SINGLE IMAGE RESTORATION USING SCENE AMBIENT LIGHT DIFFERENTIAL

Yan-Tsung Peng and Pamela C. Cosman

Department of Electrical and Computer Engineering,
UC San Diego, La Jolla, CA 92093-0407.
Email: {yapeng, pcosman}@ucsd.edu

ABSTRACT

In this paper, we restore images degraded by scattering and absorption such as hazy, sandstorm, and underwater images. By calculating the difference between the observed intensity and the ambient light in a degraded image scene, which we call the scene ambient light differential, we estimate the transmission map. In the restoration process, we first enhance the degraded images based on the proposed transmission estimation using the image formation model, and then use an adaptive color correction method to restore color. Experimental results on various degraded images demonstrate the proposed method outperforms other enhancement and restoration methods.

Index Terms— Haze, sandstorm, underwater, image restoration, transmission estimation

1. INTRODUCTION

Images captured in fog, haze, a sandstorm, or water suffer from color and contrast degradation because the propagated light is scattered and absorbed with distance from the camera through the turbid medium. The degradation reduces the visual quality of the images and affects the performance of computer vision applications. Thus, developing an effective method to restore color and contrast for such images is very desirable.

Much research [2–7] has been done on dehazing using the image formation model (IFM) [1] via estimation of the ambient light and transmission. He et al. [2] proposed the dark channel prior (DCP) to remove fog/haze in natural terrestrial images, which motivated many image restoration approaches [3–14] that improve and extend the DCP for different goals and applications. However, smog and haze with different color casts may lead to under- or over-estimated transmission based on the DCP, causing poor restoration results. In [6, 7], restoration methods for hazy and sandstorm images were presented; they used adaptive gamma correction to solve the transmission over-estimation and color correction to compensate for the color cast. Nevertheless, these methods are still unable to restore heavily tinted sandstorm images because most blue light is greatly scattered and absorbed, which causes the DCP to fail.

There are some attempts in restoring underwater images based on the DCP [8–10, 14] or its variants [11–13]. However, measuring transmission for underwater images based on the DCP [8–10, 14] frequently fails to generate accurate results since red light is more attenuated than other wavelengths underwater, and thus the DCP based on RGB channels ends up considering only the red channel, causing unreliable transmission estimation. The DCP variants consider either only the green and blue channels [11, 12] or the RGB channels with the red inverted [13] to try to estimate transmission underwater, but they may still fail due to different underwater lighting conditions. For example, all the DCP-based restoration methods are unable to restore underwater images with dim ambient light, where the background pixels are dark and would be wrongly judged as being close. In [15], underwater transmission estimated using image blurriness was proposed, but transmission estimation may be imprecise due to the non-adaptive fixed-range transformation from image blurriness to transmission.

In this paper, we propose to estimate transmission for degraded images that can be modeled by the IFM using the scene ambient light differential. The transmission map describes the portion of the scene radiance that is not scattered or absorbed and reaches the camera. With ambient light assumed to be known and transmission estimated, the degraded images can be enhanced based on the IFM. At the end, an adaptive color correction method is applied to remove the color cast of the enhanced images. The proposed method can be used to enhance and restore foggy, hazy, sandstorm, and underwater images, including both well-lit images and those without sufficient lighting. In this work, we assume ambient light is given and focus on improving transmission estimation.

The rest of the paper is organized as follows. In Section 2, dehazing based on the DCP [2] is briefly reviewed. Section 3 details the proposed method. Experimental results and conclusions are in Section 4.

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2. SINGLE IMAGE DEHAZING USING THE DCP

Assuming that light attenuation is homogeneous, the simplified IFM [1] is given by:

$$I^c(x) = J^c(x)t(x) + A^c\big(1 - t(x)\big), c \in \{r, g, b\} \quad (1)$$

where $I^c(x)$ is the observed intensity in color channel c at pixel x, J^c is the scene radiance, A^c is the ambient light, and t is the transmission, where c is one of the RGB channels. Note that we assume I^c, J^c, and $A^c \in [0, 1]$.

