Maritime surveillance image enhancement: a comparison and improvement of dehazing techniques

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Abstract—**The dehazing problem where different atmospheric particles brings certain amount of noise to images is very important in outdoor video surveillance systems. This paper compares the most significant single image dehazing approaches, proposes additional enhancement step in dehazing algorithms, and presents test results on maritime surveillance images that represents one group of long-range images.**

Index Terms—**dehazing; image enhancement, surveillance imaging, long-range imaging.**

I. Introduction

Image enhancement techniques have been widely used in various image processing applications where the subjective quality of images is important for human interpretation. The presence of haze directly influences visibility of the scene, by reducing contrast and obscuring objects visibility. The definition of a haze is "a slight obscuration of the lower atmosphere, typically caused by fine suspended particles" [1]. It can be caused by various types of particles, like fog, mist, dust, rain, snow… The haze influence on scene visibility is directly correlated with scene depth – far objects visibility is more obscured than near objects visibility (Fig. 1).

Fig. 1 Typical hazy image

The haze problem, because of its nature, is very important in outdoor video surveillance systems. There is a continuous need for surveillance video enhancement, especially for scenes taken under bad weather conditions and/or scenes that contain objects at distant ranges from surveillance sensor, which are obscured by atmosphere turbulences. There are two types of video enhancement techniques in such systems – online and offline video enhancement. Online video enhancement is performed in real-time, while offline video enhancement can be applied to a video segment taken in some specific circumstances, for example, triggered by some predefined events like new object appearance in the scene.

The haze removal is especially important for multi-sensor electro-optical monitoring and surveillance systems that integrate various high definition imaging sensors and provide ultra-long range target detection, recognition and identification based on sensors, optics and image processing. These systems are designed to detect various objects at very large distances (more than 20km), where the influence of various atmospheric disturbances is very high.

The haze removal algorithms can be applied directly on a row image signal, prior to the compression, in processing units embedded at the multi-sensor platforms. It can also be performed prior to the image stabilization algorithms, which are very important for long-range imaging systems. The dehazing algorithms help the system to get the most of features from the images, which are used for image stabilization (for example, corners presented on image scene).

The driving force and final goal of this research is to find dehazing solution that is suitable for real-time high resolution multi-sensor electro-optical maritime surveillance systems.

This paper compares the most significant single image dehazing approaches [2] [3] [4], proposes an additional enhancement step in dehazing algorithms, and presents test results on maritime surveillance images[1] (Fig. 2), that represent one group of long-range images.

The paper also considers usage of prior-based single image dehazing algorithms for offline and online video processing.

Fig. 2 Maritime surveillance hazy images examples

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[1] Maritime surveillance images used in this paper are obtained with VLATACOM Multi Sensor Imaging System 2 [16]

The paper is organized as follows. The Section II describes the image dehazing problem, including the existing approaches, the haze imaging model and the dehazing problem formulation, together with typical dehazing algorithm components. Section III presents statistical and visual comparison of the tested dehazing methods. The Section IV proposes an additional enhancement step to the exisiting approaches and presents visual results for this additional step. The Section V lists conclusions and future work in this research area.

II. Image Dehazing Problem

A. Existing approaches

The dehazing problem is a typical computer vision problem. All the existing approaches, in order to dehaze a single image, require some additional information regarding the image itself, like additional images of the same scene, or adoption of some priors related to hazy image settings. The existing approaches can be categorized as follows [2]:

- Multi-image approaches – The approaches where multiple images of the same scene, taken under different settings (like polarization), are required. We found these approaches unsuitable for real-time applications.
- Prior-based approaches – The approaches where all data required for dehazing is present on the hazy image itself. These approaches impose extra constraints using some "priors" – some knowledge or assumptions known beforehand. The main goal of these approaches is to find a suitable prior. A prior can be some statistical/physical properties, or heuristic assumptions.

