Chapter 1

Introduction

Haze refers to a meteorological phenomenon characterized by the presence of suspended fine particles, smog, dust, and other pollutants in the atmosphere. This leads to reduced visibility and a translucent or milky appearance in the air. Haze can occur in both urban and rural areas and is often linked to various human activities and natural events. In atmospheric scattering models, haze is an important factor that influences the scattering of light in the atmosphere. These models are used to understand how light interacts with the particles and molecules present in the Earth's atmosphere, leading to various optical phenomena, including haze. Haze in atmospheric scattering models is typically caused by the presence of small particles, such as aerosols and particulate matter, suspended in the air. These particles can scatter and absorb light, leading to reduced visibility and a hazy appearance in the atmosphere. The primary process responsible for haze in atmospheric scattering models is Mie scattering [1]. Mie scattering occurs when the size of the scattering particles is similar to the wavelength of the light being scattered. In the case of haze, the scattering particles are often on the order of micrometers or smaller, which is comparable to the visible light wavelengths. When sunlight passes through the

Earth's atmosphere, it interacts with these small scattering particles. The light is scattered in all directions, including sideways and backward, leading to a diffusion of light. This scattering of light causes the haze and reduces the clarity of distant objects.

Haze is also responsible for the phenomenon of Rayleigh scattering [2], which occurs when the size of the scattering particles is much smaller than the wavelength of light. Due to Rayleigh scattering the sky appears blue during the daytime, as shorter wavelengths of light (blue and violet) are scattered more efficiently than longer wavelengths (red and yellow).

In addition to natural sources like dust and sea spray, human activities can contribute to haze through the emission of aerosols and particulate matter, such as from industrial processes, vehicle exhaust, and agricultural burning. Atmospheric scattering models take into account the properties of the scattering particles, the wavelength of the incident light, and the distribution of particles in the atmosphere to simulate the scattering effects accurately. These models are essential for understanding and predicting atmospheric conditions, as well as for various applications like climate modelling, remote sensing, and visual effects rendering in computer graphics.

1.1 Haze Imaging Model

A haze imaging model is a computational approach used to simulate and understand the degradation of images caused by atmospheric haze. It aims to model the scattering and absorption of light by haze particles in the atmosphere and their impact on the quality of captured images. Such models are essential for various applications, including image restoration, computer vision, and remote sensing.

The key components of a haze imaging model [3] as shown in Figure 1.1 include:

- **Scene Radiance**: The model begins with the scene radiance, which represents the true colors and intensities of objects in the scene without any atmospheric interference.
- **Atmospheric Map/Light**: The atmospheric light refers to the light that is directly scattered and reflected by haze particles towards the imaging sensor. It represents the illumination of the scene due to the scattered light from the atmosphere.
- **Transmission Map/ Light**: The transmission factor represents the fraction of light that reaches the imaging sensor after being scattered and absorbed by haze particles. It is usually computed based on the scene radiance and the atmospheric light.
- **Haze Density**: The haze density or optical thickness characterizes the concentration of haze particles in the atmosphere. Higher haze density results in more severe degradation of the captured image.
- **Scattering Model**: The scattering model describes how light interacts with the haze particles in the atmosphere. Commonly used models include Mie scattering for larger particles and Rayleigh scattering for smaller particles.

The haze imaging model [4, 5] typically follows the equation:

