Advanced Engineering Informatics 33 (2017) 96–111

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Full length article

Restoration of the distorted color to detect the discoloration status of a steel bridge coating using digital image measurements

Kuo-Wei Liao [a,*,1], Di-Rong Cheng [b,1]

[a] Associate Professor, Department of Bioenvironmental Systems Engineering, National Taiwan University, Taipei 106, Taiwan
[b] Revlis Biotech Company Limited, Taiwan

ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form 12 February 2017
Accepted 24 April 2017
Available online 7 June 2017

Keywords:
Discoloration
Digital image
Spectral power distribution
Spectral reflectance
Matrix restoration

ABSTRACT

Discoloration, representing the degradation of the coating, is often a trigger of a progressive damage process for a steel bridge. The detection of discoloration status often relies on a routine visual inspection in Taiwan, resulting in subjective results. To minimize human error in such inspection, this study provides an alternative approach, in which the digital image measurement is adopted. The process of acquiring images in any means is, in fact, a duplicate of the cross-media color process and often results in distorted colors. Consequently, to determine the discoloration between fading and its authentic color, one first must perform the color restoration for the acquired faded images. To reduce error in the restoration process, this study uses the least-square support vector machine (LS-SVM), spectral power distribution, spectral reflectance and matrix restoration to form an integrated algorithm. The average color difference between distorted and undistorted fading color of the proposed approach is approximately 5 (NBS value), which is applicable in the industry, requiring a 4th level of color difference for steel bridge coating inspections. A smartphone application is developed based on the algorithm established to facilitate the application for detecting color differences in steel bridges.

1. Introduction

Degradation is often observed later in the life of bridges. If maintenance is not provided over time, the bridge strength may be reduced, resulting in loss of human life in the case of serious failure. Thus, one of the major expenses for steel bridges is anti-corrosion maintenance, and the maintenance schedule depends on the results of regular inspections [10,23,8]. According to the inspection and evaluation results, bridges require appropriate repair to prevent continuous degradation and to maintain the required functions such that their service lifetime can be prolonged. Steel bridges are likely to undergo corrosion because of their locations and environmental influence. Typically, coating systems are used to protect bridge steel from the external environment to prevent corrosion. Nonetheless, coating systems have lifetime limits, and once the coating systems fail to provide the expected function, the endurance and strength of the structure can be adversely affected. The damaged coating surface can be repaired in the following three ways: (1) repainting the entire structure, (2) repainting parts of the structure, or (3) partial repainting. Selections of the damaged coating system surface treatment methods must consider the degradation level of the coating prior to the repair. Coating system degradation defects include yellowing, discoloration, cracking, blistering, rusting, and spalling. Based on the "Inspection and reinforcement regulations for highway steel bridge in Taiwan" for bridges, the rusted area percentage, the levels of coating spalling, cracking, discoloration (e.g., efflorescence), and the environment of the structure are evaluated, and a corresponding score is assigned to each item. Table 1 provides the urgency for repainting bridges based on these criteria under different conditions. Among these criteria, the discoloration evaluation standards are shown in Table 2.

Tables 1 and 2 indicate that the discoloration often occurs at the beginning of the coating system degradation. Discoloration of the coating system can be an early warning signal for steel bridge health. However, the current evaluation standard only provides a qualitative and vague requirement: the coating color can be identified or not. In addition, the current coating color evaluations are typically performed manually, and their accuracy cannot be easily controlled. To improve the current evaluation process, this study develops an intelligent system that takes advantage of the digital imaging approach. Because the color of images acquired on a

* Corresponding author.
E-mail address: kliao@mail.ntust.edu.tw (K.-W. Liao).
[1] formerly, Associate Professor, Department of Civil & Construction Engineering, National Taiwan University of Science & Technology, Taipei 106, Taiwan.

http://dx.doi.org/10.1016/j.aei.2017.04.005
1474-0346/

Table 1
Evaluation of coating systems in Taiwan.

Evaluation results	Status	Average value of total evaluation score	Determination on repainting schedule
I	Rusting, cracking or spalling is found on the coating surface, the anti-corrosion function of the coating fails completely.	70–100	Requires urgent repainting
11	Lots of rusted spots are found on the coating and cracking, rusting, spalling occur at partial areas while some parts remain coated.	40–70 (exclusive)	Requires immediate repainting (2–3 years)
III	Coating has nearly no rusts; however, the glossiness is clearly reduced and discoloration appears such as efflorescence.	20–70 (exclusive)	Repainting should be performed at an appropriate period (4–5 years)
IV	Coating has no abnormalities	Smaller than 20	Continue tracking

Table 2
Evaluation standards of discoloration (e.g., efflorescence) in Taiwan.