The multi-image approaches require strict scene conditions, which may not be available in practice – they fail in processing dynamic scenes, especially taken by moving camera [2]. Because of this, together with the additionally required processing time and setup complexity, we found prior-based approached more suitable for real-time applications.

There are three most important prior based approaches for color image dehazing:

- Dark channel prior (DCP) model, originally proposed in [2] by He et al., and significantly improved in [5], by the same group of authors. It is based on certain statistics of haze-free outdoor images - the authors assume that in most of the image local regions which do not cover the sky, very often some pixels have very low intensity (close to zero) in at least one RGB color channel. A number of variants of the original DCP model has been proposed in the literature [6] [7] [8] [9] [10] [11] [12] [13] [14].
- Color attenuation prior (CAP) model [3], proposed by Zhu et al. constructs a linear relationship between the scene depth and the hazy image, with parameters of the model learned by a supervised method.
- DehazeNet (DNET) model [4], proposed by Cai et al., utilizes a trainable CNN (Convolutional Neural Network) based end-to-end system for medium transmission estimation. DehazeNet takes a hazy image as input, and outputs its medium transmission map that is subsequently used to recover the haze-free image.

B. Haze Imaging Model

The *haze imaging equation* is given by:

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

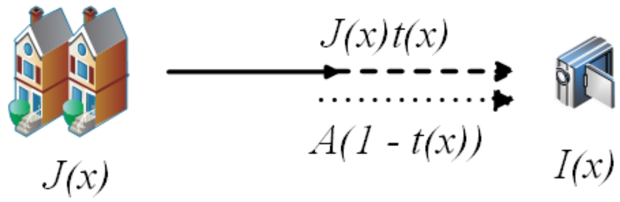

Fig. 3 Haze imaging model

where:

- *x = (x,y)* represents coordinates *(x,y)* of a pixel's position in the image; it is a 2D vector.
- *I* represent the hazy image; it is a 3D vector of the color (RGB) at a pixel.
- *J* represents the scene image radiance; it is a 3D RGB vector of the color of the light reflected by the scene; it represents the image that need to be reconstructed - the haze-free image.
- *t* is the transmission map or transparency of the haze; it is a 2D vector of scalars in the range [0, 1]; for example *t(x) = 0* means a completely hazy and opaque pixel, *t(x) = 1* means a haze-free pixel.
- *A* is the atmospheric light; it is a 3D RGB vector usually assumed to be spatially constant. It is often considered as "the color of the atmosphere, horizon, or sky"

The haze is formed by the particles in the atmosphere, like dust, sand, water droplets, or ice crystals absorbing and scattering light, like numerous tiny light sources. The term J(x)t(x) in (1) is called direct attenuation. The light reflected from an object is partially absorbed by the particles in the atmosphere and is attenuated. The airlight is due to particles playing the role of light sources.

Thickness of the haze t(x) is directly related to the scene depth - the distance of the scene objects to the observer d(x).

It is found that the haze transmission t is physically related to the depth d in a following manner:

$$t(x) = exp\left(-\int_0^{d(x)} \beta(z)dz\right), \tag{2}$$

where, β is the *scattering coefficient* of the atmosphere (determined by the physical properties of the atmosphere).

In all proposed dehazing approaches it is assumed that the physical properties of the atmosphere are homogenous - and the scattering coefficient β is a spatial constant, which leads to the following:

$$t(x) = exp(-\beta d(x)), \tag{3}$$

or equivalently:

$$d(x) = -\frac{\ln t(x)}{\beta}. \tag{4}$$

C. *Problem Formulation and Dehazing Procedures*

The goal of haze removal algorithms is the following: given the input hazy image *I*, recover the scene radiance image *J*, and usually *t* and *A*.

Based on the physical model described above, the typical dehazing workflow includes the calculation of transmission map and atmospheric light, which are used to restore the haze-free images.

The wide class of dehazing algorithms can be decomposed into three components (Fig. 4).