$$I(x) = J(x)t(x) + A(1 - t(x)), \tag{1.1}$$

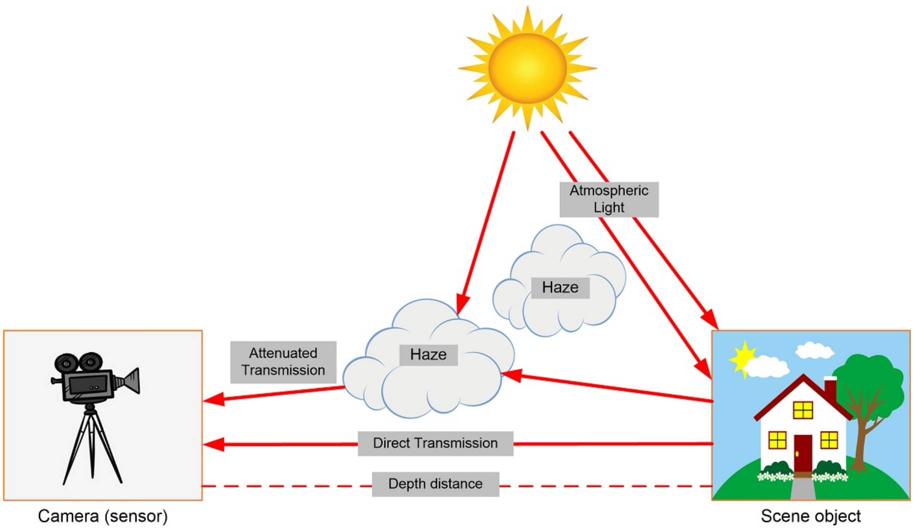
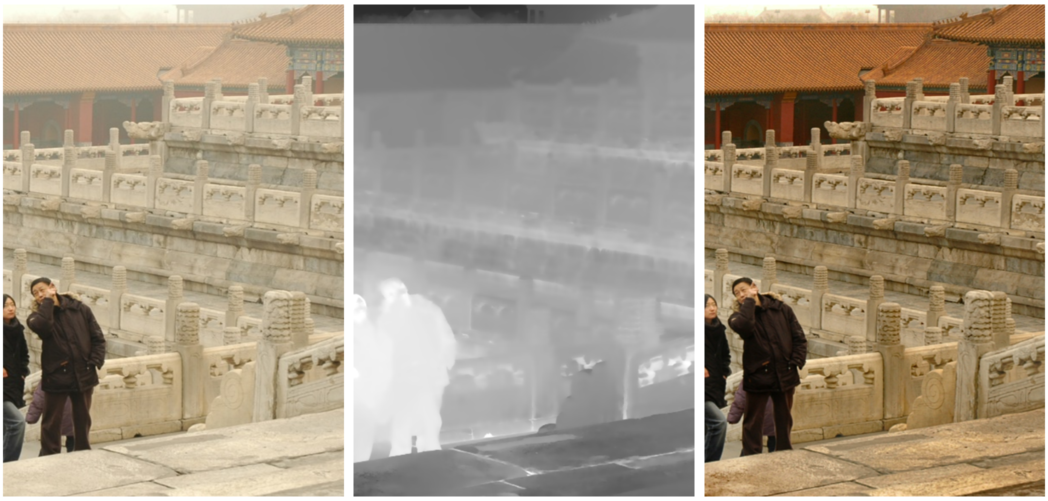


FIGURE 1.1: Haze imaging model.

where x is pixel's position in the image. It is a 2D vector denoting the coordinates (m', n') of pixel's position in the image, $I(x)$ is input hazy image, $J(x)$ is output dehazed image or scene radiance, $t(x)$ is the medium transmission map, and A is the global atmospheric light or map. In (1.1), the first term $J(x)t(x)$ and the second term $A(1 - t(x))$ are called direct attenuation and air-light, respectively.

In practical applications, the haze imaging model can be used for image dehazing, where the hazy image is processed to recover the true scene radiance and improve image quality. Various dehazing algorithms and techniques have been developed based on different assumptions and prior knowledge about the scene and the haze distribution. Dehazing is a challenging task, especially when the haze density is high or when the scene contains low-contrast regions or objects with similar colors to the haze. Therefore, ongoing research in image dehazing aims to improve the accuracy and efficiency of haze removal algorithms for real-world applications.



(a) Input hazy image (b) Transmission map $t(x)$ (c) Dehazed Image

FIGURE 1.2: Haze removal from input image

1.2 Motivation of the Research Work

The motivation behind image dehazing is driven by the desire to improve the visibility and quality of hazy or degraded images captured in various real-world scenarios. Haze in the atmosphere can significantly impact the clarity and visual perception of images, leading to reduced visibility and loss of fine details. Image dehazing aims to restore the original scene radiance and enhance the visual quality of hazy images for better human perception and automated image analysis.

Below are some key motivations for image dehazing:

- **Enhanced Visibility:** Dehazing allows us to see distant objects and scenes more clearly, even in the presence of atmospheric haze. This is crucial for applications like surveillance, remote sensing, and aerial photography, where obtaining clear and detailed images is essential.
- **Improved Image Analysis:** Hazy images can hinder accurate image analysis tasks, such as object detection, recognition, and segmentation. Dehazing

improves the performance of computer vision algorithms by providing clearer input data.

- **Visual Appeal:** For photography and visual media, dehazing can significantly enhance the aesthetic quality of images, making them more appealing to viewers.

- **Environmental Monitoring:** In remote sensing applications, dehazing plays a vital role in obtaining clearer satellite or aerial imagery for monitoring environmental changes, such as land cover, vegetation health, and pollution levels.

