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Satellite Image Enhancement using MATLAB and Simulink with FPGA Implementation

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ABSTRACT

Enhancing satellite images plays a vital role in areas like remote sensing, geosciences, and disaster management, where high-resolution images are necessary for precise analysis. Conventional enhancement methods, including Discrete Wavelet Transform (DWT) and Singular Value Decomposition (SVD), can enhance image quality but are often computationally intensive, making them less suitable for real-time applications. This paper presents an FPGA-based approach to satellite image enhancement using Simulink and Xilinx System Generator, leveraging model-based design for efficient algorithm development and hardware implementation. The proposed method integrates inversion, brightness, and contrast adjustment techniques within Simulink's intuitive framework, enabling rapid prototyping and seamless deployment onto FPGA hardware. While previous related works implemented enhancement techniques like negative, brightness, and contrast adjustments independently, the current project uniquely integrates all three into a unified Simulink model, enabling efficient and simultaneous processing on FPGA. Hardware co-simulation validates the system's effectiveness, demonstrating its potential for real-time processing with improved efficiency over traditional software-based methods. The results highlight Simulink's capability in developing scalable, high-performance FPGA-based solutions, providing a practical alternative for real-time satellite image enhancement.

Keywords: Simulink, Image enhancement, Contrast Stretching, Gray Scale Conversion, Image negative, Field Programmable Gate Array (FGPA).

I. INTRODUCTION

Satellite imaging has become an essential tool in various fields, including agriculture, urban planning, national security, disaster management, and environmental monitoring. High-resolution satellite images are crucial for accurate analysis, but their quality is often degraded due to factors such as atmospheric interference, sensor noise, and lighting variations. Enhancing satellite images is critical for improving visibility, contrast, and feature extraction, enabling better decision-making in remote sensing applications. Traditional image enhancement techniques rely on software-based processing methods, which are computationally intensive and unsuitable for real-time applications. To overcome this challenge, Field-Programmable Gate Arrays (FPGAs) serve as an effective hardware solution, enabling high-speed parallel processing, real-time performance, and flexibility for satellite image processing applications.

This paper introduces an FPGA-based method for enhancing satellite images using Xilinx System Generator and Simulink. It utilizes a model-based design approach to implement and evaluate different image processing algorithms efficiently. The proposed system integrates techniques such as contrast enhancement, and inversion, ensuring improved clarity and precision in satellite images. Hardware co-simulation enables real-time verification and optimization, making FPGA-based processing a powerful alternative to conventional software methods. By utilizing FPGA acceleration, this approach provides a scalable, high-performance solution for satellite image processing, enhancing the efficiency of remote sensing applications and facilitating better data interpretation for critical domains such as climate monitoring, disaster response, and geospatial analysis. The advancement of satellite image enhancement has led to various FPGA-based implementations designed to improve processing speed and efficiency. Below is a comparative analysis of related research, highlighting their methodologies, applications, and contributions to the field. Below are notable approaches identified in previous studies which introduced an FPGA-based technique to enhance vehicle number plate images, making them more readable for Optical Character Recognition (OCR). Their approach incorporated contrast stretching, histogram equalization, and sharpness adjustments, which significantly boosted processing speed compared to conventional CPU-based techniques, making it more viable for real-time applications in traffic monitoring systems. [2] Focused on real-time biomedical image enhancement using FPGA hardware acceleration. Utilizing Xilinx System Generator within MATLAB/Simulink, they demonstrated improved brightness control, segmentation, contrast adjustments, and inversion techniques. Their findings emphasized that brightness control produced the most significant improvements, making FPGA a valuable tool for medical imaging applications. [3]

developed an FPGA-based system capable of executing multiple image enhancement techniques concurrently. Their research targeted real-time applications requiring high-speed processing; demonstrating that parallel execution within FPGA could optimize computational efficiency without degrading image quality. The study highlighted the system's adaptability for remote sensing and security-related image processing. [4] worked on enhancing vein pattern images for biometric authentication through FPGA-based contrast adjustments and noise reduction techniques. Their approach aimed to improve vein visibility, enabling more accurate identification in biometric security systems. Compared to traditional software methods, their hardware-based approach provided faster and more reliable processing. [5]

