

Chapter 1

Introduction

Real-time image processing refers to the analysis and manipulation of visual data at high speeds, typically with minimal delay, to produce immediate results. This technology is widely used in applications that require quick decision-making, such as autonomous vehicles, facial recognition, medical imaging, and industrial automation. Unlike traditional image processing, which can afford delays in computation, real-time image processing relies on powerful hardware, optimized algorithms, and parallel computing techniques to ensure fast and efficient processing. Methods used in real-time image processing include edge detection, object tracking, noise reduction, and feature extraction, all of which help in identifying and analyzing key elements within an image or video feed. One of the critical challenges in real-time image processing is achieving high accuracy while maintaining low latency. This is often addressed using specialized hardware such as Graphics Processing Units (GPUs), Field-Programmable Gate Arrays (FPGAs), and Application-Specific Integrated Circuits (ASICs). Additionally, modern artificial intelligence techniques, particularly deep learning-based computer vision models, have significantly improved the capabilities of real-time image processing by enabling systems to recognize patterns, detect anomalies, and classify objects with high precision. Applications such as augmented reality, real-time surveillance, and automated quality inspection in manufacturing rely heavily on real-time image processing to enhance efficiency, security, and user experience. As technology advances, the integration of 5G networks, edge computing, and AI-driven

optimizations will further enhance the speed and accuracy of real-time image processing systems. Some prominent real-time image processing applications are given below.

1. **Healthcare and Medical Imaging**

- Enhancement of images obtained from MRI, CT scan, ultrasound, etc.
- Assistance in minimally invasive surgeries.
- Transmission of medical images for remote consultation.

2. **Surveillance and Security**

- Identifying the face of the unauthorized intruders using live video streaming.
- Identifying people involved in unauthorized activities.

3. **Autonomous Systems**

- Lane detection, collision avoidance, parking assistance, etc., in modern vehicles.
- Automatic robots for industrial work.

4. **Industrial Automation**

- Defect detection in manufactured products.
- Detection of faults and wear of automated machines.

5. **Consumer Electronics**

- Providing a real and mesmerizing experience using virtual reality.
- Enhancement of images captured from a smartphone camera using various filters and beautification modes.

6. **Traffic and Transportation**

- Live monitoring of roads for traffic decongestion.
- Automatic traffic challan system for violating safety norms.

7. Entertainment and Media

- Live streaming of high-quality events and shows.
- Video editing for increased information content.

8. Agriculture

- Analysis of crops and soil health using land images.
- Monitoring of cattle and their health indicators.

9. Military and Defense

- Vision improvement in low light conditions.
- Real-time reconnaissance and mapping.

10. Environmental Monitoring

- Remote sensing to anticipate disasters.
- Monitoring of illegal and environmental degradation activities.

Some of the key characteristics of a real-time image processing system are

- **Low Latency:** A real-time image processing system should be fast enough to produce results within the permissible time, which can vary depending on the application.
- **Continuous Processing:** A real-time image processing system should be able to continuously process image frames to support video processing.
- **Automation:** A real-time image processing system should act autonomously based on the acquired data.

A general flow of the processes involved in a typical real-time image processing system is shown in Fig.1.1. A brief overview of these processes is given below

- **Image Acquisition:** Captures images using camera sensors at a specific frame rate.

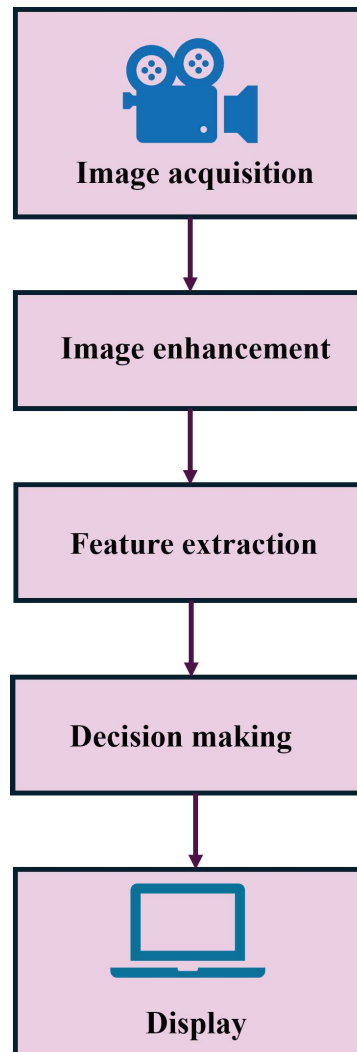


Figure 1.1: Block-level representation of processes in a typical real-time image processing system.

