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Original Research Article

VLSI Design of Ibex RISC-V Processor

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Abstract

This paper presents a Discrete Wavelet Transform (DWT)-based approach for medical image fusion, implemented using Verilog HDL and verified with Xilinx ISE. The methodology involves fusing CT and MRI images using the Haar wavelet transform and validating the results through simulation and synthesis. Tools such as MATLAB are used for cross-verification. The objective is to enhance diagnostic accuracy and support medical imaging applications through efficient hardware design.

Keywords: Image Fusion, Discrete Wavelet Transform (DWT), Verilog, Medical Imaging, Xilinx ISE, Haar Wavelet.

I. INTRODUCTION

Image fusion integrates complementary information from multiple images into a single, more informative image, enhancing the overall quality and interpretability of visual data. This technique plays a critical role in domains where precise image interpretation is essential, such as medical diagnostics, remote sensing, surveillance, and robotics. In medical imaging in particular, the fusion of multi-modal data—such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT), and Positron Emission Tomography (PET)—has revolutionized clinical diagnosis and treatment planning. Each modality captures unique information: for instance, CT offers detailed anatomical structure, while MRI provides superior soft-tissue contrast and PET captures metabolic activity.

By combining these complementary datasets, image fusion improves diagnostic confidence, minimizes false positives or negatives, and enables clinicians to detect subtle abnormalities that may go unnoticed in single-source imaging. Fusion techniques can be broadly classified into three levels: pixel-level fusion, which combines raw pixel data; feature-level fusion, which merges extracted features such as edges or textures; and decision-level fusion, which integrates outcomes of separate analyses for a higher-level decision.

Among the various algorithms used, Wavelet Transform has gained prominence for its ability to decompose images into multi-scale, frequency-based components that preserve both spatial and spectral information. Similarly, Pyramid Fusion techniques leverage multi-resolution analysis, allowing fusion at different levels of image detail. These methods are particularly effective in preserving important anatomical features and enhancing contrast in fused outputs.

The application of image fusion in medicine is vast. In oncology, fused PET/CT images assist in identifying tumor boundaries and metastasis; in neurology, MRI/CT fusion helps visualize brain lesions, strokes, and epilepsy-related anomalies; in cardiology, it aids in evaluating cardiac function and vessel conditions; and in orthopedics, it enhances fracture assessment and pre-surgical planning. The integration of these techniques into clinical workflows significantly improves patient outcomes by providing clinicians with a unified and clearer view of the patient's condition.

II. LITERATURE REVIEWS

Literature indicates successful hardware implementations of image fusion using Verilog and FPGAs. Studies show advantages in speed, accuracy, and efficiency compared to software-based systems. Researchers have used various fusion strategies (pixel, feature, decision levels) with FPGA hardware to enable real-time processing. Challenges remain in design complexity and verification, but advancements continue to improve performance and integration capabilities.

The field of medical image fusion has seen significant advancements with the application of wavelet-based algorithms and hardware acceleration using FPGA. Below are some of the referenced works and related research:

Li *et al.,* in the paper *"Real-time Image Fusion on FPGA"*, implemented a real-time image fusion algorithm using Verilog on an FPGA platform. Their work demonstrated significant performance improvements over software-based fusion techniques, especially in speed and responsiveness, which are critical for medical imaging and surveillance applications [1].

Suri *et al.,* in *"Hardware Implementation of Medical Image Fusion Using FPGA"*, presented a method for fusing medical images from modalities like CT and MRI on an FPGA using Verilog HDL. The real-time capability of FPGA systems was shown to enhance clinical workflows by enabling on-the-fly diagnosis and visualization [2].

Zhang *et al.,* in *"Efficient FPGA-based Architecture for Remote Sensing Image Fusion"*, proposed a wavelet-based image fusion architecture for remote sensing applications. Their design highlighted the trade-offs in energy efficiency and speed achievable through FPGA, particularly using spatial-frequency domain approaches such as DWT [3].

