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Design and Implementation of Medical Image Fusion System on FPGA

Mithun S[1], Vivek G T[2], Jarikala H D[3], Arpitha C S[4], Lakshmi D L[5], Goutham V[6]
[1, 2, 3, 4,5]*Department of ECE, BGS Institute of Technology, Bengaluru, Karnataka, India.*
[6]*Principal, SJBS Polytechnic, Bengaluru, Karnataka, India.*

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Abstract: *Medical image fusion is a critical process in modern diagnostic systems, combining complementary information from multiple imaging modalities such as CT, MRI, and PET to provide more accurate and comprehensive visualization for clinical analysis. This project presents the design and implementation of a real-time medical image fusion system on a Field-Programmable Gate Array (FPGA) platform. By leveraging the parallel processing capabilities and reconfigurability of FPGAs, the system achieves high-speed performance suitable for real-time applications, while maintaining image quality and accuracy. The proposed system employs a multi-resolution fusion algorithm, such as Discrete Wavelet Transform (DWT), to integrate features from different medical images. Hardware modules are designed using VHDL/Verilog and synthesized on an FPGA development board. The architecture is optimized for resource efficiency, latency, and throughput.*

Key Word: *DWT (Discrete Wavelet Transform), FPGA, Medical image fusion, CT-MRI fusion*

I.INTRODUCTION

Medical imaging is essential for accurate diagnosis and treatment planning. Different imaging modalities such as CT, MRI, and PET provide unique types of information—CT offers detailed bone structure, MRI provides soft tissue contrast, and PET highlights metabolic activity. However, relying on a single modality may not give a complete picture. Medical image fusion combines images from multiple modalities into one, enhancing the overall information content and aiding in more accurate clinical decisions. Software-based image fusion methods often involve high computational complexity and are not suitable for real-time applications. Field Programmable Gate Arrays (FPGAs) offer a hardware-based solution, providing high-speed, parallel processing capabilities with low latency and power consumption. These features make FPGAs ideal for real-time medical image processing systems. This project focuses on the design and implementation of a medical image fusion system using FPGA technology. A Discrete Wavelet Transform (DWT)-based fusion algorithm is used to effectively extract and merge important features from source images. The system is implemented using VHDL/Verilog and synthesized on an FPGA development board. The goal is to achieve real-time image fusion performance while maintaining high accuracy and efficiency, making it suitable for embedded medical diagnostic devices and portable imaging systems.

II.MATERIAL AND METHODS

NEXYS A7: The Nexys A7 is a powerful FPGA development board featuring the Xilinx Artix-7 FPGA, designed for both educational and professional applications. It offers high-performance logic, making it suitable for a range of projects, from basic digital circuits to complex embedded systems. Some key features include:

- Programmable logic slices: Up to 15,850 slices, each with four 6-input LUTs and 8 flip-flops.
- Memory: 16 MB of fast block RAM.
- Clock management: Six tiles with phase-locked loops (PLLs) for precise timing.
- DSP slices: 240 DSP slices for efficient signal processing.
- Connectivity: USB, Ethernet, and various I/O ports for interfacing with external devices.

It is an ideal platform for implementing a real-time medical image fusion system due to its combination of hardware resources, performance, and accessibility. The nature of image fusion especially using algorithms like Discrete Wavelet Transform (DWT) requires fast, parallel data processing and efficient memory usage, both of which the Nexys A7 supports well.

PC: A PC is essential in this medical image fusion project for several key purposes. It serves as the development platform where the FPGA design is created, simulated, and synthesized using tools like Xilinx Vivado. The PC is also used to preprocess and format medical images, converting them into compatible data files for FPGA input. During operation, the PC facilitates communication with the FPGA board via USB or UART interfaces, enabling data transfer and debugging.

Additionally, it is used to receive and analyze the fused output images, comparing them against reference results to evaluate performance and quality. Overall, the PC acts as the central hub for programming, controlling, testing, and validating the entire system.