- **Enhancement:** Performs denoising, dehazing, contrast and brightness adjustments, etc.
- **Feature Extraction:** Extracts information such as edges, textures, objects, etc.
- **Decision-Making:** Uses certain algorithms to interpret the extracted features for triggering an action.
- **Output Generation:** Displays the enhanced output or logs the processed data of various processing stages.

To achieve the aforementioned operations, a real-time image processing system uses the

following technologies

- **Algorithms:** Machine learning, deep learning, and classical image processing techniques.
- **Hardware:** Field Programmable Gate Arrays (FPGAs), Application Specific Integrated Circuits (ASICs), and high-performance Graphics Processing Units (GPUs) for accelerated computation.
- **Software:** Libraries and frameworks like OpenCV, TensorFlow, PyTorch, etc., or tools like MATLAB.

Images acquired by the machine vision systems often suffer from detail loss due to low-resolution [1]; motion blur [2], [3]; distortions [4]–[6]; bad weather [7]–[10]. Therefore, image enhancement is necessary to improve the performance of machine vision systems and make them resilient to adverse conditions.

Image enhancement is the process of improving the visual quality of an image by adjusting its features such as contrast, brightness, sharpness, and noise levels. The goal of image enhancement is to make important details more distinguishable, which can be useful for applications like medical imaging, satellite image analysis, digital photography, etc. Various techniques are used to enhance images, including histogram equalization, contrast stretching, and filtering methods such as sharpening and smoothing. These techniques help in emphasizing relevant features while reducing distortions or unwanted artifacts, thereby improving the interpretability of images for both human viewers and computer-based analysis. As shown in Fig. 1.1, image enhancement is one of the important processes in most image processing systems, and it plays a crucial role in the proper functioning of further processes such as feature extraction and decision-making.

There are two main categories of image enhancement techniques: spatial domain and frequency domain. Spatial domain techniques directly manipulate pixel values to enhance specific characteristics of an image, such as adjusting brightness or applying edge detection filters. On the other hand, frequency domain techniques involve transforming an

image into the frequency space using methods like the Fourier Transform, allowing for selective enhancement of certain frequency components. Modern advancements in artificial intelligence and deep learning have also introduced new ways to enhance images, such as super-resolution techniques that can reconstruct high-quality images from low-resolution inputs. With continuous technological progress, image enhancement is becoming increasingly sophisticated, playing a crucial role in fields like medical diagnostics, remote sensing, autonomous vehicles, etc. The main objectives of image enhancement include

1. **Improved Visibility and Clarity:**

- Enhancing contrast, brightness, or sharpness to make details more visible.
- Removing noise or artifacts that obscure important features.

2. **Highlighting Specific Features:**

- Bringing out details of interest, such as edges, textures, or patterns.
- Enhancing specific regions in the image to aid in analysis or interpretation.

3. **Correction of Image Deficiencies:**

- Addressing issues like low resolution, poor lighting, or motion blur.
- Correcting color balance or distortions caused by imaging conditions.

4. **Preparation for Further Processing:**

- Making images suitable for tasks such as object recognition, segmentation, or feature extraction.
- Aligning or normalizing images to meet requirements for algorithms or machine learning models.

5. **Aesthetic Improvements:**

- Enhancing images for presentation, marketing, or artistic purposes.
- Applying filters or adjustments to create visually pleasing results.

6. Facilitation of Scientific or Technical Analysis:

- Improving the accuracy of data extraction in medical imaging, satellite imagery, or microscopy.
- Revealing hidden or subtle information for research or diagnostics.