For each pixel x in an image, the DCP [2] finds the minimum value among RGB channels in a local patch $\Omega(x)$ around x. For an outdoor terrestrial haze-free image, J_{DCP} often equals zero, because at least one of the three color channels will usually equal zero in $\Omega(x)$. It was asserted in [2, Eq. (9)] that

$$J_{DCP}(x) = \min_{y\in\Omega(x)} \left\{ \min_{c\in\{r,g,b\}} J^c(y) \right\} = 0, \quad (2)$$

for about 75% of non-sky pixels in haze-free images.

Dividing both sides of Eq. (1) by A^c and then applying the minimum operators to it, the transmission estimate $\widetilde{t}(x) = \min_{y\in\Omega(x),c} t^c(y)$, described in [2, Eq. (11)], is

$$\widetilde{t}(x) = 1 - \min_{y\in\Omega(x)} \left\{ \min_{c\in\{r,g,b\}} \frac{I^c(y)}{A^c} \right\}. \quad (3)$$

Since $\widetilde{t}$ has block-like artifacts, it can be refined by either image matting [16] or guided filtering [18]. In general, ambient light A^c is selected from one of the haziest pixels in the input image. Finally, by putting I^c, $\widetilde{t}$ and A^c into Eq. (1), the estimated scene radiance is calculated as:

$$J^c(x) = \frac{I^c(x) - A^c}{\max\big(\widetilde{t}(x), t_0\big)} + A^c, \quad (4)$$

where t_0 is set to 0.1 to increase the exposure of J^c for display.

3. PROPOSED METHOD

3.1. Transmission Estimation based on Scene Ambient Light Differential

Based on the IFM, image degradation is determined by transmission t and ambient light A^c. The observed intensity $I^c(x)$ for a closer scene point consists more of the scene radiance and less of the ambient light, while the observed intensity for a farther scene point consists less of the scene radiance and more of the ambient light. Therefore, we propose to estimate transmission by measuring the absolute difference between the observed intensities of scene points and the ambient light for restoring degraded images with different color casts, as follows. Note that we assume ambient light is known in the paper.

Eq. (1) leads to $\mid I^c(x) - A^c \mid = t(x) \mid J^c(x) - A^c \mid$. Dividing both sides by $\overline{A^c} = \max\{A^c, 1 - A^c\}$ and then applying the maximum operators to both sides, we obtain

$$\max_{c,y\in\Omega(x)} \left(\frac{\mid I^c(y) - A^c \mid}{\overline{A^c}} \right) = \max_{c,y\in\Omega(x)} \left(\frac{t(y) \mid J^c(y) - A^c \mid}{\overline{A^c}} \right). \quad (5)$$

Assuming t is uniform in a small local patch $\Omega(x)$, we have $I_A(x) = t(x)J_A(x)$, where $I_A(x) = \max_{c,y\in\Omega(x)} \left(\frac{|I^c(y)-A^c|}{\overline{A^c}} \right)$ and $J_A(x) = \max_{c,y\in\Omega(x)} \left(\frac{|J^c(y)-A^c|}{\overline{A^c}} \right)$.

Using 60 degradation-free images with a wide variety of natural content, we empirically found that $J_A \geq 0.88$ for more than 75% of pixels, where $\Omega(x)$ was a 15×15 local patch, and A^c was assumed to take on the values $\{\frac{1}{8}, \frac{2}{8}, \ldots 1\}$. Because J_A is generally close to 1, the result $I_A(x) = t(x)J_A(x)$ suggests we could take our transmission estimate $\widetilde{t}(x)$ to be roughly equal to $I_A(x)$:

$$\widetilde{t}(x) \approx I_A(x) = \max_{c,y\in\Omega(x)} \left(\frac{\mid I^c(y) - A^c \mid}{\overline{A^c}} \right) \quad (6)$$

The intuition behind this expression for $\widetilde{t}(x)$ is that the numerator captures the absolute difference between the observed intensity and the ambient light, and large values of this quantity correlate with proximity to the camera. When the ambient light is bright ($A^c \to 1$), which holds for some foggy and hazy images, the normalization term in the denominator causes the expression to become identical to the DCP, where dark pixel values within $\Omega(x)$ mean the scene point is close to the camera. The normalization also gives sensible transmission estimates for low and intermediate ambient light levels, which is where the DCP does poorly. Because J_A is usually slightly less than 1, and also because (as with Eq. (4)) we want to increase the exposure of J^c for display, we modify Eq. (6) to estimate $t(x)$ as a linearly stretched version of $I_A(x)$:

$$\widetilde{t} = \frac{\big[I_A - \min(I_A)\big](u_b - l_b)}{\max(I_A) - \min(I_A)} + l_b, \quad (7)$$

where we set $l_b = 0.1$ and $u_b = \max(I_A)$ to stretch I_A to the range $[l_b, u_b]$. Then, guided filtering [18] is applied to $\widetilde{t}$ for refinement. Finally, the scene radiance J is recovered using Eq. (4) with the $\widetilde{t}$ calculated in Eq. (7).

