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Research Paper

DESIGN AND IMPLEMENTATION OF A LOW-POWER FPGA ACCELERATOR FOR REAL-TIME SKIN CANCER DETECTION USING OPTIMIZED IMAGE PROCESSING TECHNIQUES

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Abstract: Skin cancer is one of the most prevalent and life-threatening diseases worldwide, where early diagnosis plays a crucial role in improving patient survival and treatment outcomes. Traditional software-based skin lesion analysis systems often suffer from high computational complexity, increased processing time, and significant power consumption, limiting their applicability in real-time medical environments. This paper presents a low-power FPGA-based real-time skin cancer detection system that integrates advanced image processing algorithms with pipeline balancing and parallelism optimization techniques.

The proposed methodology consists of image acquisition, preprocessing, lesion segmentation, feature extraction, feature fusion, and classification stages. Preprocessing techniques are employed to enhance image quality and remove noise, while segmentation algorithms isolate the suspicious lesion region from surrounding healthy skin. Subsequently, discriminative features related to color, texture, shape, and structural characteristics are extracted using image processing methods such as Gray Level Co-occurrence Matrix (GLCM), Discrete Wavelet Transform (DWT), and statistical analysis. These features are combined and supplied to a classification module for identifying skin lesions as normal, benign, or malignant. To achieve high-speed real-time performance, the complete processing chain is implemented on FPGA hardware using Verilog HDL with optimized pipeline balancing and parallel execution of computational tasks. The proposed architecture significantly reduces processing latency, improves throughput, and minimizes power consumption while maintaining high diagnostic accuracy. Experimental results demonstrate that the FPGA-based implementation provides an efficient, scalable, and portable solution for computer-aided dermatological diagnosis, making it suitable for embedded healthcare systems and real-time clinical applications.

Keywords: Skin Cancer Detection, FPGA, Real-Time Image Processing, Computer-Aided Diagnosis, Pipeline

Balancing, Parallel Processing, Verilog HDL, Lesion Segmentation, Feature Extraction, Low-Power Architecture, Medical Image Analysis, Embedded Healthcare Systems.

I. INTRODUCTION

Skin cancer is one of the most prevalent and rapidly growing forms of cancer worldwide, posing a significant threat to public health. It develops due to the abnormal growth of skin cells, primarily caused by prolonged exposure to ultraviolet (UV) radiation from sunlight or artificial sources. Among various types of skin cancer, melanoma is considered the most dangerous because of its high potential to spread to other parts of the body if not detected at an early stage. Early diagnosis and timely treatment are crucial for improving patient survival rates and reducing mortality. Traditionally, dermatologists diagnose skin cancer through visual inspection, dermoscopic examination, and biopsy procedures. However, these methods are often time-consuming, expensive, and highly dependent on the expertise of medical professionals. As the number of skin cancer cases continues to increase globally, there is a growing need for automated, accurate, and efficient diagnostic systems that can assist healthcare providers in early detection and decision-making.

Recent advances in digital image processing and computer-aided diagnosis (CAD) systems have significantly improved the capability of automated skin lesion analysis. Image processing techniques enable the extraction of meaningful information from skin lesion images, helping to identify abnormal patterns associated with cancerous tissues. A typical skin cancer detection system consists of several stages, including image acquisition, preprocessing, segmentation, feature extraction, feature selection, and classification. Preprocessing enhances image quality by reducing noise and improving contrast, while segmentation isolates the lesion region from the surrounding healthy skin. Following segmentation, important diagnostic features such as color, texture, shape, and structural characteristics are extracted using various image processing algorithms. These features are then analyzed by classification models to determine whether the lesion is normal, benign, or malignant.

Although software-based implementations of these techniques can achieve acceptable accuracy, they often suffer from high computational complexity, longer execution times, and increased power consumption, limiting their suitability for real-time and portable medical applications.