1.1 Background

The visibility of objects in an image captured by an image acquisition device varies with environmental conditions such as haze, rain, dust, light, etc. Mathematical equations and physical principles can be used to model the formation of the image under different conditions by quantifying the degradation effect of these varying environmental factors. Thus, mathematical models play a crucial role in enhancing images by providing a systematic and precise framework to analyze, interpret, and manipulate image data. These models enable the identification and correction of various forms of degradation. To alleviate the deterioration caused to an image by environmental factors, the corresponding degradation factors in the mathematical image formation model are readjusted. However, this readjustment of the degradation factors in the mathematical model, if not done carefully, may further lead to unwanted outcomes in the enhanced image in the form of halos, color distortion, etc. Therefore, prior knowledge of some general characteristics of the images captured under different environmental conditions is necessary and helpful in framing the constraints, which are further employed to simplify the mathematical image formation model corresponding to a given environmental condition and obtain the enhanced image with preserved details and naturalness. Thus, the degradation in the captured images can be mitigated efficiently.

Among many environmentally imposed challenges, perturbation caused by **haze** and **low lighting conditions** is often encountered in various machine vision applications. In order to tackle these environmentally imposed challenges, one must understand the underlying physics and mathematical models used to define the images affected by haze or low light. Therefore, a brief introduction to image dehazing and low-light image enhancement is

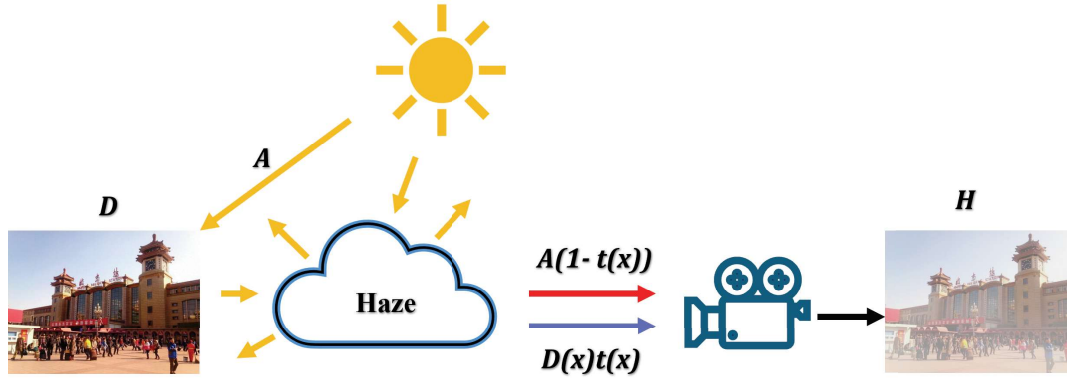


Figure 1.2: Pictorial representation of hazy image formation model.

presented here, and a detailed explanation is provided in the subsequent Chapters.

1.1.1 Image Dehazing

Image dehazing is the process of improving the visibility and quality of images captured in hazy or foggy conditions. Haze is caused by particles in the atmosphere, such as dust, smoke, or water droplets, which scatter light and reduce contrast, color saturation, and clarity in images. Dehazing techniques aim to compensate for these effects and restore the original appearance of the scene.

The process of image dehazing utilizes the most popular hazy image formation model [11] widely used in machine vision given below

$$H(x) = D(x)t(x) + A(1 - t(x)) \quad (1.1)$$

where H is the hazy image, D is the image without haze, i.e., dehazed image, t is the transmission of the hazy medium, A is the atmospheric light, and x is the coordinate of a particular pixel located in the image. In (1.1), the term $D(x)t(x)$ is known as direct attenuation, while the term $A(1 - t(x))$ is known as airlight. The pictorial representation of (1.1) is shown in Fig. 1.2. Since t represents the fraction of light reaching the observer from the scene without being scattered by the haze particles, its value ranges from 0 to 1. A higher value of t indicates less scattering with clearer visibility and vice versa. In normal

