PRIOR-BASED OPTIMIZATION APPROACHES FOR SINGLE IMAGE DEHAZING

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THESIS CERTIFICATE

This is to certify that the thesis titled **Prior-based Optimization Approaches for Single Image Dehazing**, submitted by **Sidharth Gautam**, to the Indian Institute of Technology, Delhi, for the fulfillment of the requirements for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

A hazy environment obscures visibility and hinders the performance of many computer vision tasks. The process of removing haze using a single image and compensating for the attenuated radiance is known as *single image dehazing*. Retrieving haze-free results using a single image is an ill-posed and under-constrained problem due to the lack of information such as the transmittance-map (i.e, T-map) and the global air-light vector (A_∞). This research aims to develop *novel priors and boundary constraints using statistical/physical properties or heuristic assumptions to forecast the unknown information required for dehazing*. To this aim, we propose dehazing techniques for restoring visibility in aerial, terrestrial, and underwater imaging under diverse illumination and haze conditions. We begin with an introduction to the dehazing problem and provide a literature review of the related works to investigate the challenges and the ambiguities associated with haze-free image retrieval. Unmanned Aerial Vehicle (UAV) based imagery provides a valuable source of information for both the consumer and computational photographers. But unfortunately, these images are often obfuscated by many factors such as clouds occlusion, poor atmospheric illumination, unpleasant weather conditions, and the limited imaging capability of the UAVs. To retrieve the visibility in aerial imaging, a model-based dehazing scheme using radiance *boundary constraint and graph model* has been proposed. In dehazing, the over-estimation of air-light causes darker and visually unpleasant results, while its under-estimation destroys subtle details from the bright regions such as the sky. Therefore, the accurate estimation of the global air-light to approximate the haze thickness is critical for improving the micro-level visibility. For advanced dehazing performance, a novel statistical prior called *color constancy prior (i.e., CCP)* has been proposed to improve the robustness of air-light estimation under varicolored illumination. Furthermore, adapting the local-patch under different hazy conditions is considered an open research problem in dehazing. To resolve this, a novel self-adaptive prior named *weighted median channel prior (i.e., WMCP)* has been proposed that works by leveraging the spatially changing haze statistics and selecting the optimal local-patch corresponding to the haze density of the input image, which conventional methods frequently fail to do. In addition, a follow-up technique called *Edge Modulation*, has been proposed to repair details lost due to haze. Many image priors and assumptions used in the conventional dehazing frameworks have significant inconveniences as they impose hard bounding constraints for the problem's solution and may not always produce distortion-free results under varying haze conditions. To tackle this, an iterative optimization approach is proposed to effectively estimate & regularize the T-map. The utility of the proposed methodology is to solve the dark channel's hard zeroing constraint without brute-forcing a highly non-convex equation by introducing a novel energy function that stabilizes the process of T-map estimation in haze images. Extensive experimental results on both real and synthetic haze datasets demonstrate the dehazing efficacy of the proposed method with many other progressive techniques.

