Multimodal Biometric Authentication using Back Propagation Artificial Neural Network

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***Abstract* - Recently, the biometric-based identifications are widely adopted for personnel identification. However, the unimodal recognition systems currently suffer from noisy data, biometric sensor data quality, spoofing attacks, unacceptable error rates and lack of distinctiveness of the biometric trait. These issues can be undertaken via multi-modal biometrics authentication system. This paper proposes a multi-modal framework to capture human skeletal features and facial features using imaging techniques. This modelling technique captures human joints with 3D depth data, to improve the system efficiency. This Biometric technique is used to recognize the known/unknown image from the trained images within short span of time. The proposed research has subdivided into three-folds. First, preprocessing the image, using the MinMax method which reduces the noise in data and enhance the image quality. Second, image features are extracted using Genetic method in combination with cuckoo search algorithm which is considered to be best optimization technique for image analysis. Third, the human recognition is attained via the Artificial Neural Network (ANN) which relies on back-propagation algorithm. The performance of the proposed method is evaluated based on the measure of different metric named as, true positive and negative rate, false positive and rejection rate, accuracy. The experimental results show that this new framework dramatically improves the system performance.**

Keywords - Multi-modal Biometric, artificial neural network, Microsoft Kinect Sensor, Human body joints.

I. INTRODUCTION

In the development of biometric system which identify and distinguish the person from their peers based on physical characteristics which plays important role in various industry with high precision. This evaluation of Biometric system which enhance and facilitate the authentication process that includes the security, usability and quality of data. User interaction with computer, smartphone has upgraded the growth of biometric identity with solid security, less resource intensive (computation and memory) and quicker identification. Various biometric identifiers like fingerprint, iris, face, and walking pattern are already incorporated in social environment, multiple biometric is the extendable method which overcome the complexity of the unimodal biometric and makes the system more reliable, accessibility, universal and provide resistance of fraudulence.

Biometrics can be classified into static and dynamic biometrics-based on their working and illustrated in figure 1. Static biometrics are those that remain the same in the system such as fingerprint, retina scan, and vein pattern. The system remembers the exact pattern for the next authentication and may not authenticate even if it has changed slightly [6]. They can be further divided into the types of data they use. Biological data uses a person's internal biological components like blood, saliva, urine and heartbeat whereas morphological biometrics uses exterior data like a fingerprint, face recognition and vein shape [18].

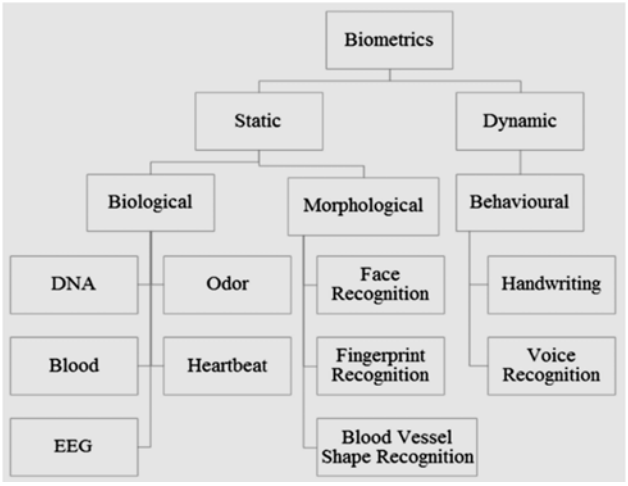


Figure 1: Classification of the biometric authentication system

Depending on biological data for verification, it is not advisable as their composition may change depending upon the person's health. Morphological data is more reliable as compared to biological since it does not change a lot over time [11].

Dynamic biometrics understands the individual behavioral and hence are known biometrics [16]. They are

able to understand the person by painting a better picture of them by studying various patterns like voice recognition, keystroke dynamics, handwriting and gestures [16]. The major drawback with this method is that it requires complex parameters and inputs to work making it more expensive as compared to simple fingerprint authentication. Combining both static and dynamic biometrics with various levels of priority may be used so as to use it effectively [18].

Many camera sensors are developed to acquire person information with the maximum distance from the camera, but depending on various factors like background noise, lightning, aging, rotation and illumination the task seems to be challenging in the field of person recognition. The research is developed by using Microsoft Kinect Sensor having 3D depth data which resolves the maximum constrained faced earlier and minimize the false recognition of the system. This Kinect sensor is used to build the generic model to construct the 3D Skeleton feature space and facial feature space. The feature space is composed of geometrical structures, the labeled curvature types of each vertex in the individualized model. Some research used statistics approaches, such as PCA, ICA and LDA [9], to form a feature space. Since they mainly rely on feature transformation procedures, which project the original feature set into a more compact set while retain the necessary information, some features that confuse the recognition task [15]. The present study focuses on the multi-model biometric system using facial features and Skeleton features based on machine learning technology which accepts large amount of data and analyze the data to produce result of high accuracy and security to the system. Genetic algorithm is used for optimizing the data and artificial neural network used for data classification.