implemented contrast stretching on FPGA to improve image clarity. By leveraging System Generator, they demonstrated how FPGA-based image enhancement could process images with minimal latency, outperforming software-based methods in terms of real-time execution speed. [6] investigated an optimized hardware co-simulation framework for image enhancement, emphasizing efficient FPGA resource utilization while ensuring high-speed processing. The research highlighted the advantages of hardware acceleration for applications requiring rapid image enhancement, such as remote sensing and surveillance. [7] presents a hybrid image enhancement technique based on Alpha Rooting, which operates primarily in the frequency domain. The method aims to improve the visual quality of images by enhancing both contrast and brightness, while preserving fine details. By combining traditional enhancement principles with frequency-based adjustments, the technique is shown to be effective in producing visually improved outputs, making it suitable for applications where image clarity is essential.[8]

propose image enhancement algorithms that leverage transform coefficient histograms and contrast entropy. The core idea is to enhance image contrast adaptively based on statistical analysis of transform domains. This method provides improved visual quality by dynamically adjusting image contrast and brightness, maintaining a balanced histogram distribution. It is particularly useful for real-time systems where consistent and perceptually optimized output is required.[9] introduces a satellite image enhancement approach using Discrete Wavelet Transform (DWT) in conjunction with Singular Value Decomposition (SVD). The technique enhances image contrast effectively by modifying singular values within the wavelet domain. Although the method achieves noticeable improvements in visual appearance and detail clarity, it involves complex computations, making it more suitable for offline or non-real-time applications.[10] introduced based on head contour geometry and wavelet subband projection. The method focuses on enhancing the accuracy of facial feature detection by utilizing the spatial relationships within head contours and analyzing image features in the wavelet domain. The outcome shows improved detection accuracy in complex or noisy visual environments, which can benefit face recognition and surveillance applications.[11] proposes a resolution enhancement method for satellite images using the complex wavelet transform. The technique emphasizes boosting the resolution of low-quality satellite images without introducing significant noise or artifacts. By employing multi-scale processing in the complex wavelet domain, the enhanced images demonstrate greater sharpness and detail, which is crucial for remote sensing and geographical analysis applications.[12]

While previous research has focused on enhancing specific types of images such as vehicle plates, biomedical scans, and vein patterns, our work expands the scope by applying FPGA-based enhancement techniques to satellite imagery, which requires high precision and scalability. The key improvements introduced in this paper include:

Integration of Multiple Enhancement Techniques: Unlike prior studies that applied individual techniques, our approach combines contrast stretching, brightness control, and inversion within a unified FPGA-based framework. Simulink-Based Model Development: We leverage Simulink for model-based design, allowing for rapid prototyping and seamless hardware implementation without requiring complex HDL coding. Optimized Resource Utilization: By employing FPGA acceleration efficiently, our method ensures optimal use of hardware resources while maintaining real-time processing capabilities. Scalability for Remote Sensing Applications: Our system is designed to process high-resolution satellite images, making it applicable to critical fields such as environmental monitoring, disaster response, and geospatial analysis.

By incorporating these enhancements, our work offers a more comprehensive and adaptable FPGA-based image enhancement framework, providing a practical alternative to conventional software-based methods.

II. METHODOLOGY

The primary goal of this paper is to develop and implement satellite image enhancement algorithms using

System Generator on an FPGA. To ensure suitability for real-time applications, this processing approach must be executed through hardware co-simulation. The FPGA-based implementation follows a prototyping methodology using Simulink and the System Generator tool, progressing through five key stages as shown in Fig. 1.

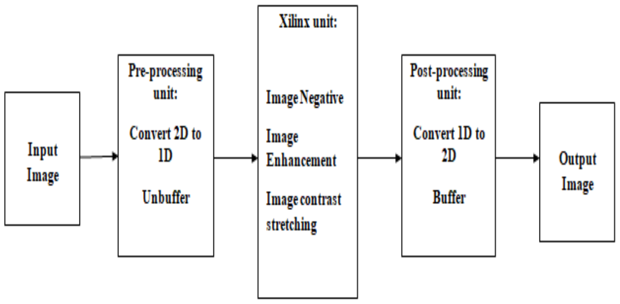

Fig. 1. Design and Implementation Flow.

The project begins with the acquisition of satellite images from reliable sources, forming the foundation for further processing. These raw images typically undergo a pre-processing stage to eliminate noise, correct distortions, and prepare the data for enhancement. Following this, the core enhancement algorithm is designed and implemented using Xilinx System Generator within the Simulink environment, allowing for a model-based, hardware-compatible workflow. After enhancement, a post-processing block is applied to refine the output and ensure it meets the desired quality standards. The final stage yields a visually improved image, highlighting the effectiveness of the proposed approach in enhancing satellite imagery for real-time applications.