JTAG cable: JTAG (Joint Test Action Group) plays a crucial role in the medical image fusion system project by enabling programming, debugging, and testing of the FPGA on the Nexys A7 board. It provides a standard interface to upload the compiled design bitstream directly to the Artix-7 FPGA, configuring the hardware to perform the image fusion tasks. Additionally, JTAG supports in-system debugging tools like the Integrated Logic Analyzer (ILA), allowing real-time monitoring and troubleshooting of the fusion algorithm implementation. This helps identify and fix errors during development efficiently. Moreover, JTAG enables boundary scan testing to verify hardware integrity without physically removing the FPGA from the board. Overall, JTAG is essential for seamless development, testing, and deployment of the FPGA-based image fusion system.

MATLAB: MATLAB plays an important role in this medical image fusion project by providing a flexible environment for algorithm development, simulation, and validation before hardware implementation. It is used to preprocess medical images by converting them into pixel matrices, resizing, and normalizing the data as needed. These pixel values are then exported and saved as hex files, which serve as input test vectors for the FPGA. After the FPGA processes the images and generates fused image pixel data, MATLAB is used again to read this output data, reconstruct the fused image from the pixel values, and visualize the result. MATLAB also supports developing and testing the fusion algorithm, such as the Discrete Wavelet Transform (DWT), and provides evaluation metrics like PSNR and structural similarity to compare the fused image quality between the software model and FPGA implementation. This integration of MATLAB ensures accuracy and aids in verifying the hardware design.

Vivado 2018.1: Vivado 2018.1 is the primary development environment used for designing, simulating, and implementing the medical image fusion system on the Artix-7 FPGA. It provides a comprehensive suite of tools for writing and editing the hardware description language (VHDL/Verilog) code, performing functional and timing simulations, and synthesizing the design into an optimized hardware implementation. Vivado's implementation tools map the image fusion algorithm efficiently onto the FPGA resources, including logic cells, DSP blocks, and memory. Additionally, Vivado facilitates generating the configuration bitstream, which programs the Nexys A7 board. Its integrated debugging tools, such as the Integrated Logic Analyzer (ILA), enable real-time monitoring and troubleshooting of the fusion system's internal signals. Overall, Vivado 2018.1 is essential for transforming the fusion algorithm from a conceptual model into a working hardware accelerator on the FPGA, ensuring optimal performance and resource utilization.

Procedure Methodology:

Data Acquisition and Preprocessing: It involves the selection of medical images from different modalities, typically CT and MRI scans, which provide complementary diagnostic information. These images are usually in formats like DICOM or JPEG. To prepare them for FPGA processing, MATLAB is used to convert the images into grayscale pixel matrices, ensuring uniformity in data type. The images are resized to a fixed resolution (e.g., 256×256 pixels) to match FPGA memory and processing constraints. Normalization is applied to scale pixel intensity values into a standard range, which helps improve fusion accuracy and hardware efficiency.

Image Conversion: Once pre-processed, the pixel data cannot be fed directly to the FPGA. Instead, MATLAB exports the image pixels into hexadecimal (.hex) files. Each pixel's intensity value is converted into hex format, creating a text file that represents the entire image as a sequence of hex numbers. These hex files are then loaded into the FPGA's Block RAM or external memory, serving as test input vectors for the fusion system.

DWT based image fusion: In this step, the core fusion algorithm uses the Discrete Wavelet Transform (DWT) to effectively combine features from the input medical images. First, each input image is decomposed into different frequency components by applying the DWT, separating the image into approximation (low-frequency) and detailed (high-frequency) sub-bands. Corresponding sub-bands from both images are then fused by applying specific fusion rules, such as selecting the maximum coefficients or averaging values, to retain the most important information from each image. After the fusion of wavelet coefficients, the inverse DWT reconstructs the fused image by combining the fused sub-bands back into a single image. This approach enhances the final image quality by preserving key structural and textural details from both original images, which is crucial for improved medical diagnosis. The algorithm is first simulated in MATLAB for accuracy, then implemented in hardware on the FPGA to achieve real-time performance.