A. Problem Statement

Biometric system is pattern recognition system which can build the model using biometric features of each individual and compares with template stored in the database. Biometric system includes Uni-modal which has single identifier and Multi-modal which include more than one identifier for person identification. Though Unimodal identifiers are seemed to be skilled, biometric recognition finds to be more challenging for large data deployment. Application of Multimodal biometric is used to reduce high risk, viability from fraudulent and strong potential of the output from the system.

B. Applications of Multimodal Biometrics

National intelligence and defense agencies requires maximum security as any vulnerability may affect national security. Biometric refers to human behavior characteristic which helps in identifying the individuals from the groups on surveillance control and helps in criminal identification.

II. RELATED WORK

Biometric recognition with human traits and facial features are studied and implemented by numerous researchers using the concept of machine learning. Machine learning is applied to analyze the vast volumes of data where the desired output is determined based on the inputs. Based on the proposed research, comparison is made with other researchers and concluded with certain findings related to proposed work.

A study by Conti et al [4] has presented an innovative multimodal biometric identification system based on iris and fingerprint traits using a template level fusion algorithm working on a unified biometric descriptor. A hamming distance based matching algorithm is used to process fingerprint, iris and iris-fingerprint-fused templates using the segmented regions surrounding singularity points and has achieved a False Acceptance Rate of 0% and False Rejection Rate of 5.71%. A study by Menotti et al. [14] talks about the same system with spoofing detection system with convolution networks and have experimentally reduced the FAR to a low level.

A study by Zhang et al. [20] has proposed a novel framework for serial multimodal biometric systems based on semi-supervised learning techniques addressing issues of user inconvenience and system inefficiency in parallel multimodal biometric systems. The dimensionality reduction method for the weaker traits based on dependence maximization is proposed. The proposed framework and SSL based method cannot work on more than two traits. De Vito et al.[21] has also used the same semi-supervised learning techniques but in artificial olfaction.

A Study by Pratibha et al. [15] has proposed face recognition system using genetic algorithm and compared the features using PCA, LDA algorithm and improved the accuracy of the system using ORL, UMIST database. Proposed system has to improve the efficiency of the system by applying filters during pre-processing stage.

During the past decade, we have viewed different kinds of meta-heuristic algorithms advanced to handle optimization problems. Among them, Meta-heuristic-based methods, such as Genetic Algorithm (GA), Particle Swarm Optimization Algorithm (PSO), Estimation of Distribution Algorithms (EDA), ant Colony Optimization (ACO), simulated annealing (SA), and Biogeography-Based Optimization (BBO), differential evolution, artificial bee colony, and cuckoo search algorithm may be one of the most popular methods [13].

Extracted features can be optimized using Genetic algorithm in addition with cuckoo search which produce best desired output. Cuckoo search algorithm finds to be best combination of Genetic search method where both helps in solving multi-criteria optimization. It has also been also studied that cuckoo search has very good characteristics and has the ability to become the global optimization algorithm [19].

A. Methodology of the Proposed Work

Multimodal biometric human recognition system is achieved by using Microsoft Kinect sensor which has skeletal tracking system to detect the human skeletal joints and face tracking system to detect the facial points including their depth data. Kinect sensor can detect 25 skeletal joints and maximum facial points with calculates distance from user to sensor. Biometric recognition technology is applied using machine learning search finds to be more prominent and reliable in solving realistic problems.

B. Image Acquisition and Preprocessing

Microsoft Kinect sensor which can detect a person from the distance of 5 feet and able to acquire image features in any environment with different background field. Image pre-processing technique which includes Image normalization, image enhancement and Image Segmentation. Pre-processing the Image is for linear scaling and for higher classification accuracy. Normalization is done using min-max approach which reduce illumination variation and for Image Enhancement, Gabor filter is applied to the biometric image by spatially convolving it. The filter bank is initially created with different scales and rotations of Gabor filter. From this, Gabor space is obtained by convolving the signal which is useful for various biometric applications. Important functions can be taken from the Gabor space to create Sparse Object Representation. Further, Image Segmentation, Discrete cosine transform is used which construct feature vectors from the image co-efficient. Image recognition with better accuracy can be achieved by discriminating co-efficient vectors. Figure 2 shows pre-processing techniques applied in skeletal feature extraction.

