A NEW MULTIPERSPECTIVE FRAMEWORK FOR STANDARDIZATION AND BENCHMARKING OF IMAGE DEHAZING ALGORITHMS

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KARRAR HAMEED ABDULKAREEM

A thesis submitted in
fulfillment of the requirement for the award of the
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Faculty of Computer Science and Information Technology
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A.P. DR. AOS ALAA ZAIDAN

DEDICATION

To my dear father and my beloved mother.. the source of my strength, and the pillar of my success, whose unconditional and unlimited love, encouragement, prayers and support made me reach to this point.

To my beloved wife, who's unlimited love, patience and constant support made it possible for me to pass the hardest times during my study.. and to her family, whose continuous care and support helped us greatly throughout this journey.

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"In the name of Allah, the Most Gracious and the Most Merciful"

Alhamdulillah, first and foremost, praise be Allah, the Cherisher and Sustainer of the World and to the Prophet Muhammad (Peace and Blessings of Allah Be upon Him) who was sent by Allah to be a great teacher to the mankind.

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ABSTRACT

A standardization and benchmarking framework for image dehazing algorithms based on multiple perspectives is not yet available. Hence, this study proposed a new multi-perspective standardization and benchmarking framework for image dehazing algorithms. Experiments were conducted in three main phases. First, the image dehazing criteria were standardized based on Fuzzy-Delphi Method (FDM). Furthermore, an objective experiment was conducted to test and evaluate the selected criteria from FDM within constraints of Pearson Linear Correlation Coefficient (PLCC) and Spearman Rank Order Correlation Coefficient (SRCC). Second, an evaluation experiment was conducted to obtain a new multi-perspective decision matrix. Third, Best Worst Method (BWM) and Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) methods were hybridized to determine the weight of the standardized criteria and rank the algorithms. To objectively validate the selection results, mean was applied for this purpose. To evaluate the proposed framework, two main approaches were applied. On the one hand, a standard dataset was tested on the selected criteria and image dehazing algorithms to select the best algorithm. On the other hand, a benchmarking checklist scenario was adopted to measure the feasibility of the proposed work compared to other methods. The results revealed that 11 criteria were selected as the best according to FDM stipulations. Furthermore, seven criteria had been satisfied with the PLCC and SRCC tests. Hybridization of BWM and VIKOR methods can effectively solve the challenges in the selection of the optimal algorithm. The ranking results identified Contrast Limited Adaptive Histogram Equalization (CLAHE) as the best image dehazing algorithm. Apart from that, the benchmarking checklist scenario showed the proposed framework was more effective than the benchmark study.

ABSTRAK

Menurut kajian sebelum ini, kerangka piawai dan penanda aras untuk algoritma penghapusan gambar pelbagai perspektif adalah belum tersedia. Oleh itu, kajian ini mencadangkan kerangka piawai dan penanda aras pelbagai perspektif yang baharu untuk algoritma penyahmampatan gambar. Eksperimen dijalankan dalam tiga fasa utama. Pertama, kriteria penghapusan gambar diseragamkan berdasarkan Kaedah Fuzzy-Delphi (FDM). Selanjutnya, eksperimen objektif dijalankan untuk menguji dan menilai kriteria terpilih dari FDM dalam batasan Pearson Linear Correlation Coefficient (PLCC) dan Spearman Rank Order Correlation Coefficient (SRCC). Kedua, eksperimen penilaian dilakukan untuk mendapatkan matriks keputusan pelbagai perspektif baharu. Ketiga, Best Worst Method (BWM) dan kaedah Vlse Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) digabungkan untuk menentukan pemberat kriteria piawai dan menentukan kedudukan algoritma. Untuk mengesahkan hasil pemilihan secara objektif, kaedah purata digunakan. Manakala, untuk menilai kerangka kerja yang dicadangkan, dua pendekatan utama diterapkan. Di satu pihak, satu set data piawai diuji berdasarkan kriteria dan algoritma penghapusan gambar yang dipilih untuk memilih algoritma terbaik. Selain itu, senario senarai semak penanda aras digunakan untuk mengukur kebolehlaksanaan kerja yang dicadangkan dibandingkan dengan kaedah lain. Hasil kajian menunjukkan bahawa 11 kriteria dipilih sebagai yang terbaik berdasarkan kaedah FDM. Selanjutnya, 7 kriteria telah dipenuhi dengan ujian PLCC dan SRCC. Gabungan kaedah BWM dan VIKOR dapat menyelesaikan masalah dalam kajian ini dengan berkesan dalam pemilihan algoritma yang optimum. Hasil pemeringkatan telah mendapati bahawa Contrast Limited Adaptive Histogram Equalization (CLAHE) sebagai algoritma penghapusan gambar terbaik. Selain itu, senario senarai semak penanda aras menunjukkan kerangka kerja yang dicadangkan lebih berkesan daripada kajian penanda aras.

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LIST OF SYMBOLS AND ABBREVIATIONS

TC	-	Time Complexity
IV	-	Image Visibility
CR	-	Colour Restoration
SS	-	Image structure similarity criteria
IQA	-	Image Quality Assessment
UAV	-	Unmanned Aerial Vehicle
SRs	-	Systematic Reviews
SLR	-	Systematic Literature Review
WOS	-	Web of Science
SD	-	Science Direct
CCI	-	Color Colorfulness Index
CNI	-	Color Naturalness Index
DCP	-	Dark Channel Prior
MOS	-	Mean Opinion Score
SVM	-	Support Vector Machine
CNC	-	Contrast, Color naturalness and Colorfulness
RBF	-	Radial Basis Function
DIAS	-	Dehazed Image Assessment using Statistics
DIQA	-	Dehazed Image Quality Assessment
DMOS	-	Difference Mean Opinion Score
MSRCR	-	Multiscale Retinex with Color Restoration
MSR	-	Multiscale Retinex
HE	-	Histogram Equalization
CLAHE	-	Contrast Limited Adaptive Histogram Equalization
AHE	-	Adaptive Histogram Equalization

NIR	-	Near-Infrared
VL	-	Visible Light
RGB	-	Red, Green, Blue
VCM	-	Visual Contrast Measure
HCC	-	Histogram Correlation Coefficient
SSIM	-	Structural Similarity Index Measure
UQI	-	Universal Quality Index
IVM	-	Image Visibility Measurement
CG	-	Contrast Gain
STD	-	Standard Deviation
AG	-	Average Gradient
IE	-	Information Entropy
GCF	-	Global Contrast Factor
EBCM	-	Edge-Based Contrast Measure
Ampl	-	Amplification of Invisible Contrast
CNR	-	Contrast-to-Noise Ratio
SNR	-	Signal-to-noise ratio
VSNR	-	Visual Signal to-Noise Ratio
WSNR	-	Weighted Signal-to-Noise Ratio
Loss	-	Loss of Contrast
VIF	-	Visual Information Fidelity
RF	-	Random field
CEF	-	Color Enhancement Factor
MS-SSIM	-	Multiscale Structural Similarity Index Measure
IW-SSIM	-	Information Content Weighted Structural Similarity Index Measure
MCA	-	Muliti Criteria Analysis
MCDM	-	Multi Criteria Decision Making
OR	-	Operations Research
DM	-	Decision Matrix
MDM	-	Multiperspective Decision Matrix

