199]	Feature	Face and Fingerprint
	Poh et. al. [200]	Decision	Fingerprint and face image
Dempster-Shafer Theory	Arif et. al [201]	Feature	Hand written signature and Hand geometry
	Singh et. al. [202]	Decision	Fingerprint
Neural Network	Jing et. al. [203]	Feature	Face and Palmprint
	Kumar et. al. [204]	Decision	Palmprint and Hand Geometry
Support Vector Machine	Sangeetha et. al.[205]	Feature	Iris and Fingerprint
	Vora et. al. [206]	Decision	Fingerprint and Palmprint

3) NEURAL NETWORK

Neural network (NN) is a type of fusion method approach that is considered a non-linear black box trained to solve computationally complex problems [197]. The neural network consists of three types of nodes i.e. input, hidden and output nodes. The input node is where the sensor decision is accepted while the output node gives the result of fusion of the decision; and the hidden nodes are those nodes that are neither input nor output. The input and output nodes are connected by weights that decide the mapping behavior [194]. During the training phase, these weights can be adjusted to get the best fusion results. This method can be applied in both the feature level and decision level.

4) SUPPORT VECTOR MACHINE

Support vector machine (SVM) is a discriminative classifier defined by a separating hyperplane. It is a universal constructive learning procedure based on statistical learning theory. It is considered as a supervised learning method and used as an optimal binary linear classifier [198]. Input data vectors in form of sets are divided as belonging to one of the two or more learned classes. This method of fusion has become of major use for data classification and related tasks such as face detection, feature categorization, modality fusion etc. As regard to fusion, this method is used to solve pattern classification problem in which case the input of the classifier is the scores given by the individual classifier [194]. The related works done on classification based fusion method as regard the approaches discussed are further presented in Table 4.

C. ESTIMATION BASED FUSION METHOD

The estimation based fusion method category includes the Kalman filter and particle fusion approach. This method is actually used to estimate the position of a moving object based on multimodal data. For instance, in human recognition, various modalities like the gait and face are fused together to estimate the position of an individual. Hence, the approaches under this method are discussed.

1) KALMAN FILTER

With certain statistical significance, Kalman filter (KM) enables the processing of real time of dynamic low-level data and gives state estimates of the system from the fused data. Linear dynamic system model with Gaussian noise is presumed for this filter to work, at time (t), the system true state, $x(t)$ and its observation $y(t)$ are modeled based on the state at time (t-1). Using the state-space model this can be represented by the equations [194]:

$$x(t) = A(t)x(t-1) + B(t)I(t) + w(t) \tag{10}$$

$$y(t) = H(t)x(t) + v(t) \tag{11}$$

From the equations, A (t) is the transition model, B (t) is control input model, I (t) is the vector input, H (t) is the observation model, w (t) is the noise process as a normal distribution with zero mean and Q (t) covariance while v (t) is the observation noise as a normal distribution with zero mean and R (t) covariance. Using the above model (state model), preserving the history of observation is not required by the Kalman filter. Hence, it depends on the state estimation data from the previous timestamp and the method is beneficial to systems with less storage capabilities. Also, the usage of Kalman filter is limited when it comes to linear systems and not suitable for systems with non-linear characteristics.

2) PARTICLE FILTER

This approach is also known as the Sequential Monte Carlo (SMC) method and they are set of sophisticated simulation-based methods that have good potential to handle complex estimation problems involving multimodal distributions [207]. Particle filter are used to estimate the state distribution of the non-linear and non-Gaussian state-space model. The particle filter approach represents the derived filtering distribution by a set of random samples with weights and compute estimates [194]. The algorithm involved in the particle filter consists of two steps namely the update and prediction steps. The update step reweighs a particle according to the latest sensory information while the prediction step propagates each particle as regards its dynamics [208].

TABLE 5. Showing related works done using the Estimation based fusion method.

Method of Fusion	Research Work	Fusion Level	Biometric Modalities
Kalman Filter	Alkkiomaki et. al. [210]	Feature	Gait
	Asaari et. al. [211]	Decision	Hand Geometry and Fingerprint
Particle Filter	Kale et. al. [208]	Feature	Gait and Face
	Raghavendra et. al. [207]	Decision	Face and Palmprint

The particle filter approach has the ability to represent arbitrary densities and can deal with non-Gaussian noise. Also, its framework enables for including multiple models. However, the approach involves high computational complexity and the number of particles increases with increase in model dimension [209]. The related works done on estimation based fusion method as regard the approaches discussed are further presented in Table 5.

VIII. CHALLENGES AND FUTURE WORK

The various biometric sensing technologies have until recently been the most efficient system for identifying and verifying individuals for private, public and security purposes. However, some challenges are still associated with the different types of biometric sensing technologies. Important examples are that some of the unique features of individuals, such as fingerprints tend to wear out as one gets older, while the voice biometric system can be a problem when an individual's voice is lost, thus making identification difficult.

The hand geometry biometric sensing system does not work with individuals who have arthritis, as they will find it difficult to place their hands on a scanner. The face recognition sensing systems at present face a number of challenges that are caused by various variations in the face. Such challenges include illumination variation, facial expression variation and most importantly occlusion. The neural network approach especially the convolutional neural network (CNN) has been seen as a recent technique to solving the issues been faced by the face recognition system. The iris biometric system can also underperform when an individual have an eye disease. Recent research has also been investigating whether the iris of an individual changes over time. The hand signatory biometric sensing system requires an individual always to sign in a consistent manner, otherwise makes enrolling and verifying difficult using the system. In voice recognition, an authentic voice can be recorded by an imposter and used for unauthorized identification.

The gait recognition system can be affected by factors such as weather conditions, viewing angle, drunkenness and weight gain. A palm vein recognition system can be a challenge when the vein patterns begin to shrink as a result of ageing and other ailments such as tumours, diabetes and so on. Similar to the face-sensing systems, the ear-sensing systems also experience challenges such as varying lighting conditions, occlusion and pose variation. Hence, these issues are hindering the performance of the sensing systems and offer opportunities for future work in this area of research.

IX. CONCLUSION

Biometric sensing technologies have indeed become popular because they use unique physical traits such as fingerprints, palms, voice, iris and the face for verification and identification. The technology helps private and public businesses and government to fight identity theft and fraud.

In this paper, we have discussed the strengths and weaknesses of the types of biometric technology sensing systems by providing a comprehensive review of each of the biometric technology systems. While discussing the advantages of each biometric system, different application scenarios were highlighted on how each biometric system was implemented using various algorithms.

Furthermore, we discussed the classification of biometric systems, namely unimodal and multimodal. Based on the flaws of unimodal biometric systems and the weakness of the various types of biometric technology systems as discussed, the multimodal biometric system has been introduced as a preferred solution to solving the various problems. The different levels and methods of fusion used in multimodal biometric systems were also covered.

Also, the different modes of biometric identification are also discussed. Hence, this review paper has made clear why more research needs to be done to find solutions to the stated problems identified in the various biometric sensing systems and also the shortcomings of the various fusion methods. However, biometric technology in its application goes beyond simple user access [212]. It can play a major role as a second authentication in addition to smart card tokens [213] and mobile applications requiring security for transactions [214].

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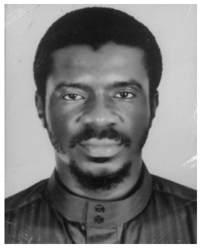

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