3.2. Color Correction

The final step is to perform color correction on the recovered J^c to compensate for possible color casts. Iqbal et al. [19] proposed to keep constant the color channel with the dominant color cast, and scale up the other channels to correct the image color. This approach suffers from color distortion when there is a strong color cast. In [20], the degree of the color cast is measured by $D_\sigma = \frac{\|\mu\|_2 - \|\sigma\|_2}{\|\sigma\|_2}$, where $\mu = (\mu_a, \mu_b)^T$ is a vector that contains the means of the chromatic components

Fig. 1: An example of the restoration process of the proposed method. (a) Original image. (b) The proposed transmission estimate $\widetilde{t}$ with chosen A^c ( ). (c) J^c. (d) J^c_f. The original image is from [24].

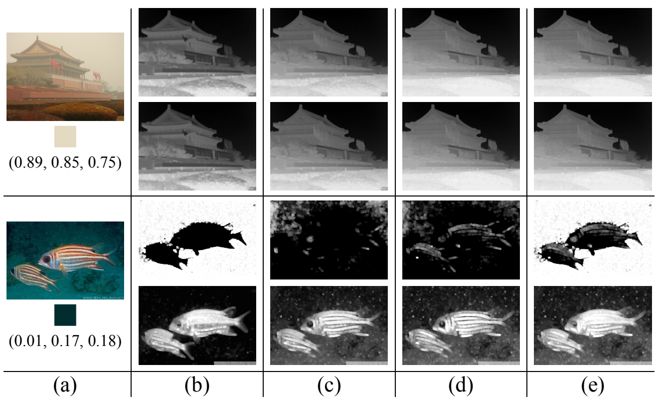

Fig. 2: Transmission estimated using the DCP-based method (top row of results for each original image) and the proposed method (second row). (a) Original images. Transmission estimated by only (b) r, (c) g, or (d) b channel, or (e) all $\{r, g, b\}$ channels. The images are from [2] and [25].

in the CIELab color space, and $\sigma = (\sigma_a, \sigma_b)^T$ has the chromatic variances. A larger D_σ means a stronger color cast, and $D_\sigma \leq \epsilon$ is taken to mean no color cast, where ϵ is a threshold. Here, we set $\epsilon = 0$. Motivated by [19, 20], and using D_σ as defined in [20], we propose an adaptive color correction:

$$J^c_f = J^c \times \left(\frac{\max_{k \in \{r,g,b\}} J^k_{avg}}{J^c_{avg}} \right)^{\frac{1}{\max(\xi(D_\sigma),1)}}, \xi(z) = \begin{cases} z, & z > \epsilon; \\ \infty, & z \leq \epsilon, \end{cases} \tag{8}$$

where J^c_f is the final color-corrected image, and $J^c_{avg} = \max(\text{avg}_x\, J^c(x), 0.1)$. When $D_\sigma \leq \epsilon$, we opt for no correction, and $J^c_f = J^c$. Otherwise, we use $\frac{1}{\max(D_\sigma,1)}$ to adjust the scaling factor so as to avoid color over-correction. Fig. 1 shows an example of the whole proposed restoration process.

4. EXPERIMENTAL RESULTS

We first discuss transmission estimation results for two degraded images, and then compare restoration results. For fair comparison, all the IFM-based methods use a 15×15 local patch, the same properly chosen ambient light, and guided filtering [18]. Fig. 2 shows the estimated transmission results from the DCP-based and the proposed methods using a single color channel or all three channels. For the hazy image with bright ambient light, the estimated transmission for the methods are almost identical. However, for dimly lit underwater images, DCP methods fail to estimate transmission correctly because dark pixels are not indicative of proximity to the camera when the overall image is dark.