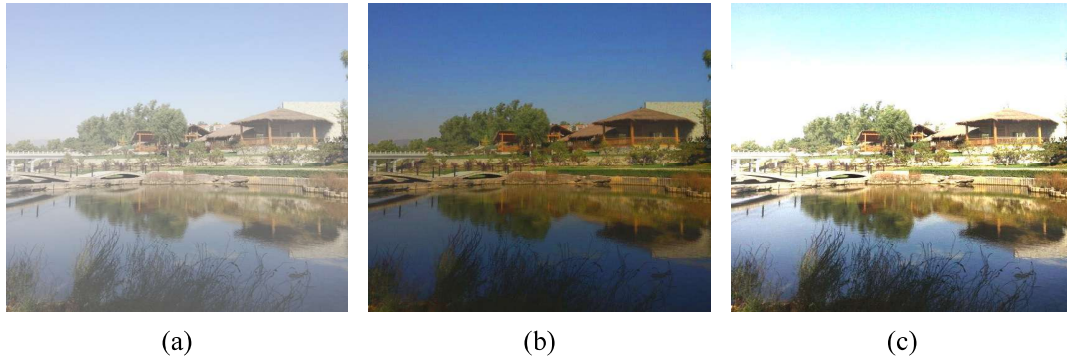


Figure 1.3: Problems in image dehazing. (a) Hazy image. (b) Oversaturated dehazed image, (c) Over-dehazed image.

weather conditions, there is little or no haze. Thus, $t \approx 1$ and $H \approx D$. However, during hazy conditions, the value of t reduces depending on the density of the haze. As a result, the visibility of objects in H is reduced due to increased scattering and added airlight. The hazy image formation model given in (1.1) can be used to obtain the haze-free image D , if t and A are known. Using certain prior-based dehazing techniques and image statistics, a fair estimate of A and t can be made. These estimated values of A and t can be further used to obtain dehazed images by simplifying (1.1). However, large inaccuracies in the estimation of A and t can result in the following problems

- A higher value of A results in a darker or oversaturated dehazed image (Fig.1.3 b) and vice versa.
- A lower value of t results in overdehazing of the hazy image (Fig.1.3 c) and vice versa.

Further, dehazing techniques may also introduce artifacts around the edges of the objects in the dehazed image. These challenges have motivated researchers to develop efficient image-dehazing algorithms capable of restoring maximum image details. The key applications of image dehazing are autonomous vehicles [12], [13], surveillance [14], aerial and satellite imaging [15], environmental monitoring, etc.

Some of the key challenges in image dehazing are as follows:

- **Reduced Visibility:** Haze reduces visibility by scattering and absorbing light as

it travels through the atmosphere. It is primarily caused by the presence of fine particles like dust, smoke, aerosols, or water droplets suspended in the air. These particles interact with incoming light and scatter it. As a result, the contrast between objects and their background is diminished, and distant objects appear faded or blurry. The effect becomes more pronounced with increasing distance because the light has to pass through more particles in its path. Thus, dehazing algorithms struggle to restore the accurate structure of the objects in a hazy image, especially the distant ones.

- **Color Distortion:** Haze causes color distortion by selectively scattering and absorbing different wavelengths of light as it passes through the atmosphere. The fine particles in haze, such as dust, smoke, or water droplets, interact with light through Mie scattering [16], affecting all visible wavelengths, but shorter wavelengths like blue and violet are affected strongly. This scattering causes a bluish or grayish cast to dominate over the hazy scene, which may worsen due to dehazing algorithms.
- **Loss of fine Detail:** Haze causes loss of detail in an image mainly by scattering light, thereby reducing contrast and blurring fine features. As a result, edges and textures that represent fine details become less distinguishable, making it difficult for the dehazing algorithms to recover these fine details.

1.1.2 Low-Light Image Enhancement

Low-light image enhancement is the process of improving the quality and visibility of images captured in poorly lit conditions. It aims to make objects and details in the image more discernible by addressing issues like low brightness, poor contrast, color distortion, and noise [17]–[20].