1. The <u>transmission map estimator</u> which is used to compute *t* in Equation (1).
2. The <u>atmospheric light estimator</u> which is used to calculate *A* in Equation (1).
3. The <u>haze-free image generator</u> which generates the haze-free image based on estimated *t* and *A*.

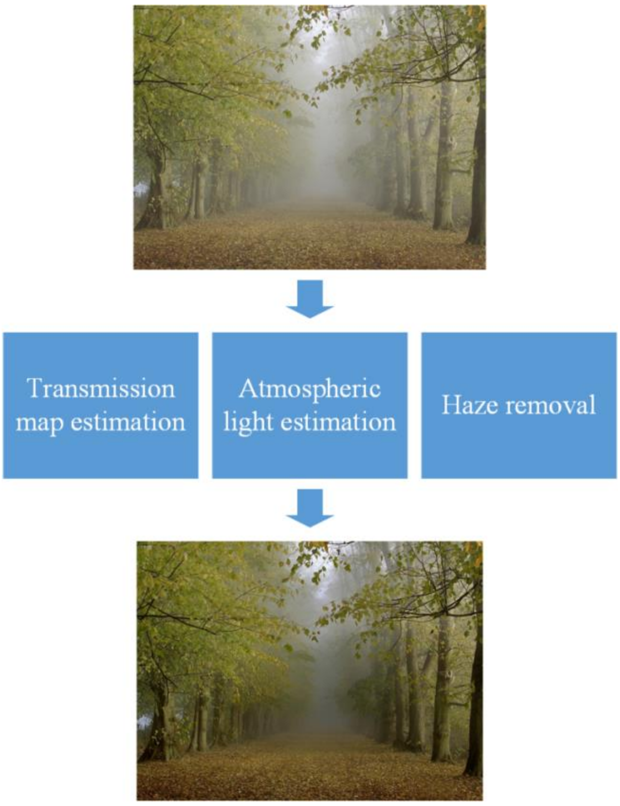

Fig. 4 Dehazing procedure

1) *Transmission Map Estimator*

Transmission map estimator computes the transmission map (or the depth map) by inputting a hazy image into a dehazing method. This part of algorithm is the most important and specific for every approach. It is also the most processing time consuming.

The DCP approach [2] estimates the transmission ***t(x)*** based on color channel I_c of hazy image *I*, and atmospheric light of color channel A_c by the following:

$$t(x) = 1 - \min_{y\in\Omega(x)}\left(\min_C \frac{I_C(y)}{A_C}\right). \tag{5}$$

The CAP approach [3] calculates the transmission map based on the linear coefficients ω_0, ω_1 and ω_2, the value channel *v* and saturation channel *s* by:

$$t(x) = \exp(-\beta(\omega_0 + \omega_1 v(x) + \omega_2 s(x))). \tag{6}$$

The DNET approach [4] directly estimates the transmission map from the hazy image, based on a previously trained CNN, called *DehazeNet*:

$$t(x) = \mathrm{DehazeNet}(I(x)). \tag{7}$$

The transmission map estimator also provides the basic processing data for the atmospheric light estimation. If the atmospheric light is required in the process on transmission map estimation, it is temporarily assumed that it takes the value of 1 [2].

2) *Atmospheric Light Estimator*

A common method to design the atmospheric light estimator is extracted from the physical model described in (1), in the following manner: when *t* tends to zero, (1) becomes$A = I(x)$. This shows that *A* can be estimated by *I(x)* at pixel *x* where *t(x)* is small enough:

$$A = I(x), \quad t(x) < t_{threshold}. \tag{8}$$

Given the described model in Equation (8), the atmospheric light estimator utilizes a hazy image and its estimated transmission map as an input for computation of the atmospheric light *A*.

In practice, all three described approaches [2] [3] [4] estimate the atmospheric light in the following manner:

- the algorithm picks the top 0.1 percent brightest pixels in the transmission map,
- the algorithm then selects the pixel with highest intensity in the corresponding hazy image *I* among these brightest pixels (on *t*) as the atmospheric light *A*.