Fig. 3: Restoration of dimly lit images: (a) Original images. The restored images obtained by (b) [2], (c) CLASH [21], (d) gamma correction ($\gamma = 0.75$), and (e) the proposed method with $A^c = 0$. The images are from [27, 28].

As shown in Fig. 3, two images with dim lighting can be modeled by the IFM, where ambient light is very dark and closer scene points have more scene radiance that reaches the camera. These images can be restored by reversing the image formation process based on the proposed transmission estimation but not by the DCP-based method. The local histogram equalization [21] and gamma correction methods are able to improve contrast of the enhanced image but unable to restore color for the farther scene points.

The first row of Fig. 4 shows a brown hazy image that can be enhanced by all the compared methods although there exists a little color difference. However, the original image in the second row has a strong color cast, which causes transmission estimation of the DCP-based methods to fail. The enhanced image obtained using the proposed method presents better contrast. Although the contrast enhancement works well, because the blue light is almost completely absorbed in the sandstorm conditions, for this particular image the adaptive color correction of Eq. (8) has little effect. While color is not significantly corrected, at least the severe color distortion (shift towards yellow, which appears in the restored image obtained using the method of [7]) is avoided.

In the first row of Fig. 5, although the contrast of all images is enhanced, the red fish is overexposed by the methods in [9] and [12] due to under-estimated transmission. For the second row, the DCP-based methods [9, 12] fail to restore this dim underwater image. The background of the two images restored by [15] is under-enhanced due to over-estimated transmission. The proposed method provides satisfactory results.

In conclusion, we proposed using scene ambient light differential to estimate transmission instead of using the DCP. Experimental results show that the proposed transmission estimation performs well under a wider range of lighting conditions than the DCP, and together with an adaptive color correction, produces better restoration results for degraded images with different color casts compared to other methods.

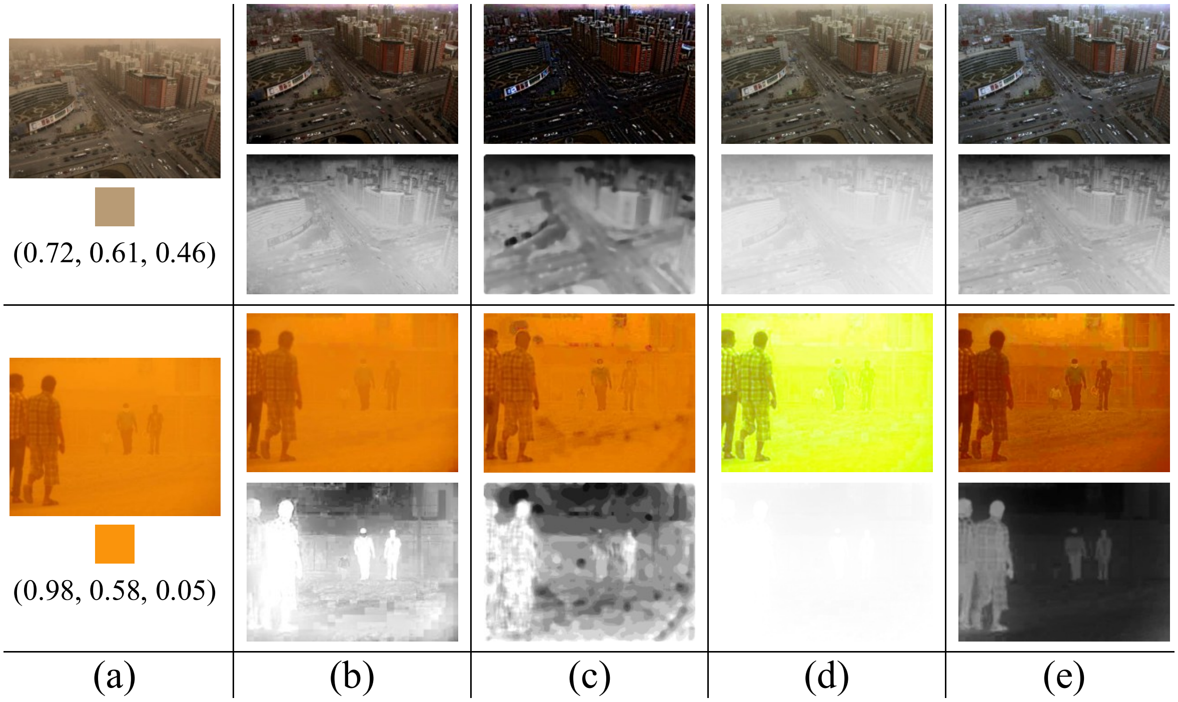

Fig. 4: Restoration of hazy and sandstorm images: (a) Original images and the chosen ambient light A^c. The restored images and the corresponding transmission estimates $\widetilde{t}(x)$ obtained using (b) [2], (c) [4], (d) [7], and (e) the proposed method. The original images are from [6, 26].