Prominent techniques used in low-light image enhancement include histogram equalization [21]–[25], gamma correction [26]–[29], Retinex-model-based enhancement [30]–[33], etc. Out of all these techniques, Retinex-based low-light image enhancement is highly popular as it efficiently restores naturalness in the enhanced images and can also

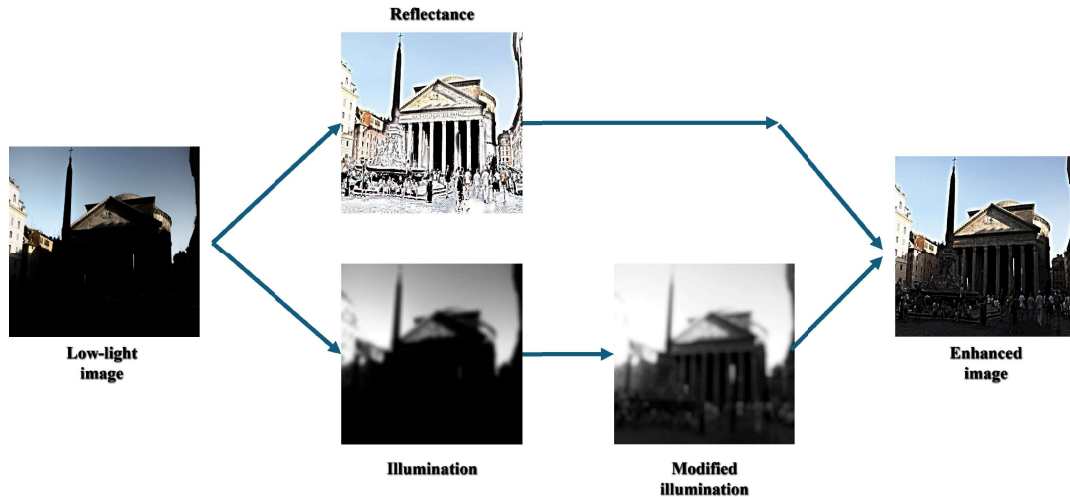


Figure 1.4: A general flow of Retinex-based low-light image enhancement method.

be applied to color images. Retinex-based low-light image enhancement is inspired by the human vision system, where the human eye perceives an image by sensing the reflected light from an object as well as the intensity of the reflected light. Hence, Retinex-based methods decompose an image into two components, viz., illumination and reflectance. The illumination channel represents the intensity of the reflected light from an object, whereas the reflectance channel contains texture and color information. For low-light images, the illumination channel has a very low value at the positions of the pixels, which are poorly illuminated by the light. To improve the visibility of the objects, the illumination channel is modified by boosting the intensity of the low-value pixels in the illumination channel. This modified illumination is then combined with the reflectance to obtain the image with enhanced visibility. A general flow of the Retinex-based low-light image enhancement method is shown in Fig. 1.4. Though Retinex-based methods have proved to be versatile, their real-time implementation is challenging because they require a large size of spatial filters for illumination estimation. This has attracted the researchers to develop adaptive and robust Retinex-based low-light image enhancement algorithms capable of producing enhanced visual results but with reduced complexity. Low-light image enhancement finds its application in several fields, such as medical imaging, autonomous vehicles, astronomy, outdoor traffic monitoring, object identification, etc.

Some of the key challenges in low-light image enhancement are

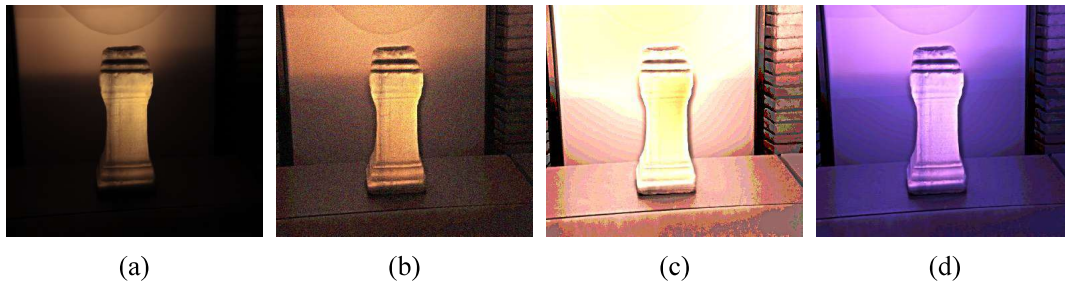


Figure 1.5: Challenges in low-light image enhancement. (a) Low-light image. (b) Enhanced image with noise amplification. (c) Enhanced image with overexposure. (d) Enhanced image with color distortion.