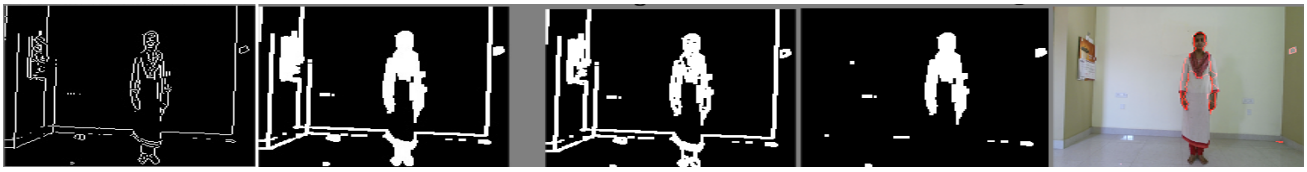


Figure 2: Binary Gradient mask, dilated gradient mask, Binary image with filled holes, segmented image, Outlined original image

C. Human-Skeletal and Face Feature Extraction

3D Imaging sensor which can extract Human features and face features at the same time of human detection and features are prioritized based on the genetic search and cuckoo search method.

(a) Skeletal Image (b) Depth Image

(a) Face Image (b) Depth Image

Figure 3 Skeletal Feature and Face Feature Extraction

These images are stored in the database as template and classification technique is applied to train the data and recognize the person as genuine or imposter. The Figure 3 shows the original image and image with depth information for both skeletal and face feature vectors.

III. GA BASED FEATURE SELECTION WITH CUCKOO SEARCH

GA use natural selection method to generate new population from the existing population that helps to evaluate fitness of each and every individual through fitness function. Functioning of GA and its evolution principle of reproduction is based on five factors: Initial population of binary chromosomes, chromosomes encoding, fitness evaluation, selection mechanism used in reproduction using genetic operators and criteria set to stop the GA. The feature extraction is done using GA as it is more advantageous compared to conventional optimization methods and has the following advantages [2]

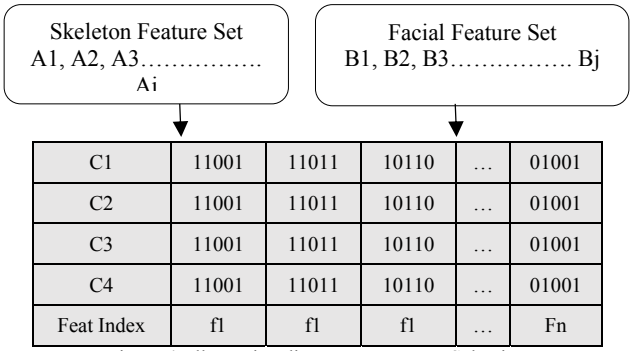
It uses the fitness score and finds the healthy solutions in a short span of computation.

It is easy to code the algorithm as well as adjusted and customized to match the problem at anytime

It searches in parallel and hence can search from many points at a time avoiding the problem of local maxima.

The time is taken to get the result can easily be predetermined from the size and number of generations of population and time taken to find a single solution.

The operation in GA are iterative procedure manipulating one population of chromosomes to new population using natural selection method. Functioning of GA starts from Initial population of binary chromosomes, Fitness Evaluation, selection of parent chromosomes. Fitness function or Objective function gives the phenotype (numerical) values and Genotype (Binary) Values float values which are used to prioritize each chromosome in the population. Binary encoding is used represent the feature selected or feature not selected from the linear expansion of training images. Skeleton feature set or Facial feature set Ai=0|Bi=0 then feature not selected and when Ai=1|Bi=1 then features selected for evaluation. Formulation of fitness function depends on problem being solved. Figure 4 explains the feature selection from skeletal set and facial set using genetic method.



C1	11001	11011	10110	…	01001
C2	11001	11011	10110	…	01001
C3	11001	11011	10110	…	01001
C4	11001	11011	10110	…	01001
Feat Index	f1	f1	f1	…	Fn

Figure 4: Illustrative diagram on Feature Selection

A. Generation of Initial Population and Chromosome Encoding

GA starts functioning in generation of Initial population where each member of the population encodes best solution to the problem. Number of samples or observation defines the population size and number of attributes defines Genome Length. Total number of bits used in chromosomes are defined. Population is generated on random basis where numbers of binary 0's and 1's are equal. Each generation starts with parameters population size and genome length and scaling constant defined for reproduction which sets a criterion to discard the weaker chromosomes.

B. Fitness Evaluation

Fitness Evaluation is performed based on the objective function defined for our task. Here the objective is to find reduced feature subset from the original features where discriminative capability of each features are defined and redundant class information is discarded.

The training data consists of a training vector of size N (again, N indicating the number of features being used) which is the feature vector x as follows and a known classification label. Consider dataset,

$\bar{X}$ = [x1, x2, x3……xN] where i = 1, 2, · · · , N,

where Xi ∈{0,1}, and N is the Original features are transformed to subset of features by using GA Evaluation.