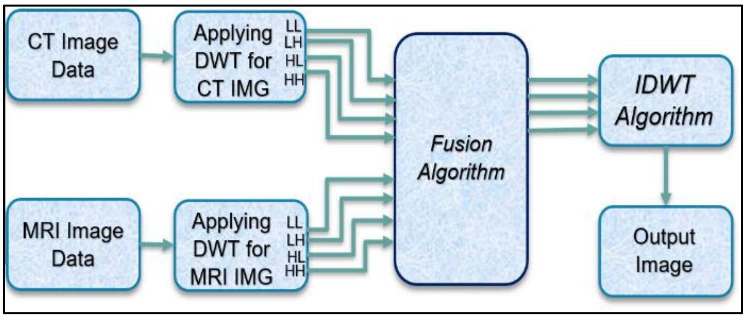
Kaur and Sikka, in *"Medical Image Fusion Using Wavelet Transform for Clinical Diagnosis: A Review"*, emphasized the role of wavelet-based fusion (especially Haar and Daubechies wavelets) in preserving structural and textural details in fused outputs, which are vital for accurate medical interpretation [4].

Wang *et al.,* in *"Comparison of Image Fusion Algorithms Based on DWT and PCA"*, evaluated multiple fusion strategies and concluded that DWT offers superior localization in both time and frequency domains, making it suitable for multimodal fusion [5].

Gupta *et al.,* in *"Design and Implementation of Image Fusion using Verilog HDL on FPGA"*, described a hardware implementation of DWT-based fusion using Verilog, which was verified through simulation tools like Xilinx ISE and validated using MATLAB, demonstrating efficiency in hardware-software co-design [6].

III. METHODOLOGY

The below given figure defines the proposed methodology, and the steps of how the project is executed using different technologies.



The fusion methodology involves acquiring CT and MRI images in 8x8 grayscale, followed by DWT using Haar wavelets. DWT decomposes images into frequency components, which are fused using averaging rules. The Inverse DWT (IDWT) reconstructs the final fused image. Verilog modules are developed to perform DWT, fusion, and IDWT. Simulation and synthesis are conducted using Xilinx ISE, while MATLAB serves for verification.

The image fusion process for medical applications involves several key steps, beginning with the acquisition of CT and MRI scans. These images are stored in an 8×8 grayscale format and prepared for processing. The fusion is performed using the Discrete Wavelet Transform (DWT), which decomposes each image into low-pass (approximation) and high-pass (detail) components, capturing both spatial and frequency features. The Haar wavelet, known for its simplicity and computational efficiency, is used for this decomposition due to its step-like basis functions and suitability for hardware implementation.

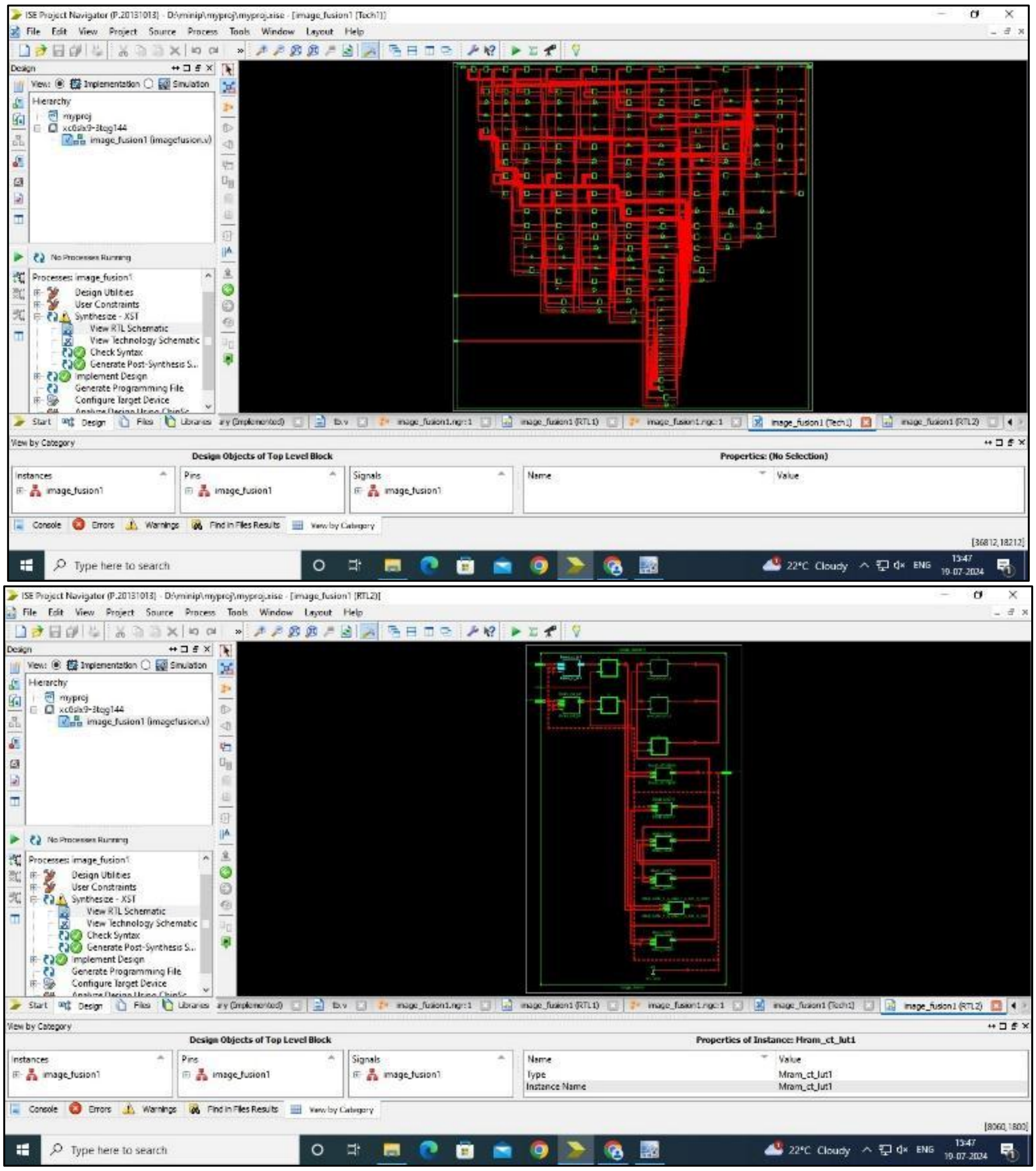
DWT is applied along both horizontal and vertical directions to extract orientation-specific features. After decomposition, corresponding coefficients from the two images are fused using an averaging method for simplicity. The fused image is then reconstructed using the Inverse DWT (IDWT).