- **Noise Amplification:** Low-light images often contain more noise in flat and dark regions. Image enhancement techniques, such as contrast enhancement, sharpening, etc., which are used to improve the visibility of details and overall image quality, often amplify both the signal and the noise (Fig.1.5 b), leading to a noticeable increase in the noise level in the enhanced image.
- **Detail Preservation:** Many enhancement techniques smooth out or filter certain parts of the image to suppress noise and unwanted artifacts. However, fine textures, edges, and small structures in the image often share similar characteristics with noise, making it difficult for the algorithms to distinguish between actual details and unwanted distortions. As a result, important features may get blurred or lost during enhancement.
- **Overexposure:** While enhancing the brightness of poorly lit areas in an image, low-light enhancement algorithms may increase the brightness of well-exposed regions, leading to overexposure. When this happens, high light details like cloud texture, skin reflections, or subtle gradients are permanently lost (Fig.1.5 c). Moreover, efforts to balance overexposed areas with the rest of the image can cause tonal inconsistencies or degrade details in well-exposed regions.
- **Color Fidelity:** While improving overall image clarity, techniques like histogram equalization can sometimes lead to oversaturation or unnatural color shifts (Fig.1.5 d), especially in areas with limited color information. This results in a loss of color information of the objects in the image.

1.2 Motivation of the Research Work

Several machine vision systems find their application in outdoor environments, such as an Automatic Driver Assistance System (ADAS), remote sensing via satellite and drones, shore monitoring, object identification, etc. Since the outdoor environmental conditions are completely dynamic and depend upon various factors, including temperature, weather, lighting, etc., the performance of the machine vision system changes with the change in these environmental conditions. This may lead to the failure of the system, rendering it incapable of delivering the desired output. To alleviate this problem, efficient image quality enhancement techniques must be incorporated into machine vision systems in order to improve their resiliency. These enhancement techniques and algorithms counter the degradation caused to the captured images due to environmental variations. Thus, it is imperative to design and integrate image enhancement subsystems that can efficiently tackle environmental challenges without affecting the overall performance of the entire machine vision system. However, achieving this is not easy as the enhancement algorithms are compute-intensive, which may lead to high hardware resource requirements, thereby adding to the overall cost of the machine vision system. Most image enhancement applications demand real-time implementation of the underlying algorithm on portable systems with limited power supply and computational capability. Thus, the enhancement subsystem should possess some key characteristics as given below

- Low power: The enhancement subsystem should consume low power so that it can be easily deployed in portable systems having power supply constraints. This will increase their usage time between successive battery charging. Moreover, heating issues will be reduced, thereby increasing reliability.
- Low complexity: The algorithmic complexity of the enhancement subsystem should be low in order to minimize resource requirements such as memory, logic units, etc.
- Low latency: The enhancement subsystem should possess low latency for faster execution such that it can be engaged in real-time systems.

With several modifications to the existing enhancement algorithms, their complexity and

latency can be reduced without significantly affecting the overall system's performance. Moreover, with the use of approximate computing and parallel processing, these algorithms can be accelerated on FPGAs and ASICs with reduced hardware resource utilization and power consumption. Thus, there is good scope for the efficient realization of image enhancement subsystems capable of operating in real-time and integrating them with various machine vision systems, which is the motivation behind this research work.