The Original Feature set:

$$\bar{\mathbf{X}} = \begin{vmatrix} F_{1,1} & F_{1,2} & \dots & F_{1,N} \\ F_{2,1} & F_{2,2} & \dots & F_{2,N} \\ F_{n,1} & F_{n,2} & \dots & F_{n,N} \end{vmatrix} \quad (1)$$

Is optimized to minimal feature set (Feature subset):

$$\bar{\boldsymbol{Y}} = \begin{vmatrix} F_{1,1} & F_{1,2} & \dots & F_{1,M} \\ F_{2,1} & F_{2,2} & \dots & F_{2,M} \\ F_{n,1} & F_{n,2} & \dots & F_{n,M} \end{vmatrix} \quad (2)$$

Where N is the number of extracted features, such that size of the feature set is M<=N. Feature extraction can be done only when criterion function set P($\overline{\boldsymbol{Y}}$) for any set evaluates selected subset $\bar{\boldsymbol{Y}}$. Here better subset can be determined by higher value of P. Problem of feature selection is based on selected feature $|\bar{\boldsymbol{Y}}|$ When M and P reaches maximum only when$\bar{Y}$ € $\bar{\mathrm{X}}$.

$\bar{Y} = P(\bar{X})$, M<=N.

C. Genetic Operators: Crossover, Mutation

From the parent trait, crossover of two chromosomes produces a pair of offspring. Based on several iteration of generation, feature optimization problem can be resolved. During each generation, a set of new chromosomes is created using crossover, inversion, mutation and other operators. Since the population size is fixed, only the best chromosomes are allowed to survive to the next cycle of reproduction. Mutation of a chromosome alters one or more genes with the probability equal to the mutation rate produces a nearly identical chromosome. Local optimum value is reduced by this process.

Cuckoo search algorithm in hybrid with Genetic search is perfect combination for image optimization. Cuckoo search method which resolve low quality responses and multi-criteria optimization problem. This advanced search learning algorithm works for global search problem based on the lifestyle of cuckoo bird and easy to implement for feature selection optimizing. For human recognition, Skeletal and face features are selected from each sample and given as input to cuckoo search algorithm which transforms the output of the image into feature vectors. The key features that are suitable for each sample are prioritized by cuckoo search and repeat the process of iteration to attain the maximum global values. Cuckoo search technique provides best solution for attaining specific set of features, processing speed and memory space reduction. Flowchart of combined Cuckoo search technique with Genetic method is shown in Figure 5.