3) *Haze-Free Image Generator*

Haze-free image generator generates the haze-free image *J* with previously estimated transmission map *t* and the atmospheric light *A*. *J* is computed from (1) as follows:

$$J(x) = \frac{I(x)-A}{t(x)} + A. \tag{9}$$

To avoid too much noise, *t(x)* is usually [2] [3] [4] restricted by a lower bound $t_0 = 0.1$:

$$J(x) = \frac{I(x)-A}{max\{t(x),t_0\}} + A. \tag{10}$$

Similar to the atmospheric light estimator, the haze-free image generator is common and generally used in the exiting dehazing methods [2] [3] [4].

III. Comparison of Image Dehazing Solutions

The described methods were tested on 100 hazy images in HD resolution (1280×720 pixels), on quad-core CPU. The main goal of this testing was to measure the average processing time of algorithm components for all three methods, in order to estimate whether they can be used for real-time video processing in surveillance systems. The results of this testing are given in the following table.

TABLE I
DEHAZING AVERAGE PROCESSING TIME COMPARISON

	DCP	CAP	DNET
Processing time (s)	4,52	4,26	8,73
Transmission map (%)	97	90	95
Atmospheric light (%)	2	6	3
Scene radiance (%)	1	4	2

The Table I shows that DNET is the most time consuming method, while CAP is the fastest algorithm, generally speaking.

The most time consuming process is the transmission map estimation, which takes more than 90% of processing time for all three approaches.

It can also be concluded that these methods cannot be used for real-time video processing in frame-by-frame processing manner without certain process parallelization. The optimal parallelization methods will be part of our future research goals.

IV. ADDITIONAL IMAGE ENHANCEMENT

Additionally, this paper proposes an additional image enhancement step that can be used with any existing dehazing approach. The proposed image enhancement method is an additional sharpening of image using the unsharp-mask technique [15]. The unsharp-mask method utilizes an adaptive filter in the correction path. The objective of the adaptive filter is to emphasize the medium-contrast details in the input image more than large-contrast details such as abrupt edges, so as to avoid overshoot effects in the output image [15]. This simple step takes around additional 3 seconds of processing time (HD images, quad-core CPU), but provides sharpened images, that visually look better than images dehazed without this enhancement step.

V. DEHAZING METHODS APPLIED TO MARITIME SURVEILLANCE IMAGES

The results of described dehazing methods applied to maritime surveillance images, and examples obtained with additional enhancement step after the original dehazing process, are presented on Fig. 5.

It can be concluded from these examples that the DCP method provides more details on the objects on the scene, but the other two methods (CAP and DNET) provide more real-life like images, where DNET has a more stable output.

It can also be concluded that the unsharp-mask brings a visible enhancement to the images, with an additional processing cost.

VI. CONCLUSION

The image dehazing problem, as a typical computer vision problem, is very important in outdoor surveillance systems, especially for long-range imaging, where there exists a strong need to extract as much of a detail as possible from images objects at long distances (for example more than 20km). The multi-sensor electro-optical monitoring and surveillance systems, that includes the maritime surveillance systems, are one typical example of long-range imaging systems.

From the results presented in this paper it can be concluded that the tested dehazing methods can be successfully used for offline video processing applications, in the frame-by-frame processing manner. These applications are usually triggered by some predefined events, like new object appearance in the scene, or sudden visibility degradation, caused, for example, by fog or smoke.

The application in real-time video processing systems requires process parallelization that should include usage of multi-core GPU units and FPGA platform. The optimal parallelization methods will be a part of our future research activities.

It can also be concluded that unsharp-mask brings visible enhancement of the images, with an additional processing cost, and that it can be used for video processing in offline mode.

The dehazing methods for real-time video processing will be part of our future research activities.