EM	-	Evaluation Matrix
GPS	-	Global Positioning System
RFID	-	Radio-Frequency Identification
AHP	-	Analytic Hierarchy Process
ANP	-	Analytic Network Process
SAW	-	Simple Additive Weighting
HAW	-	Hierarchical Adaptive Weighting
WSM	-	Weighted Sum Model
WPM	-	Weighted Product Method
MEW	-	Multiplicative Exponential Weighting
VIKOR	-	Vlse Kriterijumska Optimizacija Kompromisno Resenje
TOPSIS	-	The Technique for Order Preference by Similarity to Ideal Solution
BWM	-	Best Worst Method
FDM	-	Fuzzy-Delphi Method
RESIDE	-	Realistic Single Image Dehazing
PLCC	-	Pearson Linear Correlation Coefficient
SRCC	-	Spearman Rank Order Correlation Coefficient
TFN	-	Triangular Fuzzy Number
MSCNN	-	Multi-Scale Convolutional Neural Networks
GDM	-	Group Decision Making

LIST OF APPENDICES

LIST OF PUBLICATIONS

1. Abdulkareem, K. H., *et. al*, 2020, A new standardisation and selection framework for real-time image dehazing algorithms from multi-foggy scenes based on fuzzy Delphi and hybrid multi-criteria decision analysis methods. **Neural Computing and Applications,** ISI: Q1: Impact factor: 4.774. Published.
2. Abdulkareem, K. H., *et. al*, 2020, A Novel Multi-Perspective Benchmarking Framework for Selecting Image Dehazing Intelligent Algorithms Based on BWM and Group VIKOR Techniques, **International Journal of Information Technology & Decision Making,** ISI: Q2: Impact factor: 1.894. Published.

CHAPTER 1

INTRODUCTION

In order to present a brief map for research components, this chapter offers an overview of three vital research elements: research background, problem statement, and research objectives. It serves to illuminate the scope of this study. Section 1.1 introduces the background of the research topic. Section 1.2 provides the motivation of the study. Section 1.2 presents the problem addressed in this study. Section 1.3 introduces the research questions. Section 1.5 highlights the description of the research objectives. Section 1.6 shows the link among each of the research objectives, questions, and problems. Section 1.7 identifies the scope of the study. Section 1.8 illustrates the significance of the study. Section 1.9 shortly draws a map for the whole structure of this research.

1.1 Research Background

Haze is an atmospheric effect that shapes a gray color over the scene which lessens visibility in outdoor scene images [1]. It is also considered as one of the main sources of accidents in different environmental mediums such as underwater, air, and over-land [2]. Particles such as smoke and moisture normally spread in the air usually scatter the light that propagates through atmosphere and causes the formation of haze [3]. The procedure of eliminating haze effects from outdoor images and restoring fidelity details is called dehazing [1]. Image dehazing technique, also known as “haze removal” or “defogging” serves to conceptually eliminate undesirable visible effects and is often considered as an image enhancement technique. However, it is unlike traditional noise removal and contrast enhancement methods as the degradation to image pixels is induced by the presence of haze depending on the distance between the objects, the acquisition device, and the regional density of the haze. The effect of haze on image pixels also suppresses the dynamic range of the colors [4].

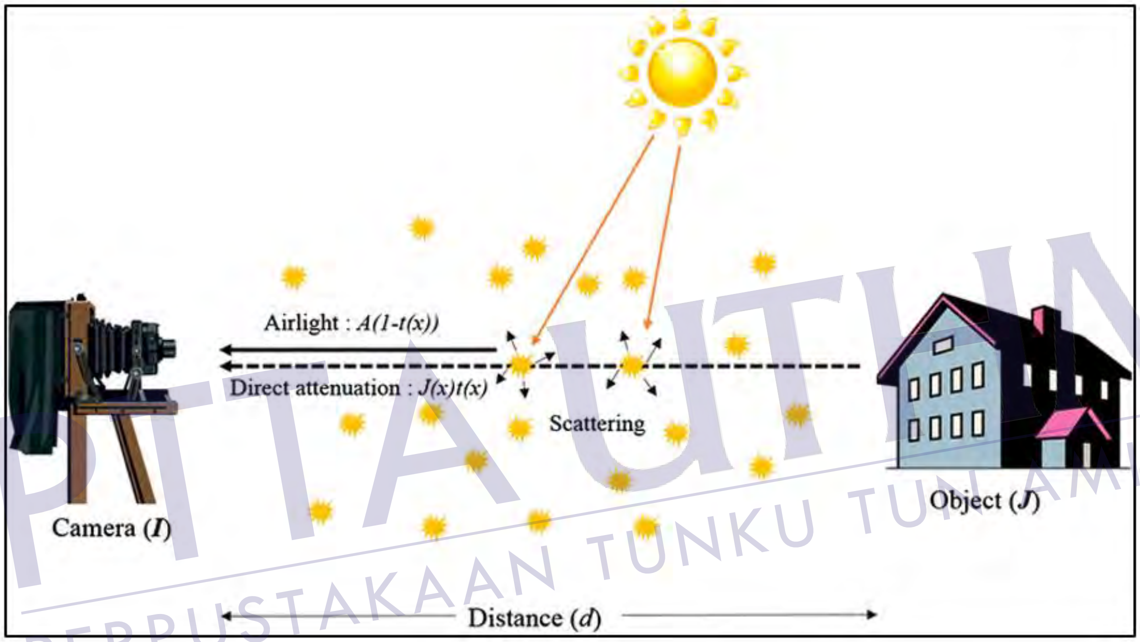

Figure 1.1: Formation of hazy image [1]

As shown in Figure 1.1, fog formation occurs because of two aspects: attenuation and airlight. Attenuation reduces the contrast and airlight increases the whiteness in the scene. Light ray that propagates from a specific scene point gets attenuated because of the scattering by atmospheric particles. This phenomenon is called attenuation [5]. Light propagated from the source is scattered through traveling on the way to camera and inserts whiteness in the scene or in another word causing color distortion. This what called airlight [6, 7]. Furthermore, the variation of effects of airlight and attenuation is restricted to the distance between the scene point and camera. Therefore, the accuracy of restoration for degraded images mainly depends on the concept of remap, usually called estimation of depth map or airlight map [5]. It is important to design an image defogging algorithm to improve the environmental adaptability of the visual system

Many improved defogging algorithms based on the physical model have been proposed for outdoor scenes [2]. Some video and image defogging algorithms have also been proposed for real-world traffic surveillance scenes [8]. In some literature, the image defogging algorithm is simply divided into two categories in terms of whether a physical model is used or not [9]. The first category is image restoration based on the physical model [10, 11] and the other is based on image enhancement [12, 13]. In later years, fusion-based defogging algorithms which enhance the image by fusing multiple input images have received much attention [14, 15].