FPGA Implementation: After validating the image fusion algorithm in MATLAB, the design is translated into hardware using VHDL or Verilog for implementation on the Artix-7 FPGA of the Nexys A7 board. The fusion algorithm is broken down into hardware modules, including wavelet decomposition, fusion logic, and reconstruction blocks, optimized for parallel and pipelined processing to achieve real-time performance. Using Xilinx Vivado 2018.1, the hardware description is synthesized, mapped, and placed onto the FPGA resources, ensuring efficient utilization of logic elements, DSP blocks, and memory. The generated bitstream file is then programmed onto the FPGA via the JTAG interface. This step brings the software algorithm into a tangible hardware accelerator capable of processing medical images rapidly, which is essential for clinical applications requiring fast and accurate image fusion.

Post-Processing and Fused image reconstruction: Once the FPGA completes the fusion process, it outputs the fused image pixel data in a raw format. This data is transferred back to the PC via communication interfaces such as UART or USB. Using MATLAB, the output pixel values are read and reconstructed into a coherent image matrix. MATLAB then performs post-processing tasks like filtering, contrast adjustment, or noise reduction if needed, to enhance the visual quality of the fused image. Finally, the fused image is displayed for evaluation, allowing comparison with the original inputs and the software-simulated fusion results. This step is vital for verifying the accuracy and effectiveness of the hardware implementation and ensures the fused image is clinically useful.

Block Diagram:

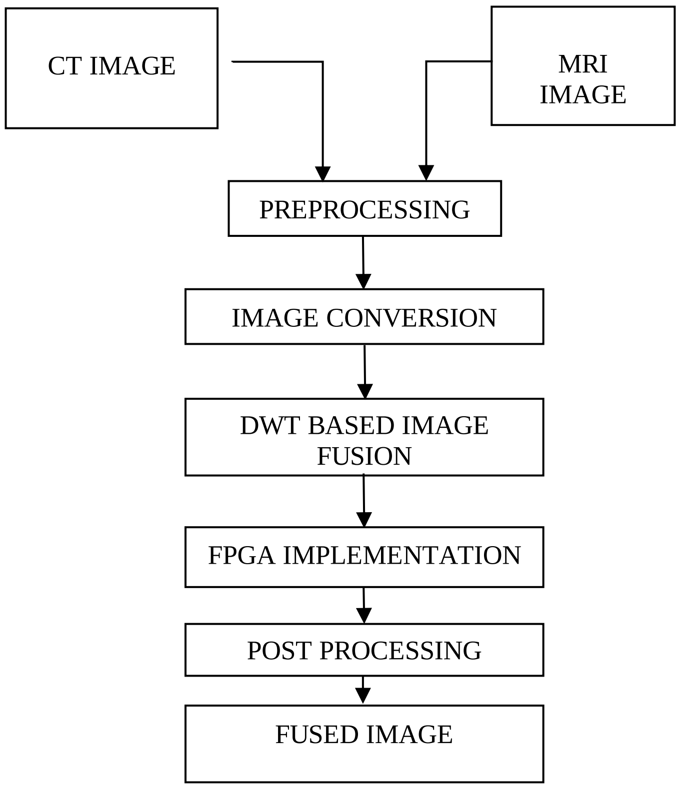

Fig 1 shows the design methodology of medical image fusion using FPGA.