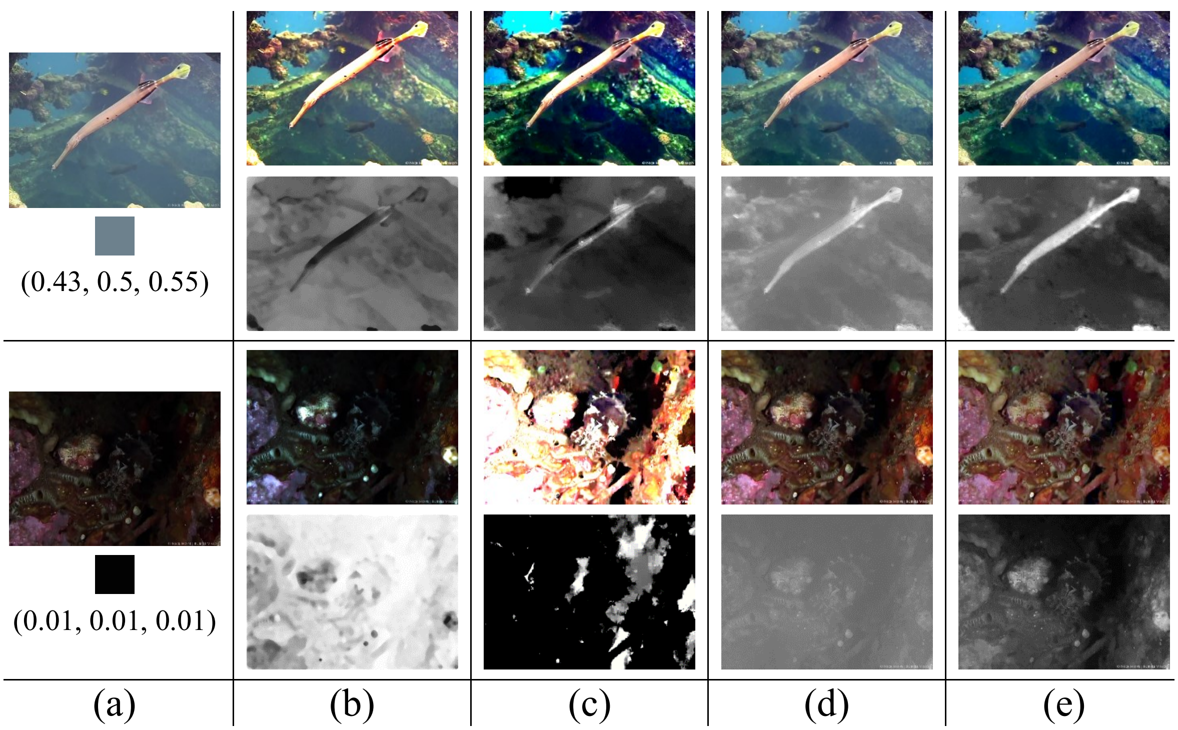

Fig. 5: Restoration of underwater image with different lighting conditions: (a) Original images and the chosen ambient light A^c. The restored images and the corresponding transmission estimates $\widetilde{t}(x)$ obtained using (b) [9], (c) [12], (d) [15], and (e) the proposed method. The original images are from [22].

5. REFERENCES

[1] R. Fattal, "Single image dehazing," *ACM Trans. Graphics*, vol.27, no. 3, pp. 721-729, 2008.

[2] K. He, J. Sun, and X. Tang, "Single image haze removal using dark channel prior," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 33, no. 12, pp. 2341-2353, Dec. 2011.

[3] H. Xu, J. Guo, Q. Liu, and L. Ye, "Fast image dehazing using improved dark channel prior," *in Proc. IEEE Int. Conf. Inf. Sci. Technol.*, Mar. 2012, pp. 663-667.