Standardization is the process of implementing and developing technical standards based on the consensus of different parties that include firms, users, interest groups, standards organizations and governments [16]. Also, Standards are the end-result of a process referred to as standardization. Standardization, here defined as the process of producing a standard, is not limited to any number or type of activities[17]. According to [18], the standardization is relevant with the process that adopted to evaluate and select the most important image dehazing criteria. However, in order to prove the efficiency of a particular algorithm, evaluation and benchmarking are necessary steps in image dehazing.

Image quality assessment methods enable us to compare the performance of different image dehazing algorithms. Various foggy scenes (multi-perspective) have been made available to test the usefulness of image dehazing algorithms [19],[20]. Multi-perspective defined as a broad term to encompass multiple and possibly heterogeneous viewpoints, representations and roles that can be adopted within both a collaborative and non-collaborative context [21]. Multi-perspective term defined as considering more than one foggy image type in the evaluation and selection of image dehazing algorithms [18, 22]. Most forms of assessment are equivalent on multi-perspective foggy scenes [2], [4], [23, 24]. For example, in [2], the authors considered multi-perspectives foggy scenes such as inhomogeneous, homogeneous, and dark foggy scenes to test the efficiency of algorithms. However, when evaluating certain algorithms, their efficiency should be tested in consideration of various characteristics and foggy perspectives. Therefore, the advantages and demerits of each algorithm should be considered within each context. Under different hazy scenes, several algorithms can work properly, such as those proposed in [25,26]. Therefore, comparing these algorithms from only one perspective is unfair [22].

Any new algorithm should be compared according to its perceived quality and time complexity (TC), which are considered as main indicators for any comparison scenario. Particularly, image dehazing evaluation is based on quality criteria group on one side and time complexity criteria on the other side. Nevertheless, most objective evaluation methods such as those introduced in [19], [23] use different metrics or criteria to measure the quality of an enhanced image [27]. The diversity of image dehazing criteria enabled us to evaluate the performance of image dehazing algorithms from several perspectives. For example, the image visibility (IV) criterion identifies the distortion of hazy images based on edge, contrast, and texture information [2], whereas others identify the degree of colour distortion of a hazy image based on the colour restoration (CR) criterion [28]. Furthermore, evaluation based on different criteria draws a picture about the efficiency of a particular image dehazing algorithm. However, the high number of criteria found in existing literature draws a significant challenge of selecting the suitable ones for evaluation and benchmarking processes. Most of the current evaluation criteria need to be investigated comprehensively, in order to provide more reliable and suitable criteria for specific evaluation and benchmarking scenarios. Furthermore, more efforts are needed to address such issues and define the most suitable method to outline the importance of existing criteria.

The efficiency of image dehazing algorithms also needs to be evaluated by using trustworthy approaches [23], [29]. In this case, how several algorithms can be evaluated and how the best algorithm is selected through an effective approach warrant further investigation. Different image quality assessment methods have been proposed for evaluation and benchmarking of image dehazing algorithms. So far, there are no reliable means to measure the quality of the image dehazing algorithms [23], [29].

From the findings of state-of-the-art image quality assessment (IQA), two concerns need to be addressed. First, determining the best enhanced image and validating the best dehazing results are difficult [19]. For instance, evaluators may not always have the same response regarding the quality of an improved image when using a subjective approach. At the same time, the conventional objective approach cannot effectively solve these problems. Second, [2], [30], and [24] reported that no single defogging algorithm shows an excellent performance across different foggy scenes. Therefore, selecting a defogging algorithm is difficult. The selection and benchmarking of the best image dehazing algorithm based on multiple foggy scenes are therefore identified as the major problems. Furthermore, questions have been raised such as how to evaluate multiple algorithms and select the best one using an efficient approach. Section 1.3 and Chapter 2 describe further details on evaluation and benchmarking problems.

1.2 Motivation

Remarkably, when it comes to comparing the quality of a pair of images, it is observed that the quality of several enhanced images is worse than hazy ones [30]. With the advancement of haze removal techniques in the past few years, effective comparison of the performance of image dehazing becomes a novel task [31]. Hence, evaluation and benchmarking process can present such an advantage in terms of measuring the effectiveness of enhancement quality for a particular algorithm against other algorithms. The evaluation and benchmarking of image dehazing methodologies is also significant to numerous researchers and organizations interested in their applications. As any scenario includes the existing two elements of haze and outdoor imaging application, the number of applications that work under this domain is huge. This scenario can also be expanded into three environmental scenes: over-land, over-sky, and underwater. Furthermore, even the concepts and tools of image dehazing have been used in non-haze scenarios such as low light conditions, localized light sources in images captured when the drivers turn on the headlights, and images taken in sandstorms.

1.3 Problem Statement

One requirement for the evaluation and benchmarking processes in image dehazing algorithms is the criterion that can indicate the degree of enhancement presented by a certain algorithm towards a specific type of distortion [19]. However, the ability to determine the best alternative under all conditions of uncertainty must be made obvious to achieve an effective selection process. The set of criteria and their importance can also influence the selection process [32-34].

When proposing an image dehazing algorithm, one needs to evaluate and compare it with the state-of-the-art algorithms, or when applying image dehazing algorithms, one needs to select the best algorithm [34]. According to [35], when the authors compared the performance of different algorithms, they found that there is still a lack of public criteria. In the same direction, authors in [19] stated that so far, no agreement was found on a single standardized evaluation criteria for the assessment of image dehazing performance. Moreover, based on Section 2.10 in Chapter 2, several objective assessment metrics have been proposed in the literature. However, the use of these metrics varies from one study to another which indicates no consensus has been reached among the scholars in considering a specific set of criteria for evaluating and benchmarking image dehazing algorithms. Additionally, a model for classifying and recommending the most appropriate measurements is yet to be developed. Therefore, providing a standard image dehazing criteria is crucial for the evaluation and selection of image dehazing algorithms. The standardization of these criteria presented a challenge for this study.

According to literature, the selection and benchmarking process is affected by four main elements: evaluation criteria, importance of criteria, trade-off criteria, and conflict criteria [36 , 37].

Even with the use of one criterion or more than one for evaluation in the existing literature, the selection of best algorithm can only be achieved from the perspective of individual criterion with no consideration of other criteria. Considering more than one criterion for evaluating and benchmarking image dehazing algorithms is quite challenging and can bring a great conflict between evaluators and developers. Moreover, all researchers in the fields of image dehazing have used either a criterion or a set of criteria defined in the literature but with different priorities. Consequently, the problem of evaluation and benchmarking process in image dehazing is considered as a multi-criteria problem with conflicting criteria [36, 37]. In this context, using multiple criteria for evaluation is one of the issues in selecting and benchmarking image dehazing algorithms, despite the conflict among them. Furthermore, the variation in the scores of these multiple evaluation criteria for one algorithm against others presents a conflict in terms of which best algorithm could be applied to enhance the foggy image. Hence, it is also considered a multi-criteria problem and one of the issues in this study.