III.RESULT

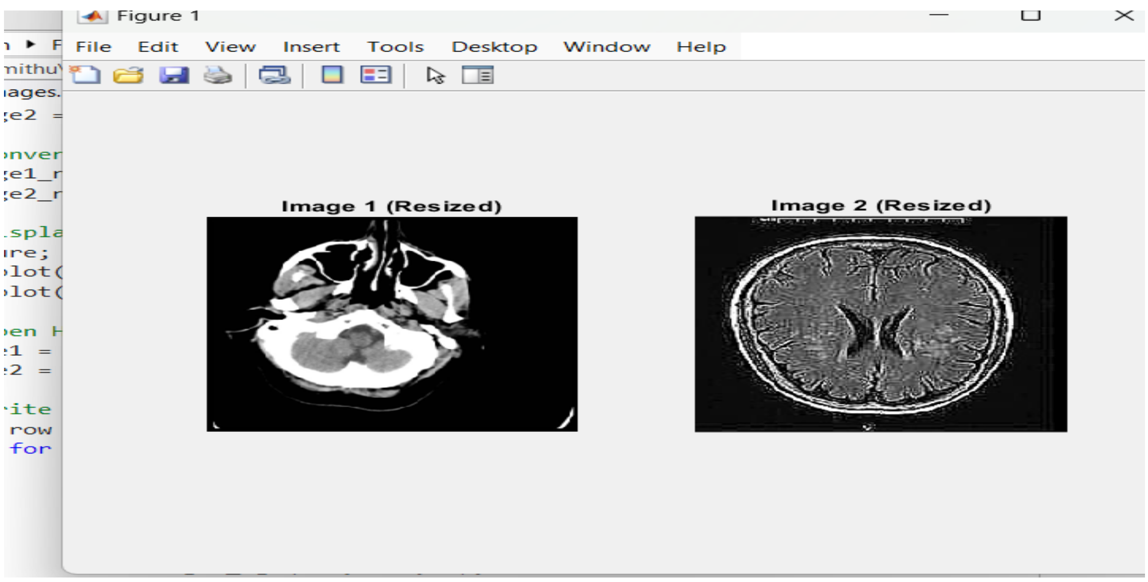

Fig 2 shows how MATLAB acquires the image and coverts them into pixels

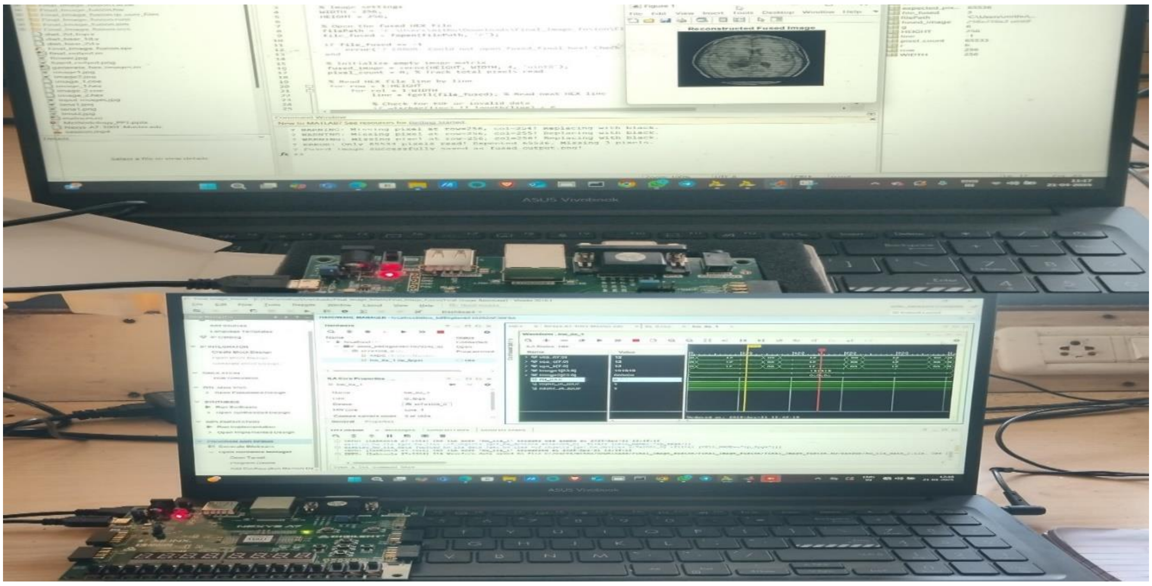

Fig 3 shows fused image pixels generated by the FPGA implementation

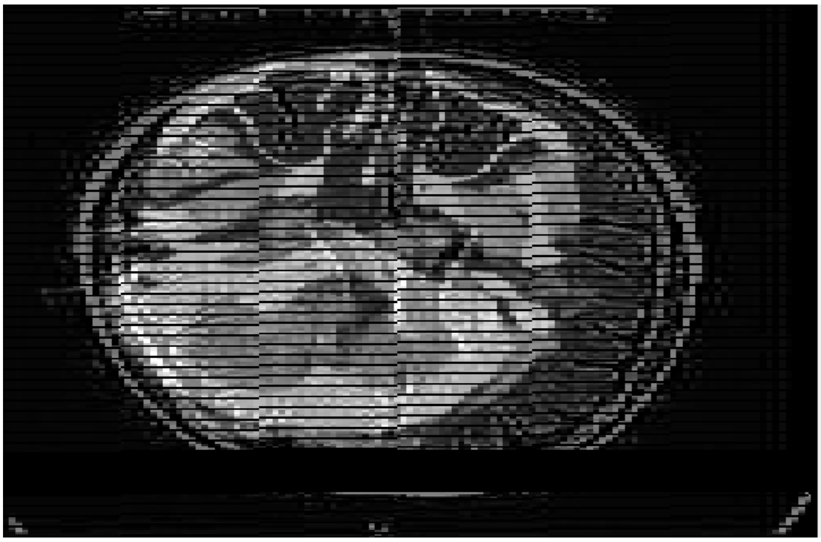

Fig 4 shows the final fused image obtained by converting the fused image pixels. The image shares similarities between both CT and MRI images.

IV.DISCUSSION

The medical image fusion system developed on the Artix-7 FPGA using the Nexys A7 board successfully demonstrates how hardware acceleration can enhance the performance of image processing tasks, particularly fusion of multimodal medical images like CT and MRI scans. Implementing the Discrete Wavelet Transform (DWT) based fusion algorithm on FPGA enables real-time processing capabilities that are often unattainable with traditional software-only approaches, especially when handling large image datasets. One key outcome is the significant speedup achieved due to the parallel processing and pipelining features of the FPGA, which allow simultaneous computations on different image parts, drastically reducing overall fusion time. This makes the system highly suitable for clinical environments where timely and accurate diagnosis is critical.The quality of the fused images produced by the FPGA closely matches the results obtained from MATLAB simulations, indicating that the fixed-point arithmetic and hardware optimizations did not compromise the accuracy of the fusion process. This validation was confirmed using objective quality metrics like PSNR and Structural Similarity Index (SSIM), which showed minimal degradation compared to the software model. However, the project also highlighted challenges such as resource constraints on the FPGA, requiring careful optimization of logic and memory usage. The fixed-point representation, while resource-efficient, necessitated fine-tuning of precision to balance accuracy and hardware complexity. Additionally, transferring image data between the PC and FPGA introduced communication overhead that could be further optimized. Overall, the project validates that FPGA-based medical image fusion systems can provide a powerful alternative to software methods, offering a practical balance between speed, accuracy, and hardware resource utilization. Future improvements could include exploring more advanced fusion algorithms, integrating higher resolution images, and enhancing communication protocols to further streamline the system for clinical applications.