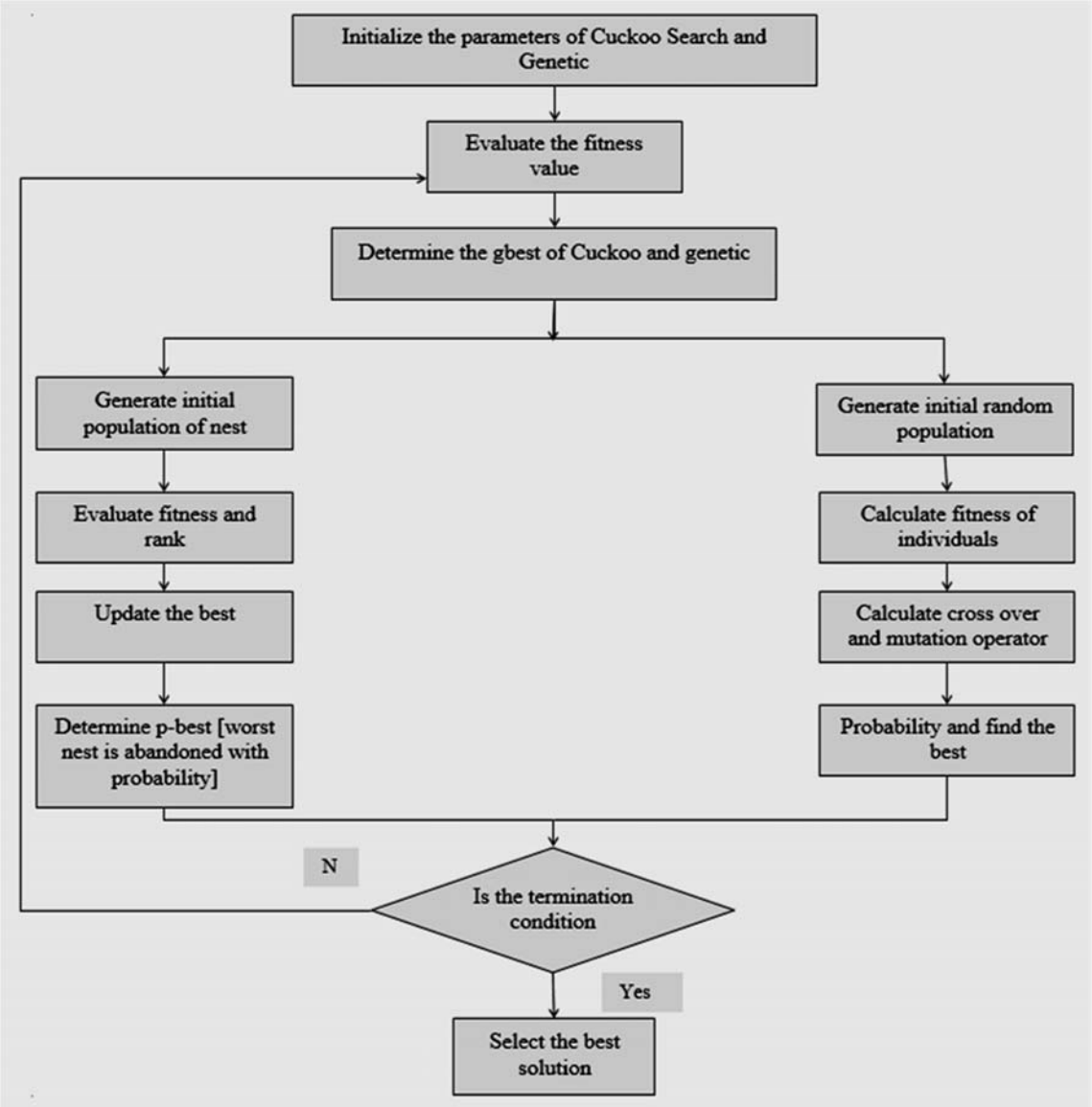


Figure 5. GA with Cuckoo Search workflow

D. Image Recognition using Artificial Neural Network (backpropagation algorithm)

ANN is an efficient classification approach which is used for discrete, vector and real-valued functions. Neural Network is used for predicting known and unknown data and works well for both linear and non-linear data set. Whereas, ANN is composed based on the artificial neurons (nodes) in the network and each node linked to each other. In this, the value of the connection is high, and then it referred as strong connection. There are three types of neurons named as input, hidden, output node. Here, the input is in the form of numeric value and information passed throughout the network.

On the basis of connection strength as transfer functions, activation value and inhibition or excitation, weights and the activation results is passed from one node to another node. In the receiver section, these nodes are added to the activation values; then alter the value based on its transfer function. The activation flows through the network, through hidden layers, until it reaches the output nodes. ANN Classification Technique uses Back Propagation Neural Network for learning the model. Feature vector of skeletal image and face image are given as input and weights of the network is initialized based on the desired output. For each iteration in neural network, Gradient descent force is applied to reduce the error rate by updating the weight parameter. ANN learning technique on training data gives robust to errors. In Gradient decent method, magnitude and direction

of weight are taken in reverse direction and continued for each iteration.

$$\Delta W_t = -\eta \frac{\partial A}{\partial w_t} \text{ where } \boldsymbol{\eta} \textit{ is the learning rate} \quad (3)$$

Weight co-efficient W are calculated by ΔW

$$W := W + \Delta W \quad (4)$$

$$\text{computed as } \frac{\partial A}{\partial W_t} = \frac{1}{n} \sum_i^n a^{(i)} \left(W_t a^{(i)} + x - b^{(i)}\right) \quad (5)$$

$\boldsymbol{a^{(i)}}$ and $b^{(i)}$ are training examples. Additional technique which speeds up gradient descent is Stochastic Gradient method. The Error rate are identified faster using iterative method.

The weight accumulation at the end may slow down the process in normal gradient method, stochastic improves it by adding weight update to each sample x w.r.t each weight y:

$$Wy := W + \Delta Wy \; where \; \Delta W_y = \eta \left(W_t a^{(i)} + x b^{(i)}\right) a^{(i)} \quad (6)$$

Back Propagation using stochastic gradient method for recognizing the human features are given with steps:

1. Create feed-forward network with set of Input vector, Target vector and Output Vector
2. Initialize the weights to some random values.
3. do until termination

For each input unit having pair of training samples are fed into feed forward network to create instance for Input unit.
Compute the Output vector with the error term for each unit in the network
Compute the Hidden vector with the error term for each unit
Update the Network weight

Proposed System Workflow:

Step 1: Collection of images are taken from Microsoft Kinect Sensor at different environment.
Step 2: Pre-processing the image using Normalization, Image enhancement and segmentation.
Step 3: Subset of features are processed using GA based Cuckoo search method local optimization and manage search variation
Step 4: Training images are collected and trained in Artificial Neural network with Back propagation technique which can predict the desired output based on previous errors, input value, weights and biases.
Step 5: Probe image is compared with gallery images which are trained in Neural Network Model and desired output of Genuine or Imposter are validated with performance metrics.