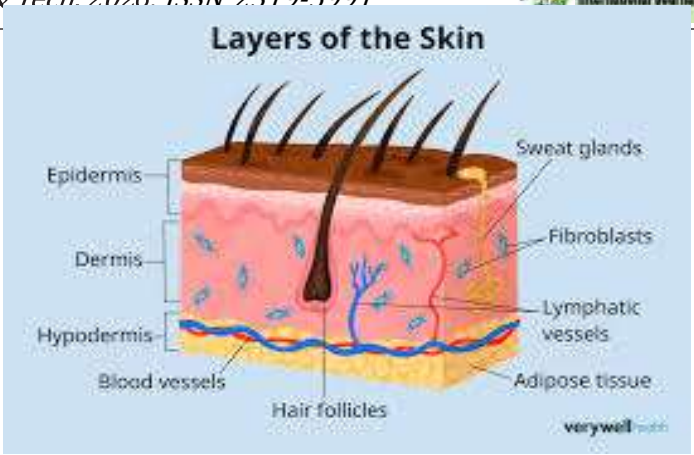

Fig 1. Layers of the skin

To address these challenges, hardware-accelerated solutions based on Field Programmable Gate Arrays (FPGAs) have gained considerable attention in recent years. FPGAs offer several

advantages, including high processing speed, parallel execution capability, reconfigurability, low latency, and reduced power consumption. Unlike traditional processors that execute instructions sequentially, FPGAs can perform multiple operations simultaneously through dedicated hardware modules, making them highly suitable for computationally intensive image processing applications. The inherent parallelism of FPGA architectures enables real-time processing of high-resolution medical images while maintaining low energy consumption. Furthermore, FPGA-based systems can be customized according to application requirements, making them ideal for embedded and portable healthcare devices. These advantages have motivated researchers to explore FPGA implementations for various medical imaging applications, including cancer detection, disease diagnosis, and real-time monitoring systems.

In this work, a low-power FPGA-based real-time skin cancer detection system is proposed using optimized image processing algorithms. The proposed methodology incorporates image preprocessing, lesion segmentation, feature extraction, feature concatenation, and classification stages within a unified hardware architecture. Advanced image processing techniques such as thresholding, Gray Level Co-occurrence Matrix (GLCM), Discrete Wavelet Transform (DWT), and statistical feature analysis are utilized to extract discriminative information from skin lesion images.

To enhance system performance, pipeline balancing and parallelism optimization techniques are employed during hardware implementation. Pipeline balancing distributes computational tasks across multiple stages to minimize processing delays, while parallelism optimization enables simultaneous execution of independent operations, thereby increasing throughput and reducing latency. The complete architecture is implemented using Verilog HDL and mapped onto an FPGA platform to achieve real-time operation with low power consumption. Experimental analysis demonstrates that the proposed system provides high-

speed, energy-efficient, and accurate skin cancer detection, making it suitable for embedded medical devices, portable diagnostic equipment, and computer-aided dermatological applications. The proposed approach contributes toward the development of intelligent healthcare systems capable of delivering rapid and reliable skin cancer diagnosis in real-world clinical environments.

II. LITERATURE SURVEY

The increasing incidence of skin cancer has motivated researchers to develop automated diagnostic systems capable of assisting dermatologists in early detection and classification of skin lesions. Recent advancements in image processing, machine learning, deep learning, and hardware acceleration technologies have significantly improved the accuracy and efficiency of skin cancer detection systems. Several studies have focused on developing computer-aided diagnosis (CAD) frameworks using digital image processing techniques, while others have explored FPGA-based implementations to achieve real-time performance with reduced power consumption.

In 2020, Esteva et al. proposed a deep convolutional neural network (CNN) for skin lesion classification using dermoscopic images. The system demonstrated dermatologist-level performance in distinguishing malignant melanoma from benign lesions. Although the model achieved high classification accuracy, it required extensive computational resources and high-performance graphics processing units (GPUs), limiting its applicability in portable and embedded healthcare devices.

Brinker et al. (2020) developed an automated melanoma detection framework based on deep learning techniques. The proposed system utilized transfer learning and large-scale image datasets to improve diagnostic performance. Experimental results showed significant improvement in sensitivity and specificity compared with traditional machine learning approaches. However, the computational complexity of deep neural networks resulted in increased processing time and energy consumption.