According to [38], it is difficult to decide the most vital features that influence visual decision and to design the corresponding evaluation metrics. As the evaluation process in image dehazing has considered multiple criteria, it is a challenge to propose a new metric without giving some weight to a specific evaluation criterion. Apart from that, it is more challenging when considering more than one evaluation perspectives. The second issue in this study is to define the importance of each criterion in image dehazing which is considered as one of the issues in multi-criteria decision analysis [36, 37].

However, numerous aspects of trade-off among different criteria used by researchers were found. Trade-offs among criteria typically cause confusion for decision makers. This phenomenon shows a conflict between the quality criteria group on one side [2], [4] and the quality criteria group with time complexity criteria on the other side [39 ,40]. In other words, all criteria significantly affect the values of each other. For example, in a real time scenario, the best case is an algorithm that enhances a specific image with high quality within a short time frame. However, when decreasing time complexity value, this is accompanied with a decrease in the quality value for a specific image and vice versa. The selection and benchmarking over multiple criteria is quite challenging especially with considerations of trade-off scenarios, regarded as one of multi-criteria decision analysis issues [36, 37].

. To end, research problem can be summarized in the following points:

- There is still a lack of public criteria as well as no agreement was found on a single standardized evaluation criteria for the assessment of image dehazing performance[35].
- No single dehazing algorithm shows an excellent performance across different foggy scenes [2],[30],[24]. Therefore, selecting a defogging algorithm is difficult.
- The selection of best image dehazing algorithm based on multi-perspective foggy scenes considered as MCDM problem.
- Four issues make MCDM as complex problem which are multi evaluation criteria, importance of criteria, trade-off, and conflict of criteria [36, 37].

Figure 1.2 shows the research problems that were determined in three specific relative directions, namely research gaps, general problems, and specific problems. Research gaps are the results of the study formulated in Section 2.3 of this thesis and the literature survey section which revealed. The summary of the study stated that there is no integrated platform based on more than one evaluation perspectives that has been implemented so far in the field of image dehazing.

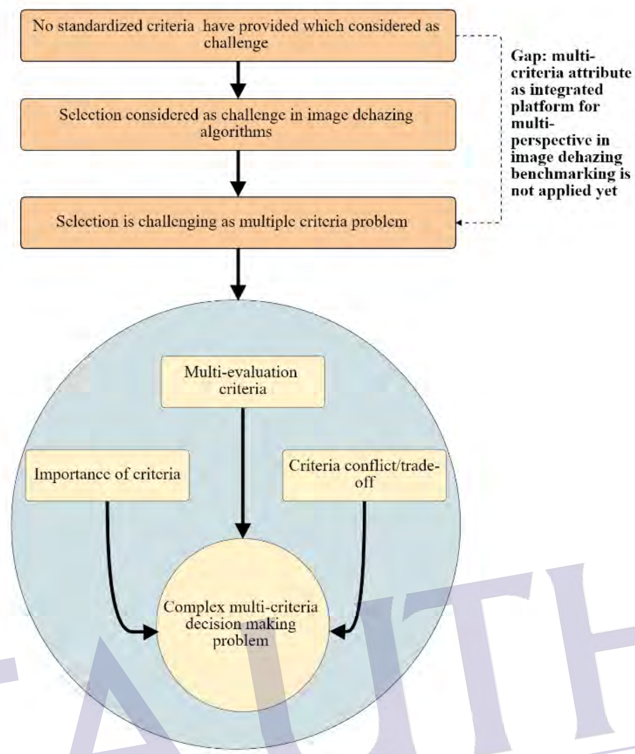

Figure 1.2: Research problem

1.4 Research Questions

The following research questions have been framed to set the direction for this research:

i. What are the criteria used for selecting the best image dehazing algorithm?

ii. Are there any standard criteria for evaluation and benchmarking of image dehazing algorithms?

iii. Is the consensus been reached between the scholars on a specific set of images dehazing evaluation criteria?

iv. What are the evaluation perspectives that should be considered in any particular evaluation and benchmarking scenario in image dehazing domain?

v. What are the requirements to develop benchmarking framework?

vi. Is there a reliable evaluation and benchmarking approach for image dehazing algorithms?

vii. Is there any evaluation and benchmarking scheme that has adopted more than one evaluation perspectives in an integrated platform to select the best algorithm?

viii. How reliable is the developed framework to select the best algorithm?

1.5 Research Objectives

This study aims to help developers, researchers, and the community of image dehazing domain to make reliable and efficient evaluation for a particular algorithm. It introduced improvements on the selection process for the best algorithm among compared ones by designing a new framework that can handle the issues reported in the literature review. Therefore, the main goal of this research is to design and develop an efficient evaluation and benchmarking framework based on image dehazing scenarios. The objectives of this study are emphasized on the development portion (our main contributions) as follows:

i. To propose a hybrid standardization model of image dehazing criteria based on Fuzzy Delphi method (FDM) and statistical evaluation method.

ii. To propose a multi-perspective decision matrix module based on intersection of 'standardized criteria' and 'image dehazing algorithms'.

iii. To develop a new image dehazing benchmarking framework based on the proposed decision matrix module using MCDM techniques.

iv. To validate and evaluate the developed image dehazing benchmarking framework based on mean deviation, standard dataset, and benchmarking checklist.

1.6 Connections among Research Objectives, Questions, and Problems

In this section, all research questions have been answered by the research objectives. Each objective is linked to one or two questions. The specific and general problems are linked to more than one research objectives and questions. Table 1.1 presents the connection amongst research objectives, research questions, the specific problem, and general problem.

Table 1.1: Connection amongst Research Objectives, Questions, and Problems

Research objectives	Research questions	Specific problem	General problem
1. To propose a hybrid standardization model of image dehazing criteria based on Fuzzy Delphi method (FDM) and statistical evaluation methods.	1. What are the criteria used for selecting the best image dehazing algorithm? 2. Are there any standard criteria for evaluation and benchmarking of image dehazing algorithms? 3. Is the consensus been reached between the scholars on a specific set of images dehazing evaluation criteria?	Determine the appropriate criteria	Standardization problem
2. To propose a multi-perspective decision matrix module based on intersection of 'standardized criteria' and 'image dehazing algorithms'.	4. What are the evaluation perspectives that should be considered in any particular evaluation and benchmarking scenario in image dehazing domain?		Multi perspectives DM for Evaluation and benchmarking problem
3. To develop a new image dehazing benchmarking framework based on the proposed decision matrix module using MCDM techniques.	5. What are the requirements to develop benchmarking framework? 6. Is there a reliable evaluation and benchmarking approach for image dehazing algorithms? 7. Is there any evaluation and benchmarking scheme that have been adopted more than one evaluation perspective in an integrated platform to select best algorithm?	• Trade off criteria and conflicting criteria. • Importance of criteria. • Multi evaluation criteria.	Selection problem (Benchmarking)
4. To validate and evaluate the developed image dehazing benchmarking framework.	8. How reliable is the developed framework to select the best algorithm?		