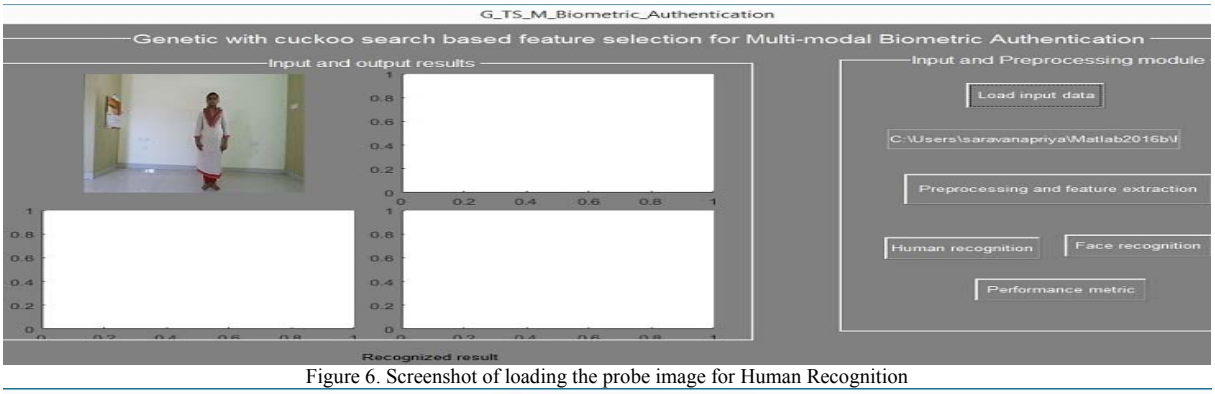


Figure 6. Screenshot of loading the probe image for Human Recognition

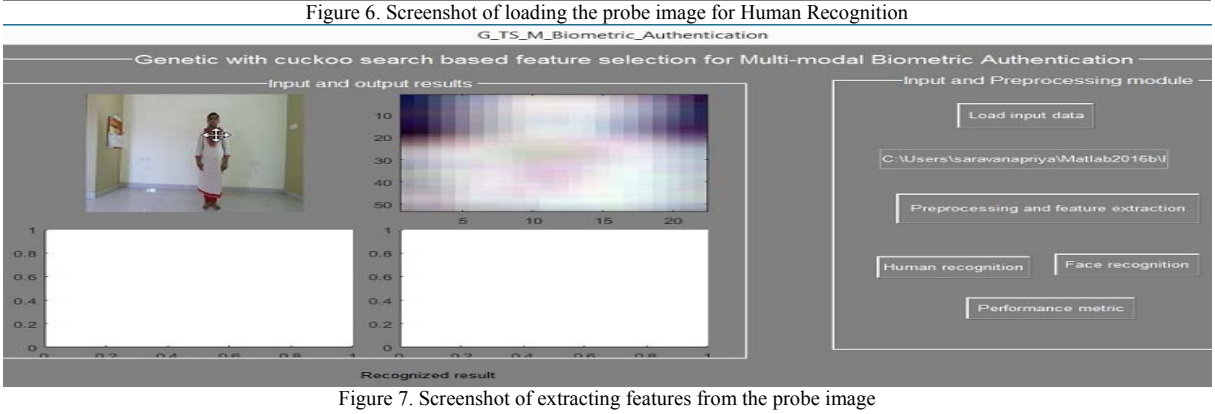


Figure 7. Screenshot of extracting features from the probe image

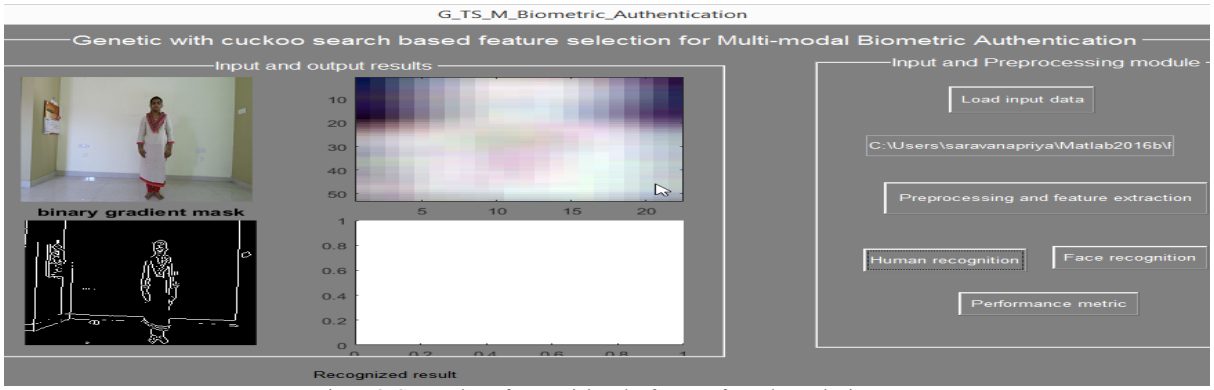


Figure 8. Screenshot of recognizing the features from the probe image

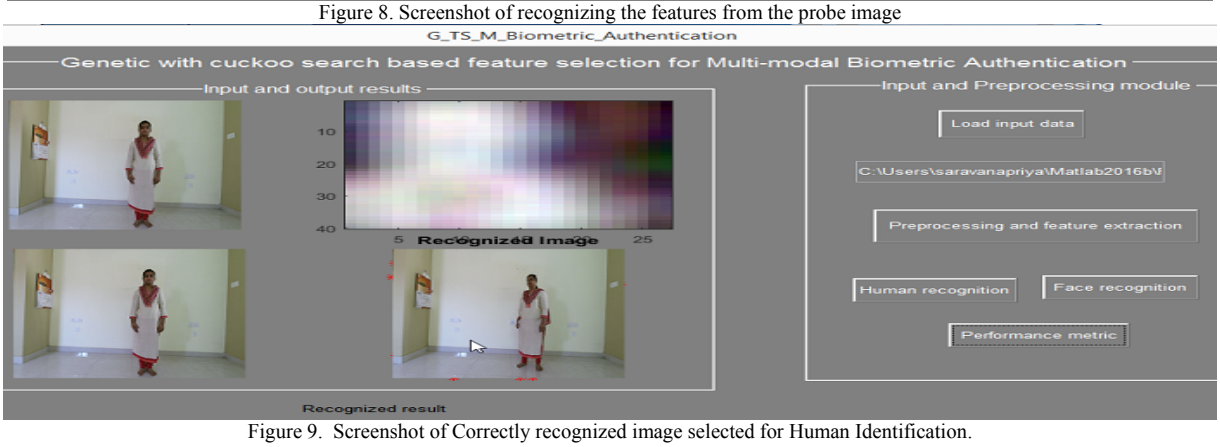


Figure 9. Screenshot of Correctly recognized image selected for Human Identification.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Using Microsoft Kinect 3D sensor, Skeletal Images and Facial Images are collected and organized in the gallery. Images captured at different environment and lightning variation. The performance of the classifier is measured by the mathematical computing software MATLAB 2016b. The obtained results of True positive rate and False positive rate are listed in Table 1.

TABLE I. OBTAINED RESULTS BASED ON THE PROPOSED METHOD

Biometric Used	True Positive Rate	False Positive Rate	Precision	Recall	Efficiency (%)
Skeletal Joints	0.713	0.38	0.75	0.768	85.27
Face Features	0.86	0.18	0.9	0.912	96.56
Skeletal and Face Combined	0.98	0.05	1	0.941	98.34

The result shows the True Positive rate is increased in fusion of skeletal and face biometric when compare to single biometric trait. In any biometric recognition, Efficiency of the system is measured by number of wrongly accepted user and number of users wrongly rejected. The proposed system shows maximum reduced rate of False Positive rate and classifier accuracy attained maximum value. Based on the performance evaluation metrics, Receiver