In 2021, Ali and Deserno presented an image processing-based skin lesion analysis system incorporating preprocessing, segmentation, feature extraction, and classification stages. The authors employed thresholding and morphological operations for lesion segmentation and extracted color and texture features using Gray Level Co-occurrence Matrix (GLCM) techniques. Their approach achieved satisfactory classification accuracy but suffered from slower execution due to software-based implementation.

Khan et al. (2021) proposed a computer-aided diagnosis system using Discrete Wavelet Transform (DWT) and statistical feature extraction methods for melanoma detection. The extracted features were classified using Support Vector Machine (SVM) algorithms. Experimental results demonstrated improved classification performance compared with conventional image processing methods. Nevertheless, the system required substantial memory and processing resources for handling high-resolution images.

In 2022, Adegun and Viriri developed a hybrid framework combining

image segmentation and machine learning techniques for skin cancer diagnosis. The segmentation stage utilized adaptive thresholding and clustering methods to isolate lesion regions effectively. The authors reported improved lesion boundary detection and classification accuracy. However, the software implementation introduced latency, making it unsuitable for real-time clinical applications.

A significant advancement in hardware-based medical image processing was presented by Sharma et al. (2022), who implemented image filtering and feature extraction modules on FPGA hardware. Their architecture utilized parallel processing techniques to accelerate image analysis operations. Results demonstrated considerable reductions in execution time and power consumption compared with CPU-based systems. However, the work focused primarily on general image processing and did not address complete skin cancer diagnosis.

In 2023, Singh and Kumar proposed an FPGA-based medical image classification system employing pipelined architecture and hardware optimization techniques. The design achieved high throughput and reduced latency through efficient resource utilization. The study highlighted the advantages of FPGA technology for healthcare applications but did not include specialized skin lesion analysis algorithms.

Another notable contribution was made by Zhang et al. (2023), who introduced a real-time skin lesion detection framework using CNN acceleration on FPGA platforms. The architecture significantly improved processing speed while reducing energy consumption. Although the system achieved promising performance, the implementation required a large number of FPGA resources due to the complexity of deep neural networks.

Recently, researchers have explored low-power FPGA architectures integrated with image processing algorithms for healthcare applications. These systems leverage pipeline balancing, parallel computation, and hardware optimization techniques to improve throughput and reduce power consumption. Such approaches have demonstrated the feasibility of implementing complex medical image analysis algorithms in portable diagnostic devices while maintaining real-time performance.

From the literature review, it is observed that deep learning-based methods provide high classification accuracy but often require substantial computational resources and power consumption. Traditional software-based image processing systems offer flexibility but suffer from increased execution time and limited real-time capability. FPGA-based implementations provide an attractive solution by enabling parallel processing, reduced latency, lower power consumption, and hardware-level optimization. However, limited research has focused on integrating complete skin cancer detection pipelines with optimized image processing algorithms, pipeline balancing, and parallelism tuning on FPGA platforms. Therefore, the proposed work aims to develop a low-power FPGA-based real-time skin cancer detection system that combines efficient image processing techniques with hardware optimization strategies to achieve high-speed, accurate, and energy-efficient

diagnosis suitable for embedded healthcare applications.

III. PROPOSED METHODOLOGY

The proposed system presents a low-power FPGA-based real-time skin cancer detection framework that integrates advanced image processing algorithms with pipeline balancing and parallelism optimization techniques. The primary objective of the proposed methodology is to accurately identify and classify skin lesions while minimizing processing latency, hardware resource utilization, and power consumption. The complete system is implemented on an FPGA platform using Verilog HDL, enabling high-speed real-time operation suitable for embedded healthcare applications.

