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| <b>Name of Scholar</b>        | Aftab Alam                                                                                                             |
| <b>Name of Supervisor (s)</b> | Prof. Abdul Quaiyum Ansari (Supervisor)<br>Dr. Shabana Urooj (Co-Supervisor)                                           |
| <b>Name of Department</b>     | Department of Electrical Engineering, Jamia Millia Islamia, New Delhi-110025                                           |
| <b>Title of the Thesis</b>    | Design and Development of Radar based Wireless Human Emotion Recognition System using Electrocardiogram (ECG) Waveform |

### **Research Summary and Findings**

Emotion plays a crucial role in everyday life. Positive emotion impacts daily routine activities positively whereas negative emotions impact everyday work negatively professionally and personally. Response of a human body is aggregate of the chemical reactions happening in the body due to the external and internal factors. The perception of a situation and reaction to the event at hand majorly depends on the person's emotional state. A negative emotion can impact the productivity and efficiency. Emotional state of a person indicates the quality of overall health especially mental health. Mental health experts like psychiatrists and psychologists try to access human emotional state with list of questionnaires to evaluate the mental state of their patients to offer counselling and prescribe required medicines. Emotion detection has been a crucial part of human civilization from the very first day of existence, human has been relying on facial and non-verbal cues to identify the threat or friendly nature of other living beings in their surroundings. With advancement of science and technology, researchers have been trying to find answer to a question "if a machine can assess the human emotion precisely and accurately". Emotional recognition systems are classified on the basis of the type of feature datasets used in the classification. The two broad categories of emotion classifiers are Physiological and Non-Physiological based systems. Non-Physiological based systems utilize features like Speech, Text, Audio, facial expression and language whereas Physiological based systems utilize bio-electrical signals namely Electroencephalography (EEG), Electrocardiogram (ECG), Galvanic Skin Resistance (GSR), Electromyography (EMG) and Skin Potential etc. The non-physiological parameters can be masked by the subject hence, not a very reliable system for emotion detection. Moreover, speech, text and

tone variation also depend on culture, ethnicity, linguistic variation and other factors which makes it challenging to come up with a system that is universally applicable. On the other hand, the physiological based systems are trained on bio-electrical signals that are generated by an Autonomous Nervous System (ANS) hence involuntary in nature and can't be controlled by the subject. The variation in physiological signals with varying emotions is not controllable by the subject under investigation and hence are more reliable systems. The major part of research articles available in literature are non-physiological based systems whereas the physiological based systems have further room for improvement in making them more feasible and capable of continuous monitoring of emotions. The on-body sensors used in acquisition of bio-electrical systems are one of the major drawbacks of physiological based systems. Most of the systems available that utilize physiological based signals in emotion classifiers fuse the non-physiological parameters in classification as well as multiple parameters are utilized in development of an accurate emotion classifier system. Major physiological based systems utilize EEG signals for emotion classification in addition to GSR and ECG etc. The very least number of literatures is available in single modal emotion classification. The acquisition of EEG signals requires EEG electrodes to be attached to the scalp of the subject which makes it cumbersome and hinders the daily activities of the subject. ECG has the potential to be used as a single modal feature for emotion classifier systems as the acquisition of ECG is possible using no-contact electrodes and even using wireless Radar based systems. This report outlines a brief review of the Radar based systems for ECG data acquisition. The mechanical movement of the chest due to heartbeat separated from the lesser frequency movement due to breathing can be translated into electrical equivalent and ECG signal can be reconstructed from the signal bounced back from the chest of the human subject. Various types of bio-radar based emotion recognition systems are briefly reviewed that outline the requirement of highly directional and high gain antenna designs. For continuous monitoring of emotions of the subject in the natural setup there is a high bandwidth requirement that enables signal processing. Keeping in view the research gap, a highly directional 24 GHz pyramidal horn antenna is designed using 3 mm brass sheet that offers maximum gain and directivity of 25 dBi and 23.5 dB respectively. The value of the return loss  $S_{11}$  parameter of -30 dB at 24GHz indicates the suitability of the design in biomedical signal processing radar systems. The pyramidal horn antenna offers a decent gain of 25 dB, BW of 9 GHz and efficiency of 95%. The horn antenna design specification has even better performance outcomes than the standard gain horn antenna of the selected operating