Operating Characteristic (ROC) Curve is drawn against TPR (True Positive Rate) and FAR (False Acceptance rate) for biometric traits named skeleton, face and combined skeleton-face fusion is shown in Figure 6. In Table II we compared the proposed system with other researchers and concluded with maximum reach of accuracy

TABLE II: COMPARATIVE STUDY WITH CLASSIFIER ACCURACY.

S.No	Author	Multimodal system	Classifier	Accuracy
1	Virginia et al.	Skeletal joints and Gait	KNN	88%
2	Singhgad et al.	Face + Ear	Fisher Discriminant Analysis	90%
3	Sheetal et al.	iris and face and voice	Score Level Fusion	92%
4	Thai Hoangle et al.	face recognition	AB and ANN	91%
5	Gawande et al.	Fingerprint and Iris	Polynomial Kernal	94%
6	Hesham et al.	Facial expression and movements	Neural Network	95.80%
7	Author	Skeletal joints and Face	GA and ANN	98.62%

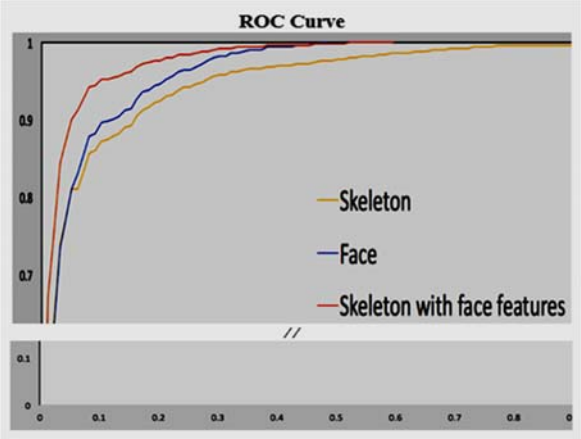


Figure 6. ROC Curve drawn against TPR and FAR

V. CONCLUSION

In this paper we have shown that Genetic Algorithms can play an important role in classification and feature extraction for high dimensionality, multi-class data patterns and local optimization is done in combination with cuckoo search method. GA with classifier ANN-BPNN are used to solve a fairly broad class of complex pattern recognition problems. Multi-modal biometric systems achieves maximum accuracy with minimum error rates to prove the robust of the system based on Skeletal and Face features extraction. Proposed system is able to achieve accuracy of 98.62% with TPR and FPR of 0.98 and 0.05 which improves the recognition ratio with dramatic increase.