	Status
0	No absorbability can be observed
5	Discoloration occurs; however, color of the paint can still be identified
10	Discoloration occurs, and the color of the paint cannot be identified

bridge site is often distorted, it is necessary to perform color restoration on a potential fading image before comparing its color difference with the corresponding authentic color. To evaluate the color difference in a quantitative approach, the standard suggested by the National Bureau of Standard (NBS) is adopted. The authentic color is often provided by the coating or painting company and is not investigated in this study.

Many researchers have developed intelligent systems that take advantage of the digital imaging approach. For example, Chen and Chang [4] assessed a steel bridge coating using a digital image with Neuro-Fuzzy for rusted area recognition. Almeida et al. [1] measured the in-plane displacement and strain via three different image processing algorithms. Regarding the application of digital imaging approach on color recognition, after observing stable results, Swain and Ballard [22] concluded that color is a good tool for identifying variations in object surfaces, even under varying light conditions. For example, Lee et al. [14] employed color image processing in digital image recognition because rust defects are distinctive in color against a background. Liao and Lee [15] determined the rusted percentage of the steel bridge coatings via a digital image recognition algorithm that consisted of three different detection techniques: K-means in H, double-center-double-radius (DCDR) algorithm in RGB and DCDR in H. Thus, this study proposes a systematic evaluation procedure in which a digital camera (or mobile phone) currently available on the consumer market is used as a primary evaluation tool to restore the faded color that can be used to detect color differences between fading (but restored) color and the authentic color in a degrading coating system.

Color distortion occurs for many reasons. Image formation mainly relies on photographing a target using a camera device under certain lighting conditions; subsequently, a display device is used to display the colors. Therefore, the light source, camera device and display device are each factors contributing to image distortion. Digital cameras primarily consist of the following three elements: an optical lens, a photo sensing element and a digital signal processor. These three parts may affect the reality of the images. A display device refers to a color reproduction device. The brightness, contrast value, γ value, white dot, phosphorous chromaticity, and black dot of a display device can affect the color distortion. Consequently, display devices of different qualities each have a different color gamut. If the color gamut of an image were greater than the color gamut of a display device, then the display device would not be able to present an image realistically, causing color distortion. The matrix method [17] considers all of the influencing factors as a whole and performs linear regression to restore the image color. Linear regression often does not provide a promising color restoration. Thus, this research aims to develop an alternative color restoration algorithm, in which a Least Square Supporting Vector Machine (LS-SVM, [21]) is used to perform color primary restoration using information from the acquired image and the ColorChecker (X-Rite Pantone, MI, USA). Next, the *XYZ* values of the restored image are combined with the spectral power distribution, spectral reflectance and the matrix method to perform a further calculation to obtain the final restored color.

Conventionally, a spectrometer is often used to measure the color difference between two colors using the spectral reflectance. The X, Y, and Z values under different light sources, such as D65, D50 and A, can then be calculated and converted into $L*a*b$. The $L*a*b$ results are further transformed into the Delta E value (ΔE), which is the regular indicator for determining the difference level between two colors. A relatively smaller ΔE indicates that the colors between the two images are closer. Because the spectrometer instrument is bulky in size and expensive, it does not facilitate onsite operations at bridge locations. Therefore, in this research, the developed color restoration algorithm is further programmed into a mobile application (APP) to increase the feasibility for onsite measurements considerably; in this APP, the common color indicator (ΔE) is adopted to measure the color similarity. The X, Y, and Z values of the restored color and its corresponding authentic color are subsequently used to calculate the ΔE.

The process of obtaining images is, in fact, a duplicate of the cross-media color process and often results in distorted colors. Consequently, color restoration plays a key role in determining the color difference for a coating system. Several important materials, such as color space and color measurement methods, which are the basis of the proposed algorithm, are introduced below. Next, the proposed color restoration algorithm, testing results, applications and conclusions are presented. Before further discussion, the following terms that frequently appear in this manuscript are defined below.

Distorted color: the color of a faded image acquired under a nonstandard environment light source (e.g., a bridge site). The light source of D65 is considered as the standard environment in this study. Undistorted color: the restored color of a distorted color. Authentic color: the color of images without fading and distortion (i.e., acquired under a standard environment). This color information is provided by the painting company and is not investigated in this study.

2. Color space

Red, Green and Blue (*RGB*) is the most commonly used color space, and it uses the additive color mixing method to generate colors by overlapping red, green and blue. *XYZ* color space is formulated based on the *RGB* system. One of the reasons for this transformation is to make the three primary colors easier to use in calculations. The color matching functions in the *RGB* chromaticity system contains negative values. The existence of these