- **Medical Imaging:** In medical imaging, haze or scattering effects can affect the quality of images from endoscopes or other imaging devices. Dehazing techniques enhance the visibility of important structures and aid in accurate diagnosis.

- **Improved Human Perception:** Hazy conditions can negatively impact human perception, leading to potential safety hazards in transportation, navigation, and outdoor activities. Dehazing can improve safety by providing clearer visual information.

- **Atmospheric Research:** Understanding atmospheric scattering and dehazing algorithms is crucial for atmospheric research, climate modeling, and remote sensing studies. Dehazing can aid in analyzing the properties of aerosols and particles in the atmosphere.

Overall, image dehazing is a fundamental preprocessing step in numerous applications where visual quality and accurate information extraction are essential. Researchers continue to develop and refine dehazing techniques to address various challenges and improve the efficiency and effectiveness of haze removal from images.

1.3 Challenges in Image Dehazing

Image dehazing is a challenging task due to the complexity of atmospheric scattering and various factors that can affect the quality of hazy images. Some of the key challenges faced in image dehazing include:

- **Non-Uniform Haze Distribution:** The distribution of haze in an image can be non-uniform, with varying thickness and density across different regions. Estimating and modeling the transmission map accurately becomes challenging in such cases.
- **Unknown Atmospheric Parameters:** In most real-world scenarios, the exact atmospheric conditions, such as the haze density and the type of scattering particles, are unknown. Estimating these parameters from the hazy image itself is a non-trivial problem.
- **Scene Depth Variation:** Haze has a more significant impact on objects located at greater distances from the camera. Dehazing algorithms need to consider the varying depth of the scene to achieve consistent and accurate results.
- **Haze and Scene Content Interference:** In hazy images, the haze and the scene content are intermingled, making it difficult to separate and isolate the scene radiance accurately.
- **Underwater and Aerial Haze:** Underwater and aerial images often suffer from severe haze due to the presence of suspended particles or fog. Dehazing these images present additional challenges because of the unique scattering characteristics of water and air.

- **Color Distortion:** Dehazing algorithms can sometimes introduce color distortion or artifacts in the dehazed images, affecting the overall image quality.

- **Real-Time Processing:** For applications that require real-time dehazing, the computational complexity of dehazing algorithms can be a significant challenge. Balancing dehazing performance and processing speed is critical in such cases.

- **Low Visibility and Low Contrast Regions:** Hazy images may contain regions with very low visibility and low contrast, making it challenging for dehazing algorithms to recover meaningful details.

- **Sensitivity to Noise:** Dehazing algorithms can be sensitive to noise present in the hazy image, leading to degraded dehazing results.

- **Lack of Ground Truth:** In some cases, obtaining a clear reference image (ground truth) for comparison can be challenging, making it harder to objectively evaluate the performance of dehazing algorithms.

  Researchers in the field of image dehazing continuously work on developing robust and efficient algorithms to address these challenges. Many dehazing techniques incorporate prior knowledge, physical models, and machine learning approaches to improve dehazing accuracy, especially in complex and real-world scenarios. Additionally, the development of large-scale dehazing datasets with ground truth is essential to evaluate and benchmark the performance of different dehazing algorithms.

Image dehazing is a significant area of research in computer vision and image processing, aiming to improve the visibility and quality of images captured in hazy or foggy conditions. Some important research questions that arise in the dissertation are summarized below:

- What is the most accurate and efficient model to represent the atmospheric haze and how can we estimate the haze parameters from a given hazy image?
- Should dehazing algorithms rely on information from a single hazy image or can they leverage multiple images of the same scene taken under different conditions?
- How can we estimate the depth map or scene geometry from a single hazy image, and how can this information be effectively used to guide the dehazing process?
- How can we ensure that dehazing algorithms enhance visibility while preserving important scene details and structures?
- What are the appropriate benchmark datasets for training and evaluating dehazing algorithms?

1.4 Contribution of the Dissertation

The aim of this dissertation is to develop some edge-preserving filtering algorithms for single image dehazing. They remove halos, over-smoothing effect and preserves edge-details precisely in both flat and sharp regions. So, this dissertation proposes some new multi-scale edge-aware weighting-based edge-preserving filters for single image dehazing.