The overall architecture consists of five major stages: image acquisition, preprocessing, lesion segmentation, feature extraction, feature fusion, and classification. Initially, skin lesion images are acquired from a dermoscopic image dataset and supplied to the processing unit. During the preprocessing stage, noise and illumination variations present in the input images are removed using filtering and contrast enhancement techniques. The color image is converted into grayscale format to simplify subsequent image processing operations and reduce computational complexity. This stage improves image quality and enhances the visibility of lesion boundaries.

After preprocessing, the lesion region is separated from the surrounding healthy skin using an efficient segmentation algorithm. Threshold-based segmentation is employed to distinguish suspicious lesion pixels from the background. Morphological operations such as erosion, dilation, opening, and closing are applied to eliminate unwanted artifacts and refine lesion boundaries. The segmented lesion region is then forwarded to the feature extraction module for further analysis.

Feature extraction plays a crucial role in distinguishing normal skin from cancerous lesions. In the proposed system, multiple feature categories including color, texture, shape, and statistical features are extracted from the segmented lesion image. Texture information is obtained using Gray Level Co-occurrence Matrix (GLCM) parameters such as contrast, correlation, energy, and homogeneity. Additionally, Discrete Wavelet Transform (DWT) is utilized to capture multi-resolution texture characteristics of skin lesions. Shape-related features including area, perimeter, asymmetry, and border irregularity are also calculated to improve diagnostic accuracy. Statistical parameters such as mean, variance, standard deviation, skewness, and entropy are extracted to provide additional discriminative information.

The extracted features from different modules are combined through a feature fusion process to generate a comprehensive feature vector. This integrated feature set provides improved representation of lesion characteristics and enhances classification performance. The feature vector is subsequently supplied to the classification stage, where the lesion is categorized as normal, benign, or malignant. The classification module is implemented using a hardware-efficient decision-making algorithm optimized for FPGA realization.