V.CONCLUSION

This project successfully designed and implemented a medical image fusion system on the Artix-7 FPGA using the Nexys A7 development board, demonstrating the practical benefits of hardware acceleration for complex image processing tasks. By leveraging the Discrete Wavelet Transform (DWT) based fusion algorithm, the system efficiently combined complementary features from multimodal medical images, such as CT and MRI scans, into a single enhanced image. The FPGA implementation provided significant improvements in processing speed due to its parallelism and pipelining capabilities, achieving real-time fusion performance that is crucial for time-sensitive clinical applications. The integration of MATLAB for preprocessing, simulation, and post-processing enabled smooth development and verification of the fusion algorithm, ensuring the hardware output maintained high accuracy and image quality. Objective evaluation using metrics like PSNR and SSIM confirmed that the FPGA-based fused images closely matched the software simulations, validating the correctness and effectiveness of the hardware design. Despite resource limitations on the FPGA and challenges related to fixed-point arithmetic and data communication, the project demonstrated that careful design and optimization could address these issues without compromising performance. The use of Vivado 2018.1 and JTAG facilitated efficient synthesis, implementation, and debugging of the hardware system. In summary, this project highlights the feasibility and advantages of FPGA-based medical image fusion systems, paving the way for further enhancements such as support for higher-resolution images, more sophisticated fusion techniques, and integration into clinical workflows. The success of this work underscores the potential of combining advanced signal processing algorithms with reconfigurable hardware to improve medical diagnostics and patient care.

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