1.7 Research Scope

The research was designed to solve the problem of standardization and benchmarking in image dehazing. The designated research method utilized to standardize, select, evaluate, and adopt a suitable multi-criteria scoring was the experimental analysis. The output of this study was a framework performed via several experiments. This framework can be used in the process of standardization and benchmarking in image dehazing and its relevant applications.

The domain of this study included three dimensions, specifically image processing, experts' system, and decision support system. Regarding the image processing domain, the image dehazing algorithms were the case study and considered among the image processing majors as they use the restoration and enhancement principles. As the proposed framework was developed based on multi-criteria decision-making techniques, the research domain involved experts' system and decision support system.

Further considerations were taken in this study as follows:

i. As mentioned in the previous section, this study concentrates on development in the direction of standardization and benchmarking or in other words, image quality assessment (IQA). Thus, this study is not concerned with the development of new image dehazing algorithm.

ii. The standardization process was based on all defined criteria in the existing literature and excluded other criteria that either fail to specify which type of distortion can be measured or are unable to quantify visual distortion. Those metrics that are only used in underwater IQA were also excluded.

iii. The evaluation and benchmarking process were restricted to case studies based on over-land scenes rather than underwater scenes and at the same time focused only on image datasets rather than video datasets.

iv. Evaluation and benchmarking study were applied on real images rather than virtual images.

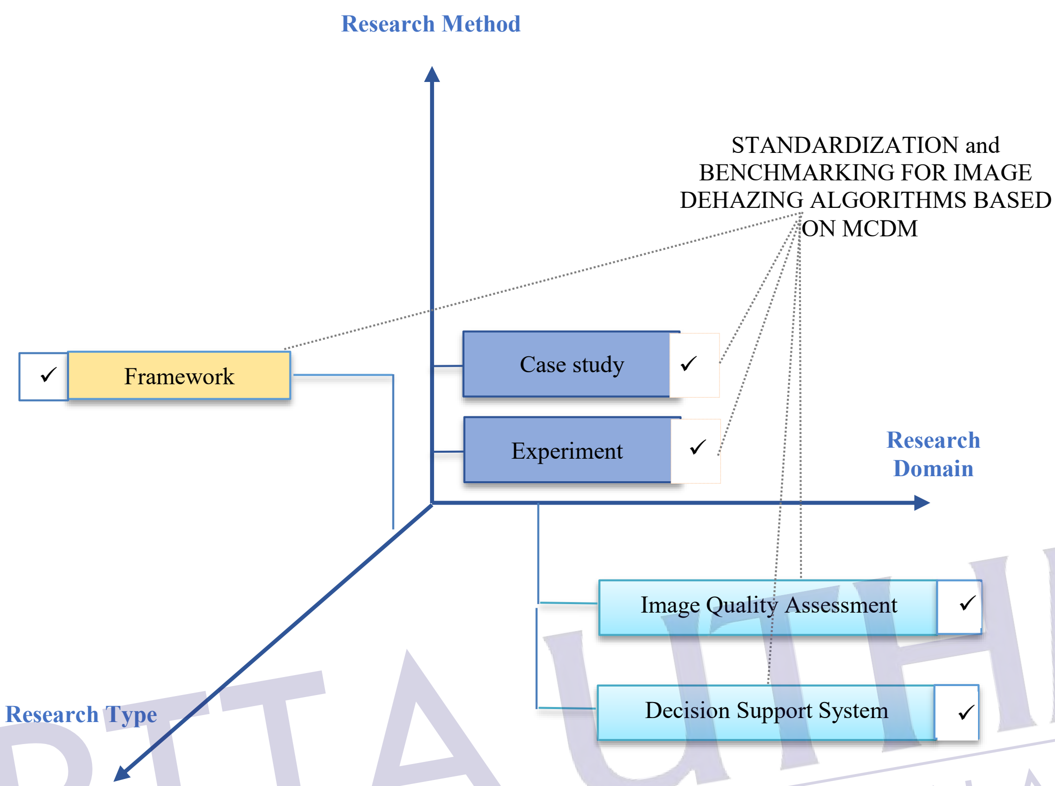

Figure 1.3: Scope of study

1.8 Significance of Study

The evaluation and benchmarking framework can assist the developers of real-time application to select the best algorithm for the proposed application. Researchers and developers can also compare their proposed algorithms under the same evaluation protocol (criteria), thus guaranteeing that the proposed work is compared to most key performance measures. Furthermore, developers or researchers can focus on adopting benchmarking framework in order to implement the online benchmarking systems. To summarize, due to the usage of image dehazing algorithms as a preprocessing stage for different industry applications, a reliable evaluation and benchmarking process can guarantee that the adopted image dehazing algorithms meet the required performance which can enhance the reliability of these applications. A huge number of image dehazing applications include underwater applications, military applications, road and traffic applications, image segmentation, image annotation, image matting, remote sensing (measurements) applications, power plant monitoring, unmanned aerial vehicle (UAV) applications, and runways and hazards' detection (aviation safety). The benchmarking and evaluation process of image dehazing algorithms is significant to recommend the most suitable adopted algorithm for the mentioned applications.

This study has contributed through adopting a systematic literature review approach to provide an overview of existing information and proofs with respect to image dehazing algorithms and their evaluation and benchmarking approach, as well as highlighting the trends of research work on this topic. This study has also contributed in filling the lack of research in this area. The proposed taxonomy of the related literature in this study can bring several benefits as well. These include imposing an organization of sort on the mass of publications, sorting out those different works into a meaningful, manageable, and coherent layout, and providing all researchers with important insights into the subject field in several ways. Other important points of the proposed taxonomy are it outlines the potential directions of research in the field, reveals gaps in research, and maps the literature on image dehazing into distinct categories highlighting weak and strong features in terms of research coverage. In addition, this study has provided a guide to the most important criteria to be adopted to evaluate image dehazing algorithms.

1.9 Research Organization

This study consists of six main chapters as follows:

Chapter One provides the research background, research problem, research questions, research objectives, relationship between research questions, research objectives with research problems, research scope, and research significance.

Chapter Two discusses the existing literature on evaluation and benchmarking methods for image dehazing algorithms. Through this chapter, the core criteria for evaluation and benchmarking are identified and linked issues with these criteria are also described in detail. Furthermore, it examines image dehazing evaluation perspectives. Existing methods of evaluation and benchmarking are discussed with related problems and issues. This chapter also includes the theoretical background of multi-criteria decision making (MCDM) in detail, presents the popular MCDM methods, and explains the main two MCDM methods: Best-Worst Method and VIKOR method. In addition, the theoretical background covers the most common standardization techniques which are Fuzzy-Delphi Method (FDM) and statistical evaluation of image dehazing criteria. The main purpose of this chapter is to figure out the research gaps and challenges as well as proposing the recommended solution.