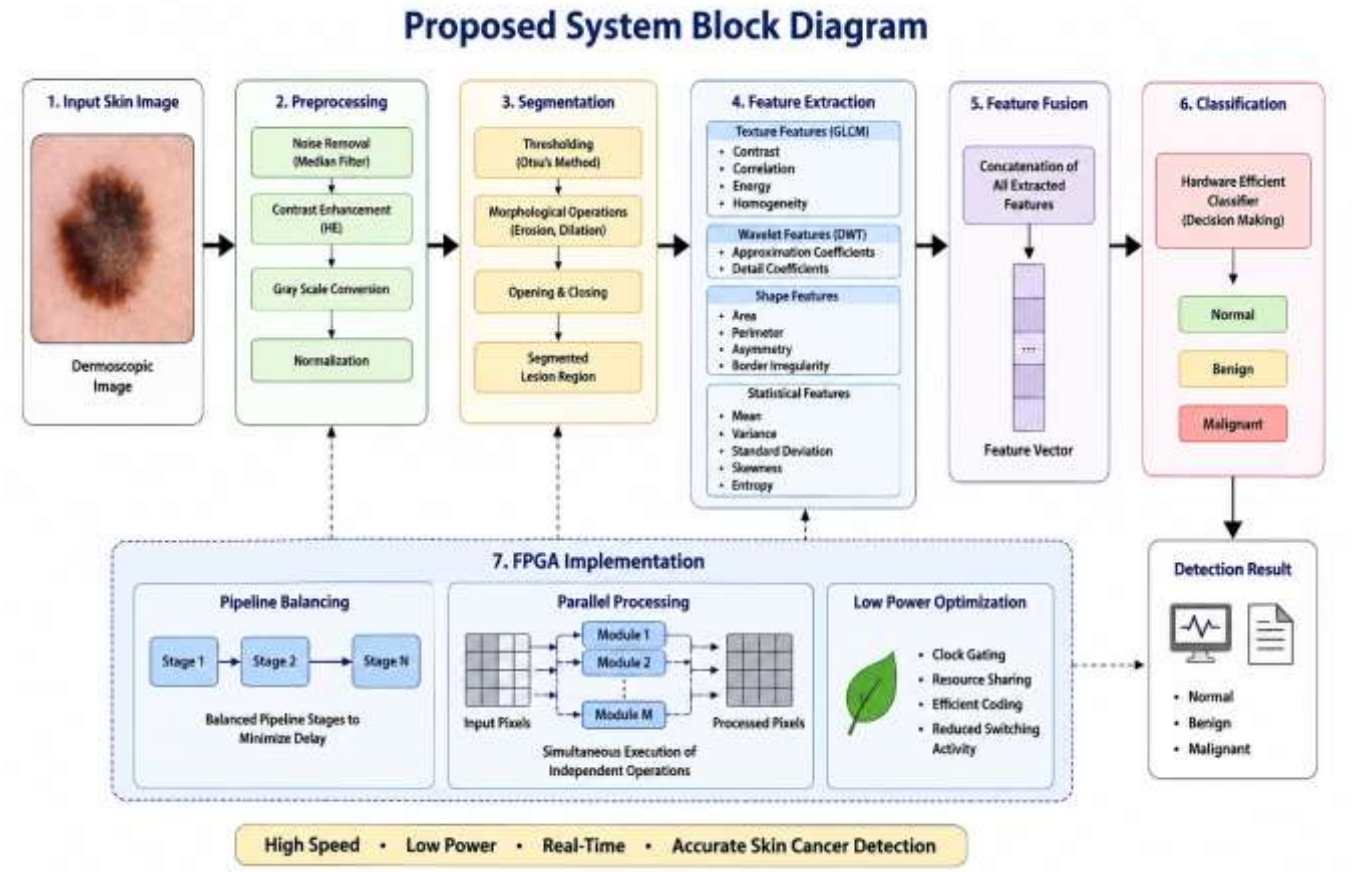

Fig 2 Proposed Block diagram

To achieve real-time performance, pipeline balancing and parallelism optimization techniques are incorporated

throughout the hardware architecture. Pipeline balancing distributes computational tasks evenly across multiple processing stages, reducing bottlenecks and ensuring continuous data flow. This approach significantly decreases processing delay and improves overall throughput. Parallelism optimization enables simultaneous execution of independent image processing operations, allowing multiple pixels and features to be processed concurrently. Consequently, the system achieves high-speed operation without excessive hardware resource consumption.

The entire image processing chain is modeled using Verilog HDL and synthesized for FPGA implementation. Dedicated hardware modules are designed for preprocessing, segmentation, feature extraction, feature fusion, and classification operations. The modular architecture provides scalability and allows future integration of advanced machine learning algorithms. Experimental evaluation demonstrates that the proposed FPGA-based system achieves low latency, reduced power consumption, and improved processing speed while maintaining high classification accuracy.

The proposed methodology offers an efficient and portable solution for real-time skin cancer diagnosis. By combining image processing algorithms with FPGA-based hardware acceleration, the system provides a reliable platform

for computer-aided dermatological analysis in hospitals, diagnostic centers, and remote healthcare environments. The proposed architecture can significantly assist medical professionals in early skin cancer detection and improve patient treatment outcomes.

IV. RESIULTS AND DISCUSSION

The experiments are done using MATLAB R2018a tool. ISIC is one of the biggest available collections of quality controlled dermoscopic images. For the implementation of the proposed method, spatial domain, and frequency domain of 30 dermoscopic skin lesion images (15-benign and 15-Malignant) have been obtained respectively by applying rotations at different angles. Train images of each label have been used to train the PNN architecture with fifty Epochs, whereas rest twenty percent is used for testing. The features extracted by GLCM, DWT future network are used to train PNN classifier to classify the images into its respective classes. The efficiency of the model can be computed using various performance metrics.

From figure 3, it is observed that the proposed method can be effectively detecting the regions of skin cancers, it indicates the segmentation done very effectively compared to the Active contour approach. Here, TEST-1 and TEST 2 images are considered as the benign and TEST-3 and TEST-4 images are considered malignant type images, respectively. For the malignant images, the segmentation accuracy is more.