1.3 Contribution of the Dissertation

Image dehazing and low-light image enhancement have a wide range of applications, as mentioned in Section 1.1. Therefore, in this dissertation, we present some efficient algorithms and their hardware architectures for real-time implementation of image dehazing and low-light image enhancement on FPGAs and ASICs. The main contributions of this dissertation are:

- A saturation-based transmission estimation method for image dehazing is proposed, where the transmission of each pixel is determined individually. Unlike existing patch-based methods, the proposed method requires neither an edge detection unit nor an image filtering unit to suppress halo artifacts around edges. This also reduces the hardware cost of the proposed method. The VLSI architecture of the proposed method yielded a maximum throughput of 624 Mpixels/s when synthesized at 65-nm for ASIC implementation, which is fast enough to process 3840×2160 resolution at a rate higher than 70 fps with only 13.2k logic gates count.
- A dynamic atmospheric light adjustment-based image dehazing method is proposed, where the atmospheric light for each pixel in an image frame is dynamically adjusted based on its intensity for efficient dehazing of the hazy scenes. Moreover, in this method, a new pixel-to-pixel transmission estimation technique is also proposed that precisely estimates the transmission of each pixel and prevents oversaturation and overdehazing of the dehazed images. The proposed dehazing architecture requires 13.8 k gates and operates at 460 MHz when synthesized using 90-nm CMOS

technology. Thus, the proposed dehazing architecture can process over 50 hazy video frames of resolution 3840×2160 in a second.

- A Retinex-based low-light image enhancement method is proposed that employs a low-cost edge-preserving filter for illumination estimation. The proposed edge-preserving filter efficiently preserves the edges and suppresses blocky artifacts in the estimated illumination. Moreover, the illumination estimated using the proposed edge-preserving filter helps in preserving fine details in the reflectance. The estimated illumination is further modified using a simple yet efficient contrast stretch function to increase the intensity of poorly illuminated pixels. The proposed architecture requires only 10868 LUTs and 7409 registers when implemented on the AMD-Xilinx ZynQ7 XC7Z020CLG484-1 FPGA. Moreover, it can process 60 frames of HD images (1920×1080) per second (fps).
- VLSI architectures for all the proposed methods are presented. The proposed VLSI architectures use the concept of approximate computing and the parallel processing capability of devices such as FPGAs and ASICs to achieve real-time implementation. The performance of the proposed VLSI architectures is compared with the existing architectures in terms of hardware complexity, power consumption, operating speed, etc. It is observed that all the proposed architectures are suitable for real-time image enhancement applications.

1.4 Organisation of the Dissertation

There are six Chapters in this dissertation. In this Chapter, we presented a brief overview of real-time image processing and image enhancement, the theory and principle behind image dehazing and low-light image enhancement, their implementation challenges and applications, the motivation behind this research work, and the contributions of this dissertation.

Chapter 2 presents a literature review related to image dehazing and low-light image enhancement. Existing state-of-the-art dehazing and low-light enhancement techniques

are discussed in this Chapter, along with their merits and demerits. Various definitions and benchmarks used for the qualitative and quantitative evaluation of proposed methods are also discussed in detail.

Chapter 3 presents a saturation-based image dehazing algorithm and its hardware architecture. Further, the advantages of the proposed architecture over the other existing dehazing architectures are discussed. Next, a comparative analysis of the quantitative and qualitative results obtained using the proposed method and other existing techniques is performed, and comments on the effectiveness of the proposed method are presented.

Chapter 4 explores image dehazing from a new perspective based on the intensity of hazy image pixels. In this Chapter, a new pixel-to-pixel atmospheric light and transmission estimation scheme for image and video dehazing is proposed. The hardware architecture of the proposed method is divided into ten pipelined stages. The quantitative and qualitative efficiency of the proposed method is tested on different hazy image datasets. The performance of the proposed method is also tested under dense haze conditions to test its suitability for autonomous vehicles.

Chapter 5 presents a Retinex-based low-light image enhancement algorithm and its hardware architecture. A low-cost edge-preserving filter for illumination estimation has been proposed in this Chapter, which requires significantly lower hardware resources and increases the processing speed of the enhancement algorithm so that the proposed system can operate in real-time. The quantitative and qualitative results obtained using the proposed method are also discussed to demonstrate its effectiveness.

Chapter 6 presents a summary of the main findings of this dissertation. It also discusses the advantages and limitations of the proposed methods, their suitability for real-time applications, and the scope of the future work to be carried out.