range. To the best of the author's knowledge, the optimized design parameters offering optimal gain and efficiency are significantly higher than most of the reported literature till now. This piece of work is the state of the art and a very nice contribution to the field of bio-radars and bio-informatics. The designed antenna has potential to be used as a transmitting and receiving antenna for wireless ECG acquisition and for emotion classifiers. Accuracy and reliability of a machine learning model depend on the quality of the dataset used for training and validation of the model. For emotion classifiers models using ECG signals, the acquisition of the ECG signals accurately is a crucial factor for further feature extraction and classification to come up with an accurate and reliable ECG based emotion classifier. Radar based ECG acquisition system suffers from clutter as well as the subject needs to be static and in line of sight of the transmitting and receiving antenna. In this research work, no-contact based ECG acquisition has been explored in detail. Firstly, an IoT based Arrhythmia detection system is developed where ECG acquisition using AgCl electrodes is designed and the accuracy of the signal processing module using discrete components has been explored. The ECG signal for a volunteer acquired 12 lead ECG system has been taken as a reference to compare the detection accuracy of Arrhythmia (Normal Sinus, Bradycardia and Tachycardia). It has been found that the developed 3 lead AgCl based electrodes and the designed signal processing module gives accurate results in classifying Arrhythmia. In addition to the usage of INA128P instrumentation amplifier and the HPF, LPF and Notch filters using LM324 low noise operation amplifiers the final circuitry has been finalized. The final circuitry module developed in this work is then used for integration with capacitive ECG electrodes in place of AgCl electrodes to come up with a no-contact ECG acquisition. The AgCl gel-based electrodes are not suitable for continuous monitoring as it dries up with time causing signal distortion as well as skin irritation problems. Dry capacitive electrodes are an alternative to this issue. To explore the applicability of capacitive based sensors two types of dry electrodes are fabricated. A textile based and silver button-based electrodes are designed and fabricated for no-contact ECG acquisition. The dry electrodes can eliminate the need of gel-based electrodes but still needs to be in touch with the skin layer to acquire ECG accurately. Furthermore, to have a non-contact ECG system an ECG belt is developed using copper tape based capacitive electrodes that is capable of acquiring ECG signal over and above the cloth of 100-micron thickness. A Copper foil with conductive acrylic Pressure Sensitive adhesives (PSA) with a thickness of  $0.06 \pm .01$  mm, width of 12.7mm, the resistivity of  $\leq 0.05\Omega/\text{sq}$  and resistance of  $\leq 1.2\Omega$ , is used. A contactless capacitive sensor is developed using this