The image source and at the end, i.e., output (image viewer) belongs to the Simulink tool environment where we can select the image and browse it while it can read it from the file and the image viewer at the end is used to compare the resulted output with the original image (image source).

The image pre-processing unit is responsible for transforming an RGB image into a grayscale format, converting two-dimensional (2D) data into a one-dimensional (1D) format, and implementing unbuffering operations. Since FPGA processes data in a 1D format, the 2D matrix representation must be converted into a single-row matrix vector signal.

The image post-processing unit reconstructs the image from the 1D data and comprises three key components: a buffer, a 1D-to-2D converter, and the final output image. The buffer facilitates the conversion of scalar samples into frame outputs at a lower rate, while the 1D-to-2D conversion block generates a 2D matrix signal at the final stage. The image enhancement algorithm and design are implemented using System Generator within the Xilinx environment. Additionally, Gateway-in and Gateway-out blocks are utilized to manage data type conversion between different processing environments, ensuring that the data format remains an 8-bit unsigned integer.

A. Algorithm for Gray Scale Conversion

Grayscale conversion acts as a crucial pre-processing step for various image enhancement techniques, including image negation, contrast adjustment, thresholding, and brightness modification as shown in Fig.2. This process simplifies computations while retaining essential image details. By removing the Red (R), Green (G), and Blue (B) color channels, it reduces data size and hardware complexity, thereby enhancing processing speed and efficiency. The grayscale intensity value can be determined using the following equation:

$$Y = 0.3R+0.59G+0.11B$$

Here, 'R' represents the red component, 'G' denotes the green component, 'B' corresponds to the blue component, and 'Y' signifies the resulting grayscale intensity.

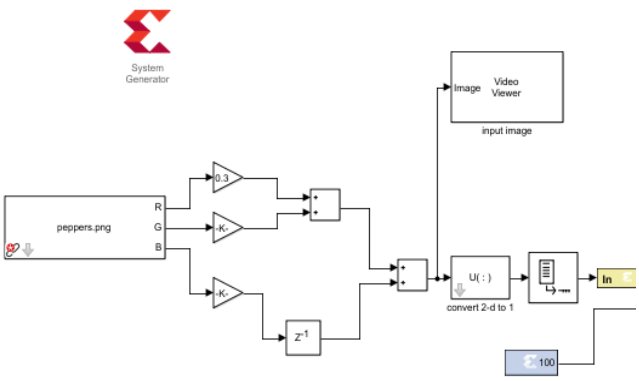

Fig. 2. Algorithm for Grayscale Conversion.

B. Algorithm for Image Negative

By using a NOT block we can create an image negative in Simulink where the operation involves in the inversing the bits of pixel values, it can effectively invert binary images or images with specific data types as shown in Fig.3. There is also an alternate block called Add Sub block where we can subtract the input value from constant 255 which can act as inverter.

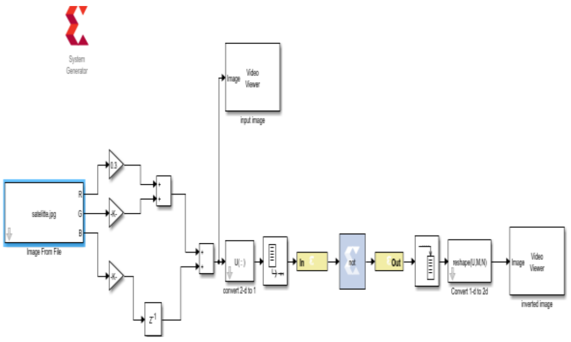

Fig. 3. Algorithm for Image negative using NOT block.

C. Algorithm for Image Enhancement

Image Enhancement which refers to process of improving an image's visual quality by changing its characteristics such as brightness and sharpness levels to make it suitable for processing where it involves manipulating the pixel intensity values of image. Here we use an Add Sub block and a constant block along with the input as shown in Fig.4. For efficient processing, use fixed-point, which are typically faster and consume less computational power and achieve high speed processing with zero latency.