This entire process is implemented in Verilog HDL, enabling real-time performance and low-power operation through FPGA deployment. The hardware-centric design ensures advantages such as parallel processing, low latency, energy efficiency, and high customizability, making it ideal for embedded medical imaging systems.

IV. Simulation and Synthesis

The Discrete Wavelet Transform (DWT) is a fundamental tool in signal and image processing, particularly effective in multi-resolution analysis. In the context of medical image fusion, DWT allows the decomposition of an image into different frequency sub-bands, capturing both coarse and fine details. This decomposition includes approximation coefficients (low-frequency components) and detail coefficients (high-frequency components), which are analyzed at various scales. Among the various wavelet families, the Haar wavelet is employed in this work due to its simplicity, fast computation, and suitability for hardware implementation. Haar wavelets work by breaking an image into pairs of adjacent pixels, calculating their average (low-pass) and difference (high-pass), and repeating this process across rows and columns.

The image fusion process using DWT follows a structured methodology. Initially, input images—specifically CT and MRI scans—are loaded and pre-processed into 8×8 grayscale pixel matrices. These images are individually subjected to DWT to obtain their respective approximation and detail coefficients. Once decomposed, corresponding coefficients from both images are fused using a simple averaging rule. Alternative fusion strategies such as maximum selection or weighted averaging may be adopted depending on the specific application, but averaging provides a balanced blend of information while maintaining computational simplicity. The fused coefficients are then passed through the Inverse Discrete Wavelet Transform (IDWT) to reconstruct the final, fused image, which combines anatomical detail from CT with soft-tissue contrast from MRI.