Chapter Three describes the development requirements of the proposed standardization and benchmarking framework for image dehazing algorithms as well as the phases followed. The methodology is designed in five key phases: preliminary study, standardization, decision matrix construction, development, and evaluation and validation. Through the phases, this chapter presents in detail how the five research objectives were achieved.

Chapter Four presents the results and discussion of the standardization process for the image dehazing evaluation criteria. The chapter demonstrates how the results of the proposed framework resolved the issues relevant to image dehazing criteria mentioned in the problem statement and Chapter Two.

Chapter Five presents the results and discussion of the benchmarking framework for image dehazing algorithms. The chapter determines how the results of the proposed framework tackled the issues mentioned in Chapters One and Two. This chapter also describes the results of evaluation and validation process.

Chapter Six concludes and summarizes the research contributions made. Furthermore, the research limitations, further research proposals, and conclusion are reported.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a detailed literature review as background for this research. Section 2.2 presents a systematic review protocol for the area of image dehazing, followed by sections of second layer of the taxonomy namely, Section 2.3 studies conducted on image dehazing, Section 2.4 review and survey, and Section 2.5 developments of real time scenario based. Section 2.6 introduces critical review on studies conducted in the direction of image dehazing evaluation. Section 2.7 covers all type of image dehazing algorithms. In Section 2.8 illustrate evaluation perspectives in image dehazing area. Section 2.9 describes all evaluation criteria and sub criteria. Section 2.10 highlights challenges and issues in the benchmarking of image dehazing algorithms. In Section 2.11 discusses MCDM in terms of definitions, advantages, challenges, techniques, and its application. Furthermore, defines the standardization in terms of Fuzzy Delphi and statistical evaluation methods. Finally, Section 2.12 presents a summary of the chapter. However, Figure 2.1 summarized the main sections in this chapter.

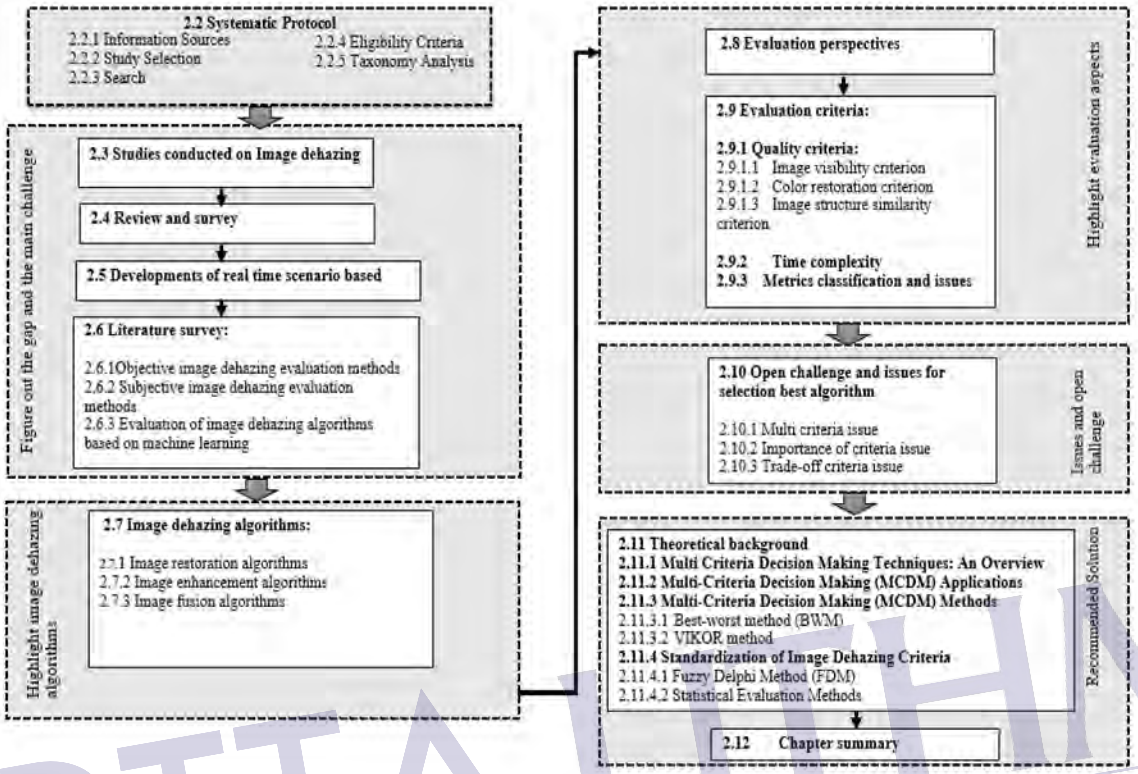

Figure 2.1: Literature review framework

2.2 Systematic Review Processes

Systematic reviews (SRs) are a type of secondary research, which refers to the analysis of data that have already been collected through primary research with a view to present an SLR (systematic literature review)[41]. SRs have been proposed as a type of research methodology that should be acceptable as the basis for a graduate research thesis[42], [43]. According to [44] The understanding of the significance of SRs and their methods could lead to greater acceptance of SRs as a form of study on the basis of a PhD thesis. Thus, systematic review has considered very important and valuable aspect in the academic sector. This section describes the processes of systematic review that involved to highlight the articles related to this study, further details discussed in the next subsections.

2.2.1 Information Sources

In terms of systematic search, we have chosen three types of most popular online search engine databases: Web of Science (WOS), Science Direct (SD) and IEEE Xplore digital library. The selection has established according to the index that eases and formulates a simple and complex search query, and especially monitors numerous journals and conference papers in sciences, computer science, and social science. The motivation behind this selection is to include as much as possible the literature that covered maximum number of articles that related Image dehazing and technical ones and provides a holistic view of researchers' achievements in a broad, but pertinent, variety of disciplines.

2.2.2 Study Selection

The technique of study selection has involved exhaustive search of related articles which is premise on two ladders. Initially, exclude the irrelevant and duplicated articles by means of scanning the titles and abstract, what's more, filtered the articles that have scanned in previous step through full text reading. Both stages have applied the same eligibility criteria.