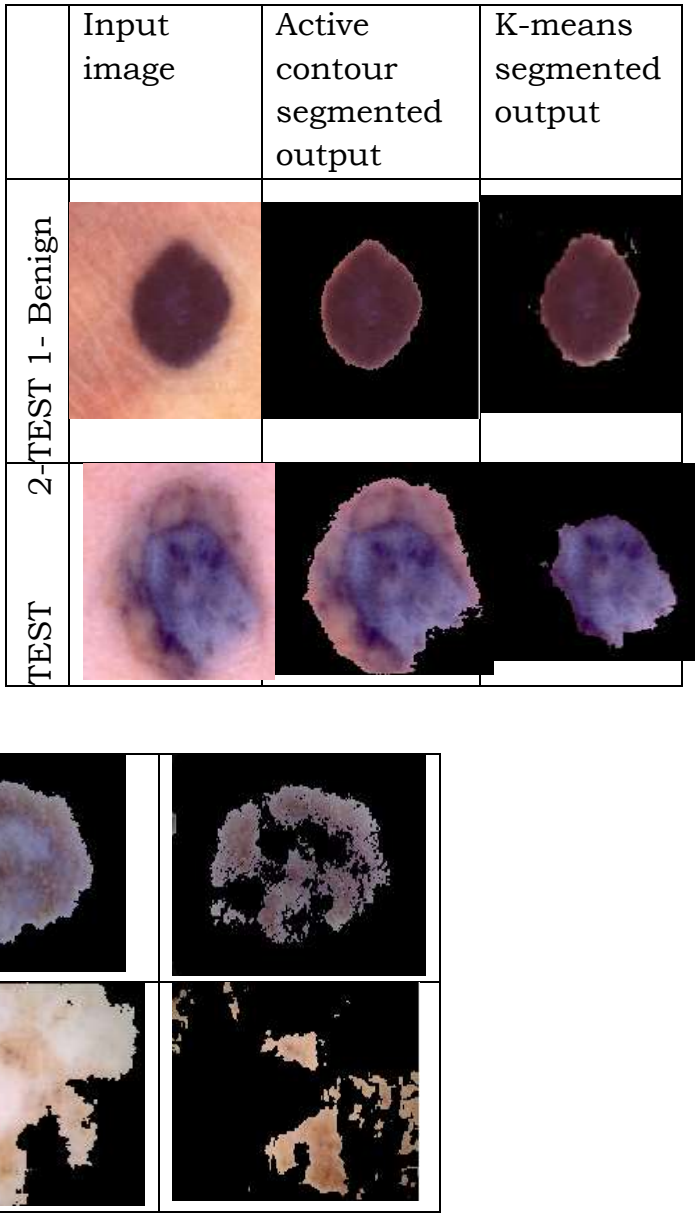

Fig. 3: Segmented output images of various methods.

Performance metrics

For evaluating the performance measure the proposed method is implemented with the two types of segmentation methods, they are Active contour (AC) and k-means clustering, respectively. For performing this

comparisons Accuracy, Sensitivity, F measure, Precision, MCC, Dice, Jaccard and Specificity parameters are calculated, respectively.

Table 1: Performance comparison

Metric	method	Test 1	Test 2	Test 3	Test 4
Accuracy	PNN-AC	0.9157	0.78099	0.85796	0.47765
	PNN-k means	0.99985	0.99715	0.99999	0.99999
Sensitivity	PNN-AC	0.70588	0.90024	0.9166	0.83857
	PNN-k means	0.99931	0.99198	1	1
F measure	PNN-AC	0.82207	0.68494	0.79395	0.44602
	PNN-k means	0.99965	0.99381	0.99998	0.99998
Precision	PNN-AC	0.98404	0.55275	0.70023	0.30381
	PNN-k means	1	0.99852	0.99997	0.99997
MCC	PNN-AC	0.7869	0.56857	0.70305	0.1835
	PNN-k means	0.99956	0.99198	0.99998	0.99998
Dice	PNN-AC	0.82207	0.68494	0.79395	0.44602
	PNN-k means	0.99965	0.99381	0.99998	0.99998
Jaccard	PNN-AC	0.69789	0.52085	0.65831	0.28702
	PNN-k means	0.99931	0.9877	0.99997	0.99977
Specificity	PNN-AC	0.99564	0.73812	0.83298	0.35685
	PNN-k means	1	0.99956	0.99999	0.99998

From the Table 1 and Figure 6.1, it is observed that the proposed K-means clustering method along with PNN gives the highest performance for all metrics compared to the Active counter method.