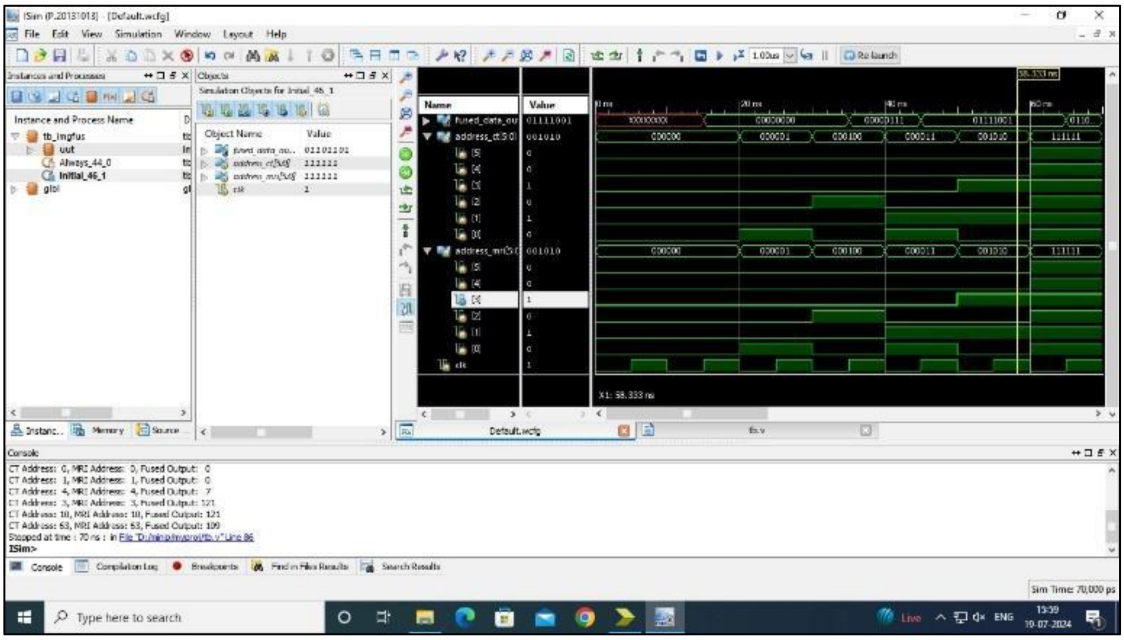


To bring this process into a real-time embedded system, the entire image fusion pipeline is implemented in Verilog HDL, targeting FPGA platforms. Dedicated modules are designed for DWT and IDWT computation, coefficient buffering, and fusion logic. Verilog's parallel processing capabilities allow for efficient, low-latency image processing with high throughput. The system architecture includes memory buffers to temporarily store coefficients and arithmetic units to perform wavelet filtering and coefficient fusion. This hardware-based approach provides advantages such as deterministic execution, energy efficiency, and adaptability to edge devices in medical environments.

In addition to Verilog implementation, the proposed algorithm is also replicated and validated in MATLAB. MATLAB's high-level functions (dwt2, idwt2) allow for quick prototyping of the DWT-based image fusion process. After loading the CT and MRI images, DWT is applied to both, and the resulting coefficients are combined using the same fusion rule as in the hardware design. The reconstructed image is then analyzed to ensure consistency with the Verilog-based results. This cross-verification between MATLAB and Xilinx ISE simulation confirms the functional correctness of the HDL code and validates the accuracy of the hardware implementation.

Further analysis of the DWT algorithm, specifically the Haar transform highlights how this method captures vital image features. The Haar transform conducts a horizontal pass where pairs of pixels are averaged (low-pass) and subtracted (high-pass) to extract structural features. These results are then processed vertically, again computing averages and differences. A scaling factor, typically close to $1/\sqrt{2}$, is applied to normalize the values and fit the transformed coefficients into 8-bit representation. In hardware, this is approximated using bit shifts for computational efficiency.

The fusion operation in this implementation involves combining the four main DWT sub-bands: dwt_ll, dwt_lh, dwt_hl, and dwt_hh. These are summed and then right-shifted by two bits (i.e., divided by four) to compute the average. The output, stored in fused_image, carries enhanced spatial and structural details from both input modalities. Although this method utilizes a basic averaging rule and Haar wavelets for demonstration, real-world applications often demand more advanced wavelets like Daubechies, Symlets, or Biorthogonal families, and employ adaptive or context-aware fusion rules to optimize clarity and diagnostic value.



In summary, the simulation and synthesis phase demonstrates a complete, hardware-compatible image fusion pipeline using DWT and Verilog. The results show that this approach not only achieves accurate fusion of CT and MRI data but also enables real-time processing capabilities suitable for embedded medical imaging systems.

V. RESULT AND DISCUSSIONS

The proposed medical image fusion system, which utilizes the Discrete Wavelet Transform (DWT) and Haar wavelet, was implemented and tested using CT and MRI images of the brain. These two modalities offer complementary diagnostic insights—CT captures structural and anatomical details, while MRI highlights soft tissue contrast. The goal of this research was to effectively combine these data sources into a single fused image with enhanced diagnostic value.

