Algorithms and their VLSI Architecture to Enhance Image Quality for Real-time Applications

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Chapter 6

Conclusions

Enhancement of degraded images is essential to improve their visual quality. Image parameters like contrast, brightness, sharpness, etc. are adjusted for this purpose. When images are captured in poor lighting or environmental conditions such as haze, they suffer from distortions. Therefore, extracting meaningful information from them is a challenging task. Image enhancement techniques are imperative while extracting hidden details from such distorted images because they improve their clarity, which aids in better interpretation. This is particularly important in applications such as advanced driver assistance systems, autonomous vehicles, remote sensing, medical imaging, satellite imagery, etc., where high-quality images are crucial for accurate assessments and decision-making.

Image dehazing plays a crucial role in computer vision tasks that rely on accurate image processing. Many automated systems struggle to perform effectively on hazy images due to the loss of important visual features. Hence, image dehazing is employed in several machine vision systems to enhance the visibility and clarity of the images captured in hazy conditions. Similarly, low-light image enhancement is crucial for improving the visibility and usability of images captured in dim or poorly illuminated conditions. Automated systems may struggle to process dark and noisy images, leading to errors or misinterpretations. So, low-light image enhancement techniques are helpful in restoring the visibility of the captured images, thereby increasing the information content stored in them.

Image dehazing and low-light image enhancement have many real-time applications. However, due to computational complexity, their real-time implementation is challenging. Platforms such as GPUs and high-end CPUs can handle the high computational requirements of image enhancement algorithms, but they would significantly increase the cost and power budget of the machine vision systems. Another solution that is suitable for the real-time implementation of image enhancement algorithms is to develop their efficient VLSI architectures and implement them on platforms such as FPGAs and ASICs, which have the capability of parallel processing. However, these VLSI architectures should be optimized in terms of power, speed, and hardware resource utilization. Therefore, this dissertation presents image dehazing and low-light image enhancement techniques and their VLSI architectures for real-time machine vision systems. The proposed VLSI architectures are optimized for power, performance, and area. They are implemented using Verilog and simulated using the AMD-Xilinx Vivado design suite. The gate-level netlist for ASIC implementation of the proposed VLSI architectures is obtained using the Cadence Genus tool. The FPGA and ASIC implementations of the proposed VLSI architectures can process images at a high frame rate, consuming low power. Thus, the proposed VLSI architectures are suitable for low-power real-time applications.

Chapter 1 presented a general flow of the processes involved in a typical real-time image processing system. Some of the key characteristics of a real-time image processing system and the objectives of image enhancement techniques are also discussed in this Chapter. Further, the background of image dehazing and low-light image enhancement methods, along with their applications and challenges, are introduced in a nutshell. The mathematical models for attaining these goals were also introduced in this Chapter.

Chapter 2 presented a literature survey on the existing state-of-the-art image dehazing and low-light image enhancement techniques. Image haze removal algorithms are broadly categorized into three types, namely prior-based, non-prior-based, and deep learning-based methods. Further, a literature review on histogram-based, Retinex-based, and machine learning based low-light image enhancement methods is also provided in this Chapter. The merits and demerits of all these methods and existing VLSI architectures for such algorithms are also presented in this Chapter. Various performance metrics, used in this dissertation, for the quantitative and qualitative evaluation of the proposed methods are also introduced in this Chapter.

Chapter 3 presented the saturation-based image dehazing algorithm and its VLSI architecture. The proposed algorithm uses saturation information of the hazy image to estimate pixel-wise transmission. The pixel-wise transmission estimation eliminates the need for special edge-preserving filters used to suppress halo artifacts around edges. A large 15×15 patch is used in the proposed method for atmospheric light estimation. It prevents the dehazed image from being oversaturated. The hardware architecture of the proposed method is divided into seven pipeline stages. Although the hardware resource requirement has slightly increased due to some extra line buffers, the proposed method performs better than many other similar methods in terms of quantitative and qualitative metrics. The proposed method yielded an average PSNR, SSIM, and CIEDE2000 score of 20.05 dB, 0.8551, and 7.5471, respectively, on the SOTS dataset. For the O-Haze dataset, an average PSNR, SSIM, and CIEDE2000 score of 16.45 dB, 0.4411, and 15.4280, respectively, were obtained, while for the NYU dataset, an average PSNR, SSIM, and CIEDE2000 score of 12.71 dB, 0.7356, and 15.6824, respectively, were obtained using the proposed method. FPGA implementation of the proposed design consumes only 1537 LUTs and operates at 85.2 MHz frequency on ZynQ7 XC7Z020CLG484-1 FPGA. ASIC implementation results show that the proposed design comprises of only 13.2k gates and consumes only 2.62 mW power at 200 MHz. Moreover, it can operate up to 624 MHz. With this speed, it can easily process 4k (3840×2160) resolution frames at a rate higher than 70 fps. Therefore, the proposed VLSI architecture is suitable for real-time image dehazing applications such as remote sensing, advanced driver assistance systems (ADAS), etc.