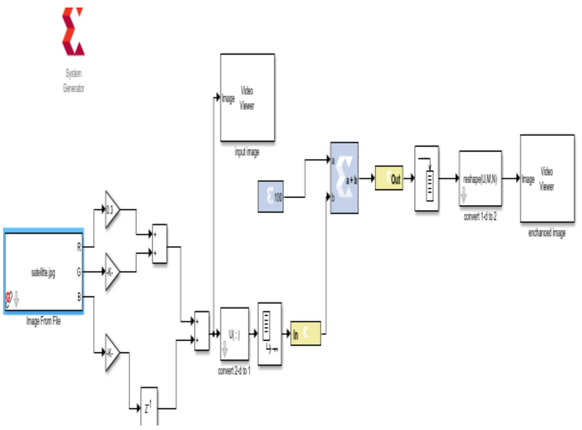

Fig. 4. Algorithm for Image Enhancement

D. Algorithm for Contrast Stretching

Contrast Stretching; also known as "Normalization", is a technique used in image processing to enhance the contrast levels of an image by expanding its range of pixel intensity values as shown in Fig.5. By this it can enhance the differences between light and dark areas, by making features in image more distinguishable. Through this following transformation equation, we can stretch the light intensity levels.

New pixel = 3(Old pixel – 127) + 112

Where, the new pixel is the resulting one after the transformation.

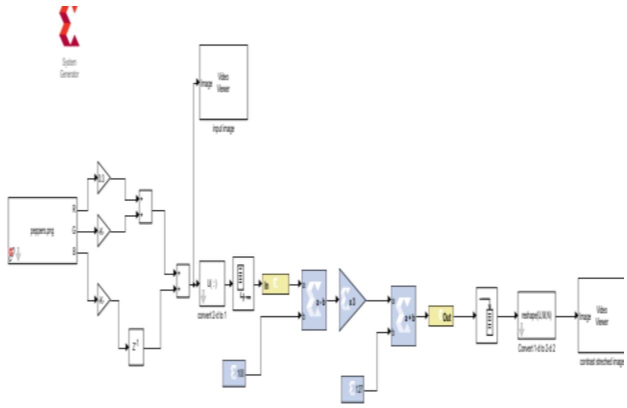

Fig. 5. Algorithm for Image Contrast Stretching.

III. RESULTS

The image 750x500 is applied to system generator, Simulink software and as well as to the FPGA (Field Array Programmable Gate Array) for hardware co-simulation. The FPGA operation is highly parallelized for real-time performance. FPGAs can efficiently process each pixel of an image simultaneously in parallel across different rows and columns. It mainly focuses on achieving high-speed processing with low latency.

FPGAs are particularly well-suited for image enhancement process because of their ability to perform simultaneous operations on large image datasets, making them ideal for applications requiring high throughput for satellite imagery processing. Implementing the hardware co-simulation by means of an FPGA to accelerate computational operations efficiently. The ZedBoard Zynq evolution and development kit is used here, targeting Zynq-7000 SoC, specifically the xc7z0202clg484-1 part which features 484 pins and operates with a speed grade of -1, ensuring optimal timing performances. The use of FPGA-based co-simulation significantly reduces verification time compared to software while leveraging high-performance computing capabilities of the Zynq-7000 platform as shown in Fig.6a-6d.

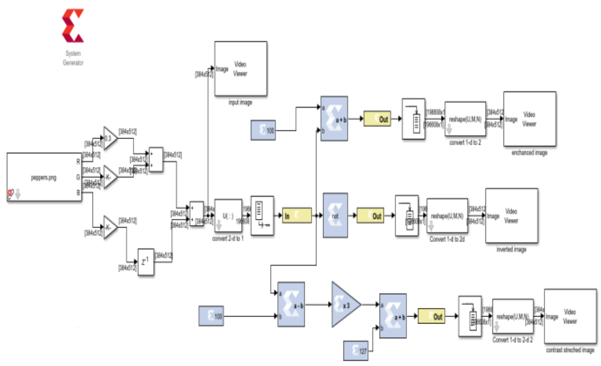

Fig. 6a. Overall Flow of Image Enhancement.