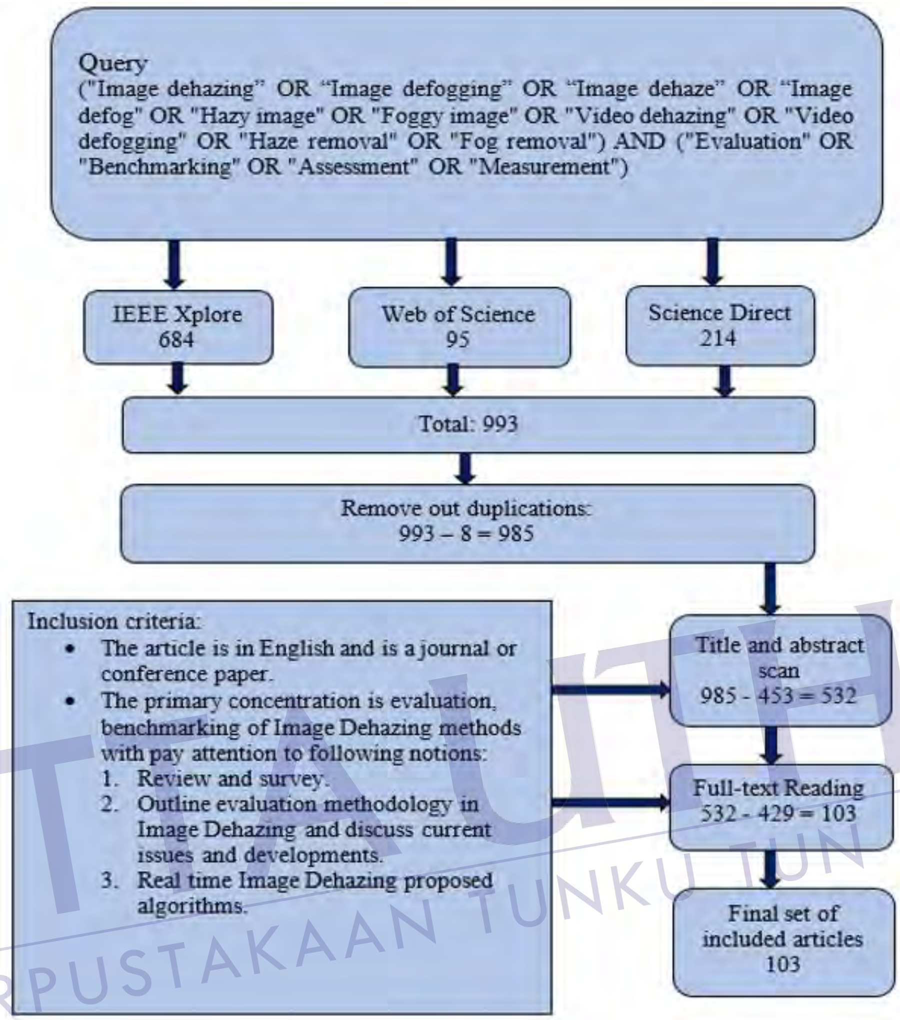

Figure 2.2: A study selection diagram

2.2.3 Article Searching Process

Articles searching process have launched on 08 March 2018, the search query was premise on the IEEE, WOS and SD databases via their search boxes. In all mentioned databases, searching have established by key in the terminologies ("image dehazing" OR "image defogging" OR "image dehaze" OR "image defog" OR "hazy image" OR "foggy image" OR "video dehazing" OR "video defogging" OR "haze removal" OR "fog removal") that combined later through "AND" operator with following keywords ("Evaluation" OR "Benchmarking" OR "Assessment" OR "Measurement") see Figure 2.2. The preferences of advanced search in each engine have employed to exclude chapters of books and other types of documents, and to select only journals and conference papers. Furthermore, we took into account the studies that were most undoubtedly immersed in latest and suitable scientific research related to our study.

2.2.4 Eligibility Criteria

Entirely articles that matched the criteria showed in Figure 2.2 were included. We have placed a primary goal of mapping the compass of research on Image dehazing into a wide-ranging and coarse-grained taxonomy of three groups. The groups were procured from comprehensive pre-review of the exiting literature with no restriction. Subsequently, the elimination of replicated articles, we excluded articles that did not match the eligibility criteria. The exclusion criteria have involved consecutive points: (1) the article is non-English; (2) the focus is on limited aspects of Image dehazing such non-real time methods;

2.2.5 Output of Searching Process

The first run of the search query reached 993 articles with following details: 684 IEEE Xplore search engine, 214 ScienceDirect and 95 articles from Web of Science, over a period of 10 years, exactly since 2008 until 2018. Eight articles are the duplicated ones have found among three exploited databases. Through title and abstract scanning, 453 articles have excluded as non-related ones, resulting in 532 articles. After finalizing the full text reading step, again 429 articles were excluded. To end, all previous phases have brought out 103 articles as final set of articles. Those articles have examined carefully in order to obtain a generic research overview on this emerging area. Even though, a variety of studies have emphasized on the same area. The categorization of articles has done based on the aim of the study and utilized to serve the process of a taxonomy formation.