copper tape and it is used to extract the signal voltage from the skin surface. The Copper tape used to have adhesive on the other side making it easy to stick on Velcro-strap. To pick the signal, there is the soldering of ECG coaxial cable AT3 probe at both ends of the Velcro strap on the copper tape. These two soldered points at two extreme ends of the belt are acting as two terminals from where the signal is to be taken from the skin. This capacitive sensor Copper tape wrapped on Velcro is named as ECG Belt. The signal processing module like amplifiers, filters are designed using compact low noise Integrated circuits and generic processor (Arduino) is integrated with a HC-05 Bluetooth module to transmit the ECG signal in hexacode format to PC for further processing. The circuit module is compact so that it can be cased into a small box that can be kept in a pocket of the subject and hence facilitate wireless, continuous and non-contact ECG electrodes-based acquisition without requirement of gel-based electrodes or in direct touch to the skin surface. This designed ECG belt system is integrated as a part of ECG acquisition system in further designing and training of emotion classifier models. Prior to the training and testing of emotion classifier models on the acquired real subject datasets, three physiological feature datasets named LUMED-2 (EEG+ GSR), SWELL (HRV), and YAAD (ECG+ GSR) are used to train models and classify emotions using MATLAB2020b software. The machine learning classifiers used are Random Forest, SVM, KNN, and/or Decision Tree. The maximum average classification accuracy achieved is close to 98% at least for one classifier in each dataset. This preliminary study re-affirms that the physiological signals like EEG, ECG, and GSR possess differentiable emotional features which can be used to detect the emotional state of a person precisely using the trained machine learning models. The CSV files containing ECG raw data are processed and features are extracted to classify the emotions in seven categories for which video stimuli were given. Ten statistical features of time series ECG signals Mean, Standard Deviation, Variance, Minimum value, Maximum value, First-degree Difference, Kurtosis, Skewness, Heart Rate, and  $RR_{\text{mean}}$  are calculated for the ECG database and used to classify seven categories of emotions such as Anger, Disgust, Fear, Happy, Neutral, Sad and Surprise. Furthermore, experiments are conducted on a total of 45 subjects while subjects were elicited with different emotions through audio-visual stimuli and corresponding ECG data were acquired simultaneously using ECG belt system. Thereafter, the above mentioned ten statistical features of the ECG data have been extracted through devised feature extraction algorithms. Seven different categories of emotions using emotion classifier models (such as SVM and RF) are categorized. The designed emotion classifier models are capable of classifying human emotions

precisely with reasonably high classification accuracies for a contactless unimodal ECG-based emotion recognition system. The minimum classification accuracies achieved with SVM and RF emotion classifier models are 86.6% and 98.2%, respectively. A unimodal emotion classifier system in which one of the physiological signals, an electrocardiogram (ECG) signal, has been used is developed. The developed classifier models offering high accuracy yet require high processing speed processor for computation of features to assess the human emotion in real-time. The memory requirement and the latency in the classifiers using SVM and RF classifiers puts challenge when it comes to on-chip integration and realizability of such systems for smart healthcare. In order to address the challenge, deep learning-based classifier models are designed and developed. A single modal classifier models utilizing ECG signal solely as feature dataset to classify emotion precisely and feasible to embed into smart wearable systems. A single modal ECG based CNN model is developed having lesser computational complexity and minimum memory requirement which make it highly suitable for smart wearable systems. ECG scalogram data from three publicly available datasets namely AMIGOS, ASCERTAIN and DECAF datasets as well as an ECG data acquired with developed hardware system are acquired using Continuous Wavelet Transform (CWT) and used to train the emotion classifier models. Three pre-trained CNN based models SqueezeNet, AlexNet and ResNet50 are trained for comparative study. The designed modified AlexNet model offers test accuracy of 95.90%, 94.62%, 92.31% and 97.73% respectively corresponding to ECG scalogram feature datasets of AMIGOS, ASCERTAIN, DECAF and with acquired ECG dataset. The proposed model offers far better accuracy than the pre-trained models with very less memory and computational requirements which makes it highly suitable for smart healthcare systems. Such systems have the potential to be realized into wearable devices capable of assessing real-time emotional state as well as identifying mental illness for early detection to provide required medical attention and care.

The following are the conclusions of this work:

1. A highly directional, high gain and wide bandwidth pyramidal horn is designed to act as transmitting and receiving antenna for bio-radar based application.
2. An IoT based Arrhythmia detection system using discrete signal processing module is devised.
3. Capacitive ECG dry electrodes are fabricated using textile electrodes and silver button electrodes.

4. An ECG belt system is developed to acquired ECG signal from above the cloth of 100-micron thickness and signal acquisition system using discrete components for wireless ECG system.
5. A SVM and RF based emotion classifier system is developed and hyperparameters are tuned using statistical features of publicly available datasets and experimentally acquired ECG datasets for 45 subjects.
6. Four types of a single modal ECG based CNN emotion classifiers (pre-trained and a proposed modified AlexNet) are designed for smart healthcare wearables systems.