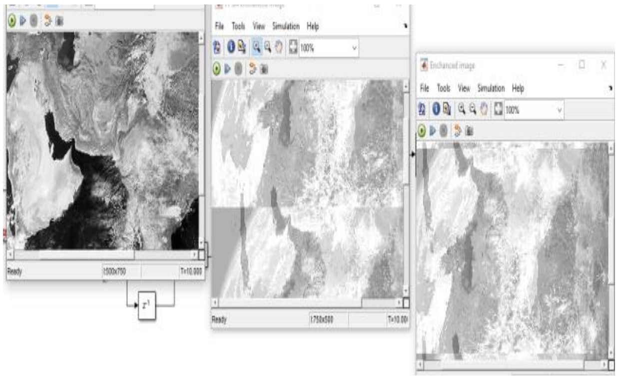

Fig. 6b. Results of Enhanced Image.

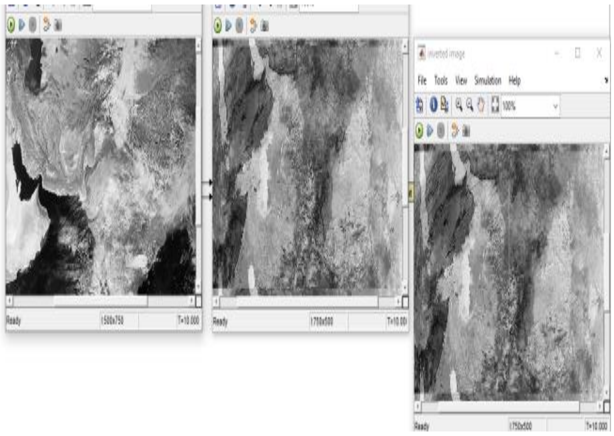

Fig. 6c. Results of Negative Image.

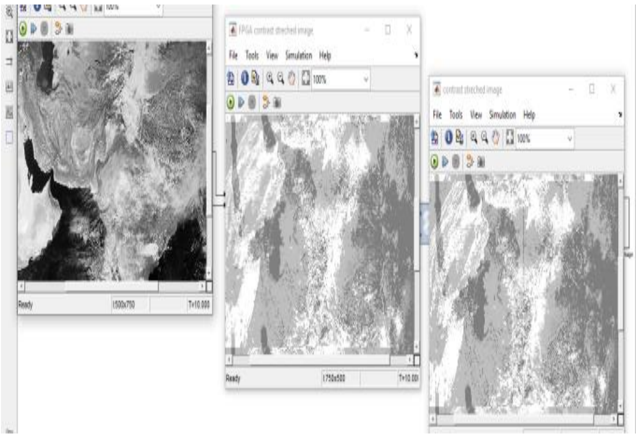

Fig. 6.d. Results of Contrast stretching.

IV. Comparison

Compared to the work by Muhammed Yildirim and Ahmet Çinar[4], which implements spatial domain enhancement techniques using Verilog in Vivado for general image processing, this project adopts a model-based design approach using Simulink and Xilinx System Generator to enhance satellite images, offering a more accessible and rapid development workflow without the need for manual HDL coding and comparison of prosed work is given in Table 1.

TABLE 1

Comparison of proposed work with existing methods.

Aspect	**Proposed work**	**Yildirim & Çinar's Paper**
Domain	Satellite image enhancement	General image processing in spatial domain
Application Focus	Targeted at real-time satellite image	Focused on general image enhancement for time-sensitive tasks
Techniques Used	Brightness adjustment, contrast stretching, image inversion	Histogram equalization, contrast stretching, image subtraction, image inversion
Programming Methodology	code-free design using Simulink blocks	Hardware description language (Verilog) for custom logic implementation

V. CONCLUSION

From this work, the implementation of Satellite image enhancement using Simulink with FPGA demonstrates an efficient hardware-based approach for real time processing. By leveraging the FPGA on Zed Board Zynq-7000, which integrates programmable logic, the proposed system significantly improves image contrast and quality while ensuring high-speed execution. Compared to software-based implementation, which relies on desktop tools and require higher computational resources, whereas the hardware co-simulation approach reduces the processing time, enhances parallelism, optimal recourses utilization and enables real time execution, apart from time analysis, implementation of both results the same effect. While Xilinx System Generator serves as a crucial mediator for hardware deployment. While previous related works implemented enhancement techniques like negative, brightness, and contrast adjustments independently, the current project uniquely integrates all three into a unified Simulink model, enabling efficient and simultaneous processing on FPGA. Satellite Images, captured by remote sensing satellites, often suffer from low contrast, atmospheric distortions and may be darker as compared, making enhancement techniques crucial for improving their quality and usability.

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