[4] K. B. Gibson, D. T. Vo, and T. Q. Nguyen, "An investigation of dehazing effects on image and video coding," *IEEE Trans. Image Process.*, vol. 21, no. 2, pp. 662-673, Feb. 2011.

[5] J.-P. Tarel and N. Hautière, "Fast visibility restoration from a single color or gray level image," *in Proc. IEEE Int. Conf. Comput. Vis. (ICCV)*, Sep. 2009, pp. 2201-2208.

[6] S.-C. Huang, B.-H. Chen, and W.-J. Wang, "Visibility restoration of single hazy images captured in real-world weather conditions," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 24, no. 10, pp. 1814-1824, Oct. 2014.

[7] S.-C. Huang, J.-H. Ye, and B.-H. Chen, "An Advanced Single-Image Visibility Restoration Algorithm for Real-World Hazy Scenes," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 2962-2972, May. 2015.

[8] L. Chao and M. Wang, "Removal of water scattering," *in Proc. IEEE Int. Conf. Comput. Eng. and Technol. (ICCET)*, vol. 2, pp. 35-39, Apr. 2010.

[9] H. Yang, P. Chen, C. Huang, Y. Zhuang and Y. Shiau, "Low complexity underwater image enhancement based on dark channel prior," *Int. Conf. Innov. in Bio-inspired Comput. and App. (IBICA)*, pp. 17-20, Dec. 2011. 17-20, 2011.

[10] J. Y. Chiang and Y.-C. Chen, "Underwater image enhancement by wavelength compensation and dehazing," *IEEE Trans. Image Process.*, vol. 21, pp. 1756-1769, Apr. 2012.

[11] H. Wen, Y. Tian, T. Huang, and W. Gao, "Single underwater image enhancement with a new optical model," *in Proc. IEEE Int. Symp. Circuits & Syst. (ISCAS)*, May 2013, pp. 753-756.

[12] P. Drews, E. do Nascimento, F. Moraes, S. Botelho, and M. Campos, "Transmission Estimation in Underwater Single Images," *in Proc. IEEE Int. Conf. Comput. Vis. Workshops (ICCVW)*, pp. 825-830, Dec. 2013.

[13] A. Galdran, D. Pardo, A. Picn, and A. Alvarez-Gila, "Automatic Red-Channel underwater image restoration," *J. of Vis. Comm. and Imag. Repres.*, vol. 26, pp. 132-145, Jan. 2015.

[14] X. Zhao, J. Tao, and Q. Song. "Deriving inherent optical properties from background color and underwater image enhancement," *Ocean Eng.*, vol. 94, pp. 163-172, Jan. 2015.

[15] Y.-T. Peng, X. Zhao, and P.C. Cosman, "Single Underwater Image Enhancement using Depth Estimation based on Blurriness," *in Proc. IEEE Int. Conf. on Imag. Process. (ICIP)*, pp. 4952-4956, Sep. 2015.

[16] A. Levin, D. Lischinski, and Y. Weiss, "A Closed-Form Solution to Natural Image Matting," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 30, no. 2, pp. 228 - 242, Feb. 2008.

[17] P. Soille, "Morphological Image Analysis: Principles and Applications," Springer-Verlag, 1999, pp. 173-174.

[18] K. He, J. Sun, and X. Tang, "Guided image filtering," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 35, no. 6, pp. 1397-1409, Oct. 2012.

[19] K. Iqbal, M. Odetayo, A. James, R. A. Salam and A. Z. H. Talib, "Enhancing the Low Quality Images using Unsupervised Color Correction Method," in Proc. IEEE Int. Conf. on Syst., Man, Cybern., 2010, pp. 1703-1709.

[20] F. Gasparini and R. Schettini, "Color correction for digital photographs," *in Proc. IEEE Int. Conf. Image Anal. Process.*, Sep. 2003, pp. 645-651.

[21] K. Zuiderveld, "Contrast Limited Adaptive Histograph Equalization," Graphic Gems IV. San Diego: Academic Press Professional, 1994. pp. 474-485.

[22] https://www.bubblevision.com

[23] https://www.thestar.com

[24] https://www.ibtimes.com

[25] https://reeflifesurvey.com

[26] https://www.cnn.com

[27] http://www.itop.freewallpaper-s.net

[28] http://iamcrown.tumblr.com/post/130370101137