In Chapter 4, an intensity-based video dehazing and its VLSI architecture are presented. The proposed method divides the hazy image pixels into near and far pixels. The atmospheric light of the near and far regions is further used to compute the atmospheric light of each pixel depending on whether it lies in the near or far region. This helps in controlling the brightness of the dehazed images. Further, a new pixel-based transmission estimation is presented in this Chapter, where a correction factor is used to provide nonlinear boosting to underestimated transmission, thereby preventing oversaturation of dehazed images. This further suppresses artifacts around depth discontinuities and relaxes the requirement of post-processing enhancement techniques. The performance of the proposed method was tested on various image datasets, and the outcomes were presented in graphical and tabular form. For $\gamma = 1.5$, the proposed method scored an average PSNR of 16.52 dB and 16.41 dB over the O-Haze and I-haze datasets, respectively, and an average SSIM of 0.46 and 0.62 over the O-Haze and I-haze datasets, respectively. FPGA implementation of the proposed design consumes only 1575 LUTs on the ZynQ7 XC7Z020CLG484-1 FPGA. The proposed dehazing architecture requires 13.8 k gates and operates at 460 MHz, consuming only 4.15 mW power when synthesized using 90-nm CMOS technology. The proposed VLSI architecture's optimal resource consumption makes it appropriate for cost-effective real-time dehazing applications such as autonomous vehicles.

In Chapter 5, a Retinex-based low-light image enhancement algorithm and its VLSI architecture are presented. An edge-preserving filter is proposed in this chapter for efficient illumination estimation, which is realized in hardware using the concept of approximate computing for minimum hardware resource utilization. The proposed algorithm preserves fine details in the decomposed reflectance by preventing the overflow of the values in the reflectance. The proposed method scored an average PSNR and SSIM of 17.021 dB and 0.7511, respectively, over the LOL dataset. Moreover, the proposed method scored an average NIQE and BRISQE score of 3.48 and 24.64, respectively, over the DICM dataset, while for the LIME dataset, an average NIQE and BRISQE score of 3.67 and 22.41 were obtained, respectively, using the proposed method. The proposed architecture requires only 10868 LUTs and 7409 registers when implemented on the AMD-Xilinx ZynQ7 XC7Z020CLG484-1 FPGA, which is significantly less than similar existing methods. Moreover, the FPGA implementation of the proposed method can process 60 full HD resolution image frames per second, making it suitable for real-time applications.

The contributions of this dissertation are:

- A saturation-based image dehazing method and its VLSI architecture are proposed. The proposed method uses saturation information of the hazy image to estimate the transmission of each pixel individually. This also suppresses halo artifacts around edges, thereby eliminating the need for post-processing techniques or special filters to suppress the artifacts. A large spatial window has been used for accurate atmospheric light estimation, and oversaturation of the dehazed images has been prevented.
- An intensity-based video dehazing method and its VLSI architecture are proposed. This method dynamically adjusts the atmospheric light for each pixel in an image frame based on its intensity. Moreover, in this method, a new pixel-to-pixel transmission estimation technique is also proposed, which precisely estimates the transmission of each pixel by providing a non-linear boost to the transmission values of the pixels depending on their depth in the hazy image. Thus, the proposed method effectively prevents oversaturation and over-dehazing of the restored images.
- A Retinex-based low-light image enhancement method and its VLSI architecture are proposed. The proposed method effectively estimates the illumination channel of the low-light image without producing any blocky artifacts in it. Moreover, fine details present in the reflectance channel of the low-light image, obtained using the estimated illumination, are preserved.
- All the proposed VLSI architectures of the methods mentioned above use the concept of approximate computing to optimize logic resource consumption and parallel processing capability of devices such as FPGAs and ASICs to achieve real-time implementation.

Future work

- The dehazing methods based on the atmospheric scattering model work well for daytime images. However, the atmospheric scattering model is unsuitable for modeling nighttime hazy images, where multiple illumination sources may be present.

Further, the outcome of the dehazing methods based on this model worsens for hazy images with color cast. Thus, hardware implementation of image dehazing for nighttime and color cast images needs to be explored in the future.

- The Retinex-based low-light enhancement algorithm may suffer from noise amplification in the decomposed reflectance due to improper illumination estimation. This would result in poor visual quality of the restored images. Thus, there is scope for improving the performance of the low-light image enhancement systems by designing and integrating a noise-smoothing module, which needs to be explored in the future.