The main contributions in the presented dissertation are listed below:

- A novel effective scale-aware edge-smoothing weighting constraint-based weighted guided image filter is proposed for single image dehazing. In this filter, effective scale-aware edge-smoothing weighting constraint is incorporated into the cost function of guided image filter (GIF). The objective of this filter is to refine the transmission map more accurately and preserves edge information effectively.

- A new robust scale-aware weighting based effective edge-preserving gradient domain guided image filter (RSAW-EEPGDGIF) is proposed for single image dehazing. The proposed filter refines the transmission map by decomposing into effective weighted base layer (EWBL) and effective weighted detail layer (EWDL), respectively. In this method, a sigmoid function-based non-linear mapping function (NLM) is employed to supress the various artifacts and noises.

- A non-local haze line averaging (NL-HLA) based robust multi-scale weighting edge-smoothing filter (RMWEF) is proposed for single image dehazing. The objective of this method is to remove morphological artifacts, over-smoothing effect strongly and preserves edge-details precisely in sharp regions.

- A new structural patch decomposition-based multi-exposure image fusion with an effective edge-aware weighting filter is proposed for single image dehazing.

- The performance of the proposed method with different existing haze removal methods are tested on indoor real hazy, outdoor real hazy, indoor synthetic hazy, and nighttime hazy images of different datasets. To asses the effectiveness of the proposed method, some full referenced and non-referenced quantification parameters are used to assess the effectiveness of the proposed method.

1.5 Organisation of the Dissertation

This dissertation is organised into seven chapters. In this Chapter, we have introduced the haze effect, atmospheric scattering models (ATSM) in image dehazing, haze imaging models, the motivation behind this research work performed, challenges and contributions made in the dissertation. The rest of the dissertation is organised as follows:

Chapter 2: This Chapter presents state-of-the-art works, background and related preliminaries to image dehazing. The experimental set-up, datasets, and relevant referenced and non-referenced quantification parameters used in this dissertation are discussed in detail.

Chapter 3: In this Chapter, an effective scale-aware edge-smoothing weighting constraint-based weighted guided image filter is presented for single image dehazing. The qualitative and quantitative analysis of the proposed method with the existing dehaze methods are discussed in detail. The proposed method is tested on real hazy, non-real hazy, and synthetic hazy images of different datasets and their comparative outcomes with the existing haze removal methods are discussed in detail. The average execution time of the proposed method with the existing haze removal methods are calculated and analysed for five benchmarks hazy images of having different resolution. The statistical analysis using box plot is also presented in this Chapter.

Chapter 4: In this Chapter, a new robust scale-aware weighting-based effective edge-preserving gradient domain guided image filter (RSAW-EEPGDGIF) is proposed for single image dehazing. The effective weighted base layer (EWBL) and effective weighted detail layer (EWDL) of the proposed method are calculated with different regularization parameter values and the results are compared with the existing edge-preserving filters. Further, the performance of the proposed method is compared with existing haze removal methods using different hazy, non-hazy, synthetic datasets. To asses the effectiveness of the proposed method, some full referenced and non-referenced quantification parameters are evaluated and discussed in detail. The average execution time of the proposed method are calculated for images having different resolution and comparison with the existing haze removal methods are discussed in detail.

Chapter 5: In this Chapter, the morphological artifacts (halo artifacts) removal method by using a non-local haze line averaging (NL-HLA) algorithm is presented. Further, this Chapter presents a new robust multi-scale weighting-based edge-smoothing filter (RMWEF) for single image dehazing. The edge-aware weighting of the proposed method is compared with the edge-weighting of the existing filters. Additionally, 1-D illustration performed between pixel intensity and pixel coordinates in the horizontal as well as in the vertical directions for different regularization parameter ε values is presented. The performance of the proposed method is tested on different indoor hazy, outdoor hazy, real hazy, and synthetic datasets. The performance of the proposed method is compared with the existing methods using various referenced and non-referenced metrics.

Chapter 6: In this Chapter, a new effective edge-aware weighting filter-based structural patch decomposition multi-exposure image fusion is presented for single image dehazing. The artificial exposure using Gamma correction, structural patch decomposition, and multi-exposure image fusion are discussed in detail. The performance of the proposed method is tested on indoor real hazy, outdoor real hazy, indoor synthetic hazy, and nighttime hazy images from different datasets and the results are discussed in detail.

Chapter 7: The main findings of the thesis are summarized in this chapter. The main contributions and future research directions in image dehazing are discussed in this Chapter.

Some important technical reports, research papers, and textbooks are listed in References. The publications of the research work presented in this thesis are listed in the List of Publications.