REFERENCES

[1] Virginia O. Andersson and Ricardo M. Araujo. Person identification using anthropometric and gait data from Kinect sensor. In Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence, AAAI'15, pages 425–431. AAAI Press,2015.

[2] Beg AH, Islam MZ. Advantages and limitations of genetic algorithms for clustering records. In: 2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA). IEEE; 2016:2478-2483. doi:10.1109/ICIEA.2016.

[3] Sheetal Chaudhary and Rajender Nath. A new multimodal biometric recognition system integrating iris, face and voice. International Journal of Advanced Research in Computer Science and Software Engineering, pages 145–150, 2015.

[4] Vincenzo Conti, Carmelo Militello, Filippo Sorbello, and Salvatore Vitabile. A frequency-based approach for features fusion in fingerprint and iris multimodal biometric identification systems. IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), 40(4):384–395, Jul 2010.

[5] Danasingh, Asir Antony, EPIPHANY, JEBAMALAR LEAVLINE, Priyanka, and Padma Priya. Dimensionality reduction using genetic algorithm for improving accuracy in medical diagnosis. International Journal of Intelligent Systems Technologies and Applications, 2016,8.10.5815/ijisa.2016.01.08.

[6] Miguel A. Ferrer, Moises Diaz-Cabrera, and Aythami Morales. Static signature synthesis: A neuromotor inspired approach for biometrics. IEEE Transactions on Pattern Analysis and Machine Intelligence, 37(3), Mar 2015.

[7] Amir Hossein Gandomi, Xin-She Yang, and Amir Hossein Alavi. Cuckoo search algorithm: a metaheuristic approach to solve structural optimization problems. Engineering with Computers, 29(1):17– 35, Jan 2013.

[8] Ujwalla Gawande, Mukesh Zaveri, and Avichal Kapur. A novel algorithm for feature level fusion using svm classifier for multi-biometrics-based person identification. Applied Computational Intelligence and Soft Computing, page 11, June 2013.

[9] Oluleye H. Babatunde, Leisa Armstrong, Jinsong Leng, and Dean Diepeveen. A genetic algorithm-based feature selection. International Journal of Electronics Communication and Computer Enggineering, Vol.5,2014.

[10] Prof. Florica Moldoveanu Hesham A. Alabbasi and Prof. Alin Moldoveanu. Real time facial emotion recognition using Kinect v2 sensor. IOSR Journal of Computer Engineering, 17(3):61–68, June 2015.

[11] Kathy J. Horadam, Arathi Arakala, Stephen Davis, and Seyed Mehdi Lajevardi Hand vein authentication using biometric graph matching. IET Biometrics, 3(4):302–313, Dec 2014.

[12] Thai Hoang Le. Applying artificial neural networks for face recognition. Advances in Artificial Neural Systems, page 15, 2011.

[13] Xiangtao Li, Jian'an Wang, and Minghao Yin. Enhancing the performance of cuckoo search algorithm using orthogonal learning method. Neural Computing and Applications, 24:1233–1247, 2013.

[14] David Menotti, Giovani Chiachia, Allan Pinto, William Robson Schwartz, Helio Pedrini, Alexandre Xavier Falcao, and Anderson Rocha. Deep representations for iris, face, and fingerprint spoofing detection. IEEE Transactions on Information Forensics and Security, vol.10 pg. 864-879 ISSN:1556-6013,No. 4, 2015.

[15] Pritpal Singh. Pratibha Sukhija, Sunny Behal. Face recognition system using genetic algorithm. Published by Elsevier, 2012.

[16] Steven J. Simske. Dynamic biometrics: The case for a real-time solution to the problem of access control, privacy and security. In 2009 First IEEE International Conference on Biometrics, Identity and Security (BIdS), page1:10. IEEE, Sep 2009.

[17] Arti A. Tekade .S.P.Narote. Feature fusion method based on fisher discriminant analysis for face and ear for multimodal recognition. International Journal of Engineering Research & Technology, 1(5), July 2012.

[18] L. Wang, H. Ning, T. Tan, and W. Hu. Fusion of static and dynamic body biometrics for gait recognition. IEEE Transactions on Circuits and Systems for Video Technology, 14(2):149–158, Feb 2004.

[19] Xin-She Yang and Suash Deb. Cuckoo search: recent advances and applications. Neural Computing and Applications, 24(1):169–174, Jan 2014.

[20] Qing Zhang, Yilong Yin, De-Chuan Zhan, and Jingliang Peng. A novel serial multimodal biometrics framework based on semisupervised learning techniques. IEEE Transactions on Information Forensics and Security,9(10):1681–694, Oct 2014.

[21] De Vito S, Fattoruso G, Pardo M, Tortorella F, Di Francia G. Semi-Supervised Learning Techniques in Artificial Olfaction: A Novel Approach to Classification Problems and Drift Counteraction. IEEE Sens J. 2012;12(11):3215-3224. doi:10.1109/JSEN.2012.219242.