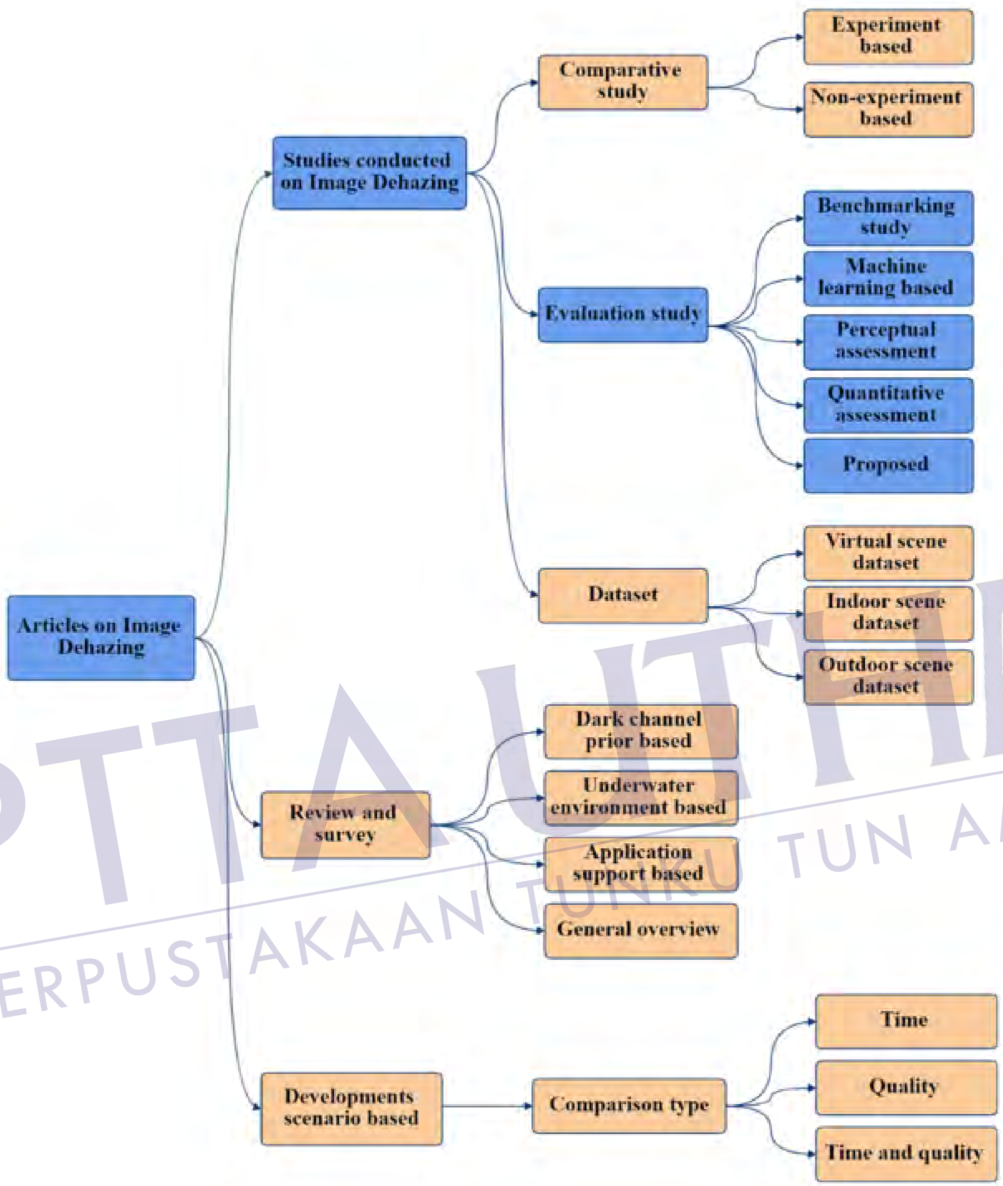

Figure 2.3: A taxonomy of research literature on Image Dehazing

Figure 2.3 shows the proposed taxonomy to review the research articles that focusing on Image dehazing. As a result, three types of article category have produced in the obtained taxonomy as follows: first, out of 103 studies, only 23 articles have focused on various studies that conducted on Image dehazing field such as comparative study of different Image dehazing algorithms, multiple evaluation methods and proposed metrics, and different datasets that based on diverse scenes and circumstance. Second, the next articles group namely, review and survey have included 11 studies that reviewed different aspects such as, multiple methods based on dark channel model, underwater Image dehazing metrics and methods, suitable method for driver assistance system, and comprehensive investigation in Image dehazing field. Third, the majority of articles have taken a place in the taxonomy is development category with 69 articles, which mainly based on methods that have concerned with real time scenario. Through aforementioned outlines, we indicated the generic categories of articles and reformed the classification into the literature taxonomy, as shown in Figure 2.2. We also illustrated numerous of subcategories in the main classes without any overlaps. The further sections will describe the perceived categories and give a simplified associated statistic.

2.3 Studies Conducted on Image Dehazing

Generally speaking, the Image dehazing literature have focused mainly on development of new methods. The second largest articles group have presented diverse studies (23/103) have conducted on Image dehazing. We divided the included works into three main sub-categories, comparative study (3/23), evaluation study (13/23), and dataset-based study (7/23). Comparative studies have presented into experiment based study [9], [45], and non-experiment based [46]. These three studies have compared prevalent approaches in this area through implementation of the methods and using most common parameters for critical analysis, on other hand, one study have compared some well-known visibility enhancement techniques without further implementation.

The largest group of articles in this section is evaluation category (13/23) which is basically introduced through different evaluation types and techniques. A benchmarking study [35] have compared the performance of different techniques for underwater autonomous vehicles where no additional hardware ,computation time and simple inputs are the most preferred characteristics. A machine learning techniques for assessing the quality of dehazed image have introduced through two studies, a novel quality assessment framework for the performance ranking of Image dehazing algorithms [31] and relative quality ranking between enhanced images rather than giving an absolute quality score for a single enhanced image [47].

Existing works have reported that image quality assessment methods mainly divided into two types, first, a subjective (perceptual) assessment which is involves psychophysical experiments where human observers are asked to grade a set of images according to a given quality criterion in order to offer agreement among observers on the quality of both haze free images and dehazed ones [48], [30]. Another type of well –known image quality assessment is quantitative (objective) assessment which is the essential element in the evaluation of perceived images quality. Also, quantitative evaluation is more structured and reliable than subjective evaluation. This tool usually uses the objective criterion and offer an identified procedure for measure the quality of image. Moreover, this method deals only with numeric results and any user wants to use this method will get the same result [19].

Even with popularity of quantitative assessment but there is a necessity of developing more consistent methods of objective evaluation in order to provide more accurate judgements on image dehazing algorithms [23]. Finally, several methods and metrics of image quality assessment have proposed. First, a method based on circularly symmetric Gaussian normalization procedure visible edges feature which does not require exposure to distorted images priori and training [20]. Second, a quantitative assessment method based on two optimization objectives is introduced where several aspects took into consideration for evaluation such as the effects of dehazing process color distortion, and halo artifacts in resorted image [49]. Third, a combination of three new methods (contrast measurement index (e), the color naturalness index CNI and color colorfulness index (CCI)) for assessing the defogging algorithm [38], a new metric based on underwater scattering and absorption aspects [50], an evaluation metric combining the contrast degree with the structural similarity [51], and a novel no-reference haze assessment method based on haze distribution is proposed for remote sensing images [52].

In terms of support the evaluation process and development of new Image dehazing algorithms a few datasets have presented in three uniforms (7/23).Virtual scene dataset, which is basically created by utilizing computer graphics methods to produce an enormous amount of hazy images dataset (2000 images) that based on road scenes with different levels of fog [53]. Indoor scene datasets have established through using real scene inside a room with fog machine generator 9 images [54], 1400+ images [55], and controlled underwater environment images through using milk to obtain turbidity in a water tank [56]. For outdoor scene datasets there are two scenarios, a database that consisting of natural scenes in outdoor uncontrolled conditions 5640 images [57] and 3464 images [58], and synthetic outdoor dataset which is created through synthesize haze in real images with complex and multiple scenes [59].

2.4 Review and Survey

Image dehazing review articles aimed to point out the new development and give a comprehensive view for image dehazing scholars. Hereinafter, the smallest number of articles in the taxonomy consist of reviews and surveys of the literature on image dehazing (11/103) articles. These articles were classified based on their support such as application support based. Not apart from this context, dark channel prior is the most popular image dehazing model because of its adequate performance and promise for more improvements and applications. Authors in [60] had studied the approaches based on dark channel prior (DCP) model. Two articles [61, 62] reviewed the latest methods that have been effectively applied in the underwater environment, exhibited the performance of underwater image dehazing and color restoration with different methods, developed an underwater image color evaluation metric, and highlighted different underwater image applications.

Only one article [63] in the existing literature reviewed state-of-the-art image enhancement and restoration methods for a suitable approach for the vision based driver assistance system. The majority of surveys and review articles were based on general views of image dehazing (7/11). These articles examined and summarized different methods in image dehazing area such as image enhancement methods, physical model restoration methods, and fusion based visibility enhancement techniques [4],[64-66]. The methods were also categorized based on the types of technique used for acquiring information needed by image restoration process such as multiple-image methods,

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