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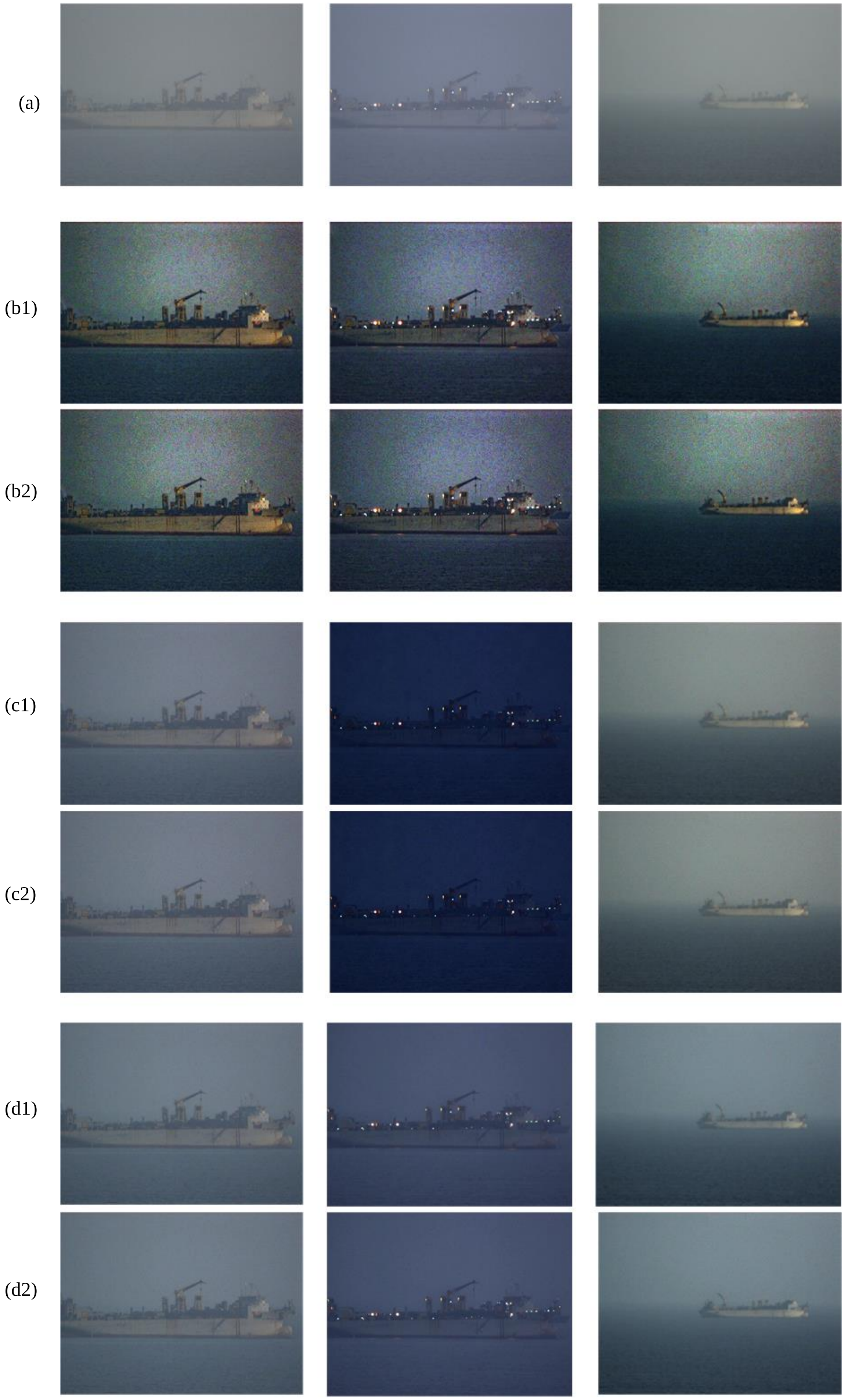

Fig. 5 Image dehazing and unsharp-mask: (a) original image, (b1) DCP, (b2) DCP&unsharp-mask, (c1) CAP, (c2) CAP&unsharp-mask, (d1) DNET, (d2) DNET&unsharp-mask