सार

एक धुंधला वातावरण दृश्यता को अस्पष्ट करता है और कंप्यूटर विज़न से संबंधित कार्यों के प्रदर्शन में बाधा डालता है। एकल छवि का उपयोग कर धुंध को हटाने और क्षीण हुई दृश्य चमक को पुनः प्राप्त करने की प्रक्रिया को Single Image Dehazing कहा जाता है। Dehazing के लिए उपयुक्त कारक जैसे संचरण-मैप (अथार्थ, T-मैप) और वैश्विक वायु-प्रकाश (A_∞) को एकल छवि का उपयोग करके धुंध-मुक्त परिणाम प्राप्त करने के लिए अनुमानित करना एक गंभीर समस्या है। इस शोध का उद्देश्य dehazing के लिए आवश्यक अज्ञात कारको का पूर्वानुमान लगाने के लिए *सांख्यिकीय/भौतिक गुणों या मान्यताओं* का उपयोग करके नए prior और boundary constraints को विकसित करना है। इस उद्देश्य के लिए, हम विविध रोशनी और धुंध की स्थिति के तहत हवाई, स्थलीय और पानी के नीचे इमेजिंग में दृश्यता बहाल करने के लिए डीहेजिंग तकनीकों का प्रस्ताव करते हैं। हम एकल छवियों मे धुंध समस्या के परिचय के साथ शुरू करते हैं और धुंध-मुक्त छवि पुनर्प्राप्ति से जुड़ी चुनौतियों और अस्पष्टताओं की जांच के लिए संबंधित कार्यों की एक साहित्य समीक्षा प्रदान करते हैं। मानव रहित हवाई वाहन (यानी, यूएवी) आधारित इमेजरी उपभोक्ता और कम्प्यूटेशनल फोटोग्राफर दोनों के लिए सूचना का एक मूल्यवान स्रोत प्रदान करती है। लेकिन दुर्भाग्य से, इन छवियों को अक्सर कई कारकों से बाधित किया जाता है जैसे कि बादलों का आना, खराब वायुमंडलीय रोशनी, अप्रिय मौसम की स्थिति और यूएवी की सीमित इमेजिंग क्षमता। हवाई इमेजिंग में दृश्यता को पुनः प्राप्त करने के लिए Boundary Constraint and Graph Model का उपयोग करके एक dehazing तकनीक प्रस्तावित की गई है। Dehazing में, वैश्विक वायु-प्रकाश का अधिक अनुमान गहरा और अप्रिय परिणाम देता है, जबकि इसका कम आकलन आकाश जैसे उज्ज्वल क्षेत्रों से सूक्ष्म विवरण को नष्ट कर देता है। इसलिए, धुंध की मोटाई का अनुमान लगाने के लिए वैश्विक वायु-प्रकाश का सटीक अनुमान सूक्ष्म स्तर की दृश्यता में सुधार के लिए महत्वपूर्ण है। उन्नत डीहेजिंग प्रदर्शन के लिए, एक नया सांख्यिकीय जिसे color constancy prior (यानी, CCP)} कहा जाता है, को विविध रोशनी के तहत वायु-प्रकाश अनुमान की मजबूती में सुधार करने के लिए प्रस्तावित किया गया है। इसके अलावा, अलग-अलग धुंध परिस्थितियों में स्थानीय-पैच को T-मैप और एयर-लाइट को अनुमानित करने के लिए अनुकूलीत करना भी डीहेजिंग में एक शोध समस्या माना है। इसे हल करने के लिए, weighted median channel prior (यानी, WMCP)} नामक एक स्व-अनुकूली तकनीक प्रस्तावित की गई है जो स्थानिक रूप से बदलते धुंध के आंकड़ों का लाभ उठाकर काम करती है और इनपुट छवि के धुंध घनत्व के अनुरूप इष्टतम स्थानीय-पैच का चयन करती है, जो पारंपरिक तरीके अक्सर करने में विफल होते हैं। इसके अलावा, धुंध के कारण खोए हुए विवरणों की मरम्मत के लिए edge modulation नामक एक अनुवर्ती तकनीक का प्रस्ताव किया गया है। पारंपरिक डीहेजिंग फ्रेमवर्क में उपयोग किए जाने वाले कई priors and assumptions में महत्वपूर्ण असुविधाएँ होती हैं क्योंकि वे समस्या के समाधान के लिए कठोर बाध्यताएँ लगाते हैं और अलग-अलग धुंध स्थितियों के तहत हमेशा विरूपण-मुक्त परिणाम उत्पन्न नहीं कर सकते हैं। इससे निपटने के लिए, T-मैप को प्रभावी ढंग से नियमित करने के लिए एक पुनरावृत्त अनुकूलन दृष्टिकोण का प्रस्ताव है। प्रस्तावित कार्यप्रणाली की उपयोगिता एक novel energy फ़ंक्शन को पेश करके non-convex equation को मजबूर किए बिना dark channel की हार्ड शून्यिंग बाधा को हल करना है जो धुंध छवियों में T-मैप अनुमान की प्रक्रिया को स्थिर करता है। वास्तविक और सिंथेटिक धुंध डेटासेट दोनों पर व्यापक प्रयोगात्मक परिणाम कई अन्य प्रगतिशील तकनीकों के साथ प्रस्तावित विधि की dehazing प्रभावकारिता को प्रदर्शित करते हैं।

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ABBREVIATIONS

DCP	Dark Channel Prior
CLP	Color Line Prior
CEP	Color Ellipsoid Prior
HLP	Haze Line Prior
AIP	Atmospheric Illumination Prior
FADE	Fog Aware Density Evaluator
ATTF	Adaptive Trigonometric Transformation Function
RHEDCT	Regularized-Histogram-Equalization and Discrete-Cosine-Transform
CCP	Color Constancy Prior
MCP	Median Channel Prior
WMCP	Weighted Median Channel Prior
AOD-Net	All-in One Dehazing Network
FAMED-Net	Fast and Accurate Multi-Scale End-to-End Dehazing Network
DCPDN	Densely Connected Pyramid Dehazing Network
CNN	Convolutional Neural Network
DCNN	Deep Convolutional Neural Network
MSCNN	Multi-scale Convolutional Neural Network
DRL	Deep Residual Learning
GFN	Gated Fusion Network
GAN	Generative Adverserial Network
EPDN	Enhanced pix2pix Dehazing Network
DD-CycleGAN	Double-Discriminator Cycle-Consistent Adversarial Networks
GIF	Guided Image Filter
LSTM	Long Short Term Memory
HQS	Half-Quadratic Splitting

NOTATION

I	Hazy Image
J	Haze-free Image
B	Image luminosity
$\mathbf{x}$	Pixel Coordinates
A_∞	Global air-light
β	Scattering coefficient of the medium
d	Scene-depth
T	Transmission-map
$\hat{T}$	Estimated Transmission-map
$\mathbb{R}$	Set of Real numbers
Ω	Local-patch
$\mathbb{N}$	Total number of pixels in image
min	Minimum filter
max	Maximum filter
med	Median filter
φ	Small positive value for computational stability
c	color-channel
K_B	Brightest pixel set
K_b	Brighter pixel set
σ	Standard deviation of the input haze image
$\ominus$	Erosion operator
ζ	Square structuring element
E_m	Edge-modulation term
Υ	Edge-modulation index
δ	Exponent parameter
$\mathcal{K}$	Laplacian kernel
λ	Unsharp masking parameter
$\mathcal{K}$	Laplacian kernel
U	Identity matrix