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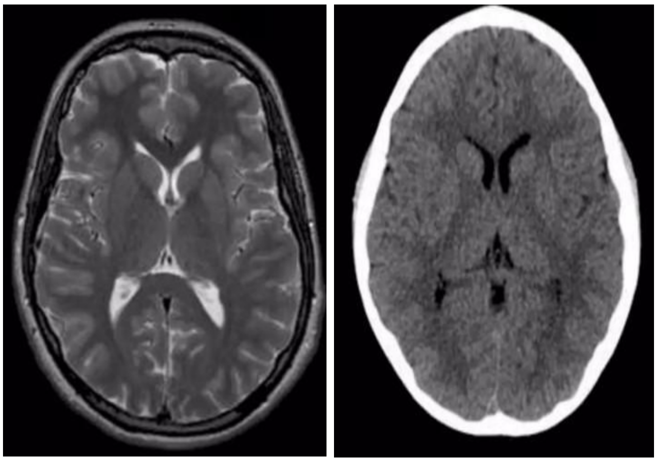
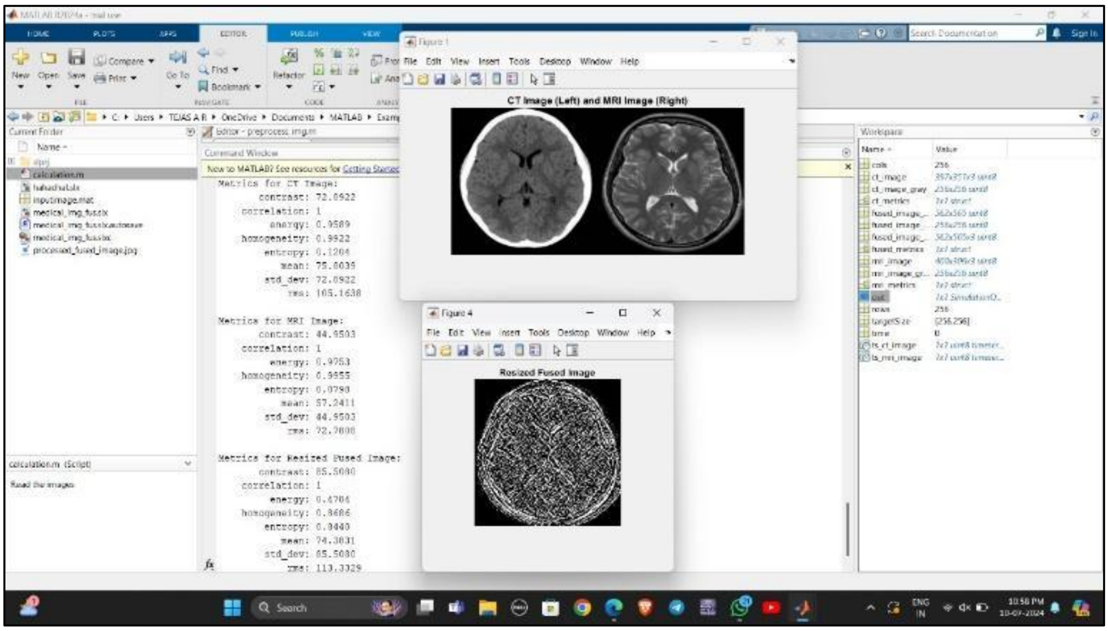


The image fusion algorithm was initially implemented in Verilog HDL and simulated using Xilinx ISE. The system successfully processed the CT and MRI input images, executing the DWT to decompose the inputs into their approximation and detail coefficients. A simple averaging rule was applied to combine corresponding coefficients from each modality. The fused coefficients were then reconstructed using the Inverse DWT (IDWT) to generate the final fused image.

To ensure the functional correctness and reliability of the Verilog implementation, the same image fusion procedure was replicated in MATLAB using the built-in dwt2 and idwt2 functions. The CT and MRI images used in both environments were identical, and the fusion process followed the same logic and parameters. The outputs from MATLAB were used as a reference to validate the results from the Verilog simulation.



Upon comparison, the fused images generated from both platforms—Xilinx ISE and MATLAB—were found to be consistent in terms of pixel values and overall image quality. This cross-verification confirms the accuracy of the Verilog code and demonstrates the successful hardware realization of the DWT-based image fusion process. Furthermore, it validates that the proposed FPGA-based implementation can achieve real-time performance while maintaining fidelity with a software-based model.

The final fused image displayed improved clarity, combining the anatomical definition of the CT scan with the soft-tissue sensitivity of the MRI. This enhancement in visual detail can aid clinicians in identifying abnormalities, planning surgeries, and monitoring disease progression with greater confidence.

Overall, the results support the feasibility of deploying this fusion method on embedded hardware platforms, offering benefits such as low power consumption, fast processing speed, and deterministic behavior. These characteristics make the proposed design particularly suitable for real-time medical applications, portable diagnostic tools, and edge-based healthcare systems.

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