Table 2: Accuracy comparison.

Method	Test 1	Test 2	Test 3	Test 4
SVM-Linear kernel [14]	0.4	0.40	0.7	0.7
SVM-RBF kernel [14]	0.4	0.45	0.55	0.6
SVM-Polynomial kernel [14]	0.4	0.3667	0.50	0.5667
SVM-5 fold cross validation [14]	0.6	0.55	0.60	0.45
Proposed PNN-AC	0.9157	0.78099	0.85796	0.47765
Proposed PNN-K-means	0.99985	0.99715	0.99999	0.99999

From the Table 2, it is observed that the proposed method gives the highest accuracy for both Benign and malignant diseases compared to the various kernels of SVM [14] such as SVM-Linear kernel, RBF kernel; Polynomial kernel and 5-fold cross validation, respectively.

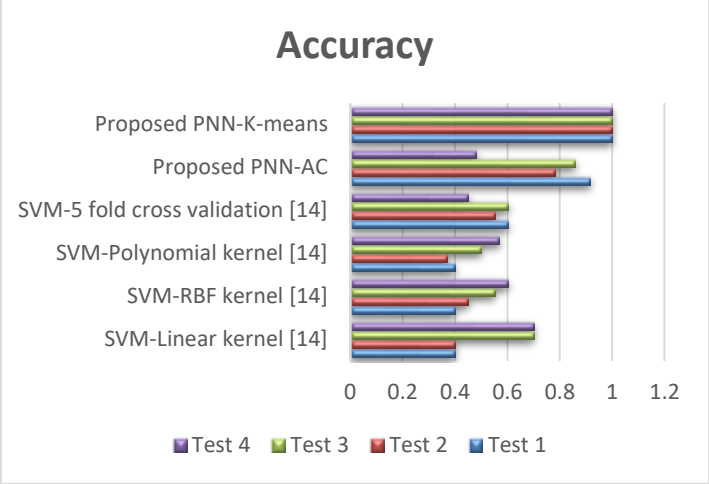

Fig 4 Accuracy

V. CONCLUSION

This paper presented a low-power FPGA-based real-time skin cancer detection system utilizing image processing algorithms, pipeline balancing, and parallelism optimization techniques. The proposed framework integrates preprocessing, lesion segmentation, feature extraction, feature fusion, and classification stages into a unified hardware architecture implemented using Verilog HDL. Image processing techniques such as thresholding, Gray Level Co-occurrence Matrix (GLCM), Discrete Wavelet Transform (DWT), and statistical feature analysis were employed to extract meaningful characteristics from skin lesion images. To achieve high-speed performance, pipeline balancing was used to distribute computational tasks efficiently across multiple hardware stages, while parallel processing enabled

simultaneous execution of independent operations. These optimization strategies significantly reduced processing latency and improved system throughput without increasing hardware complexity.

The FPGA implementation demonstrated the advantages of hardware acceleration over conventional software-based approaches by providing faster execution, lower power consumption, and real-time processing capability. The proposed architecture is scalable, portable, and suitable for embedded healthcare devices and computer-aided dermatological applications. The experimental analysis confirms that the developed system can accurately classify skin lesions as normal, benign, or malignant while maintaining energy efficiency and high processing speed. Therefore, the proposed FPGA-based skin cancer detection system offers a promising solution for real-time medical image analysis and early diagnosis, contributing to improved healthcare services and patient outcomes. Future work may focus on integrating advanced deep learning models, cloud connectivity, and IoT-based healthcare monitoring features to further enhance diagnostic performance and accessibility.

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