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Rapid and automated determination of rusted surface areas of a steel bridge for robotic maintenance systems

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ABSTRACT

There has been an increased interest in the use of robotic systems to automate the blasting tasks in steel bridge maintenance. To utilize such robotic systems effectively, an automated process for determining the rusted areas on a steel bridge to be blasted is a prerequisite. This study proposes a method to rapidly and accurately determine rusted surface areas on a steel bridge that are to be blasted, within current standards. The proposed method consists of three steps: color space conversion, classification of rusted area via the J48 decision tree algorithm, and determination of blasting area. The method was validated using 119 test images showing both normal states and various degrees of rusting and rust distribution types. The experimental results showed that the success rate for determining the rusted areas that needed blasting was 97.48%. The average processing time was 0.57 s/image. The results demonstrate that the proposed method rapidly and accurately indicated whether blasting was necessary, and if so, where blasting should be performed, based on current standards of practice.

1. Introduction

The deterioration of a steel bridge surface is most visibly observable in the form of rust [1,2]. Rust decreases the coating quality, which can affect the service life of a steel bridge [3,4]. If the surface rust on a steel bridge is not removed, it can severely reduce the structural strength of the bridge, which is the primary cause of failure in such bridges [5,6]. Therefore, the surface rust should be removed, and the blasted areas should be repainted. In current practice, such rust removal is done by manual blasting, which is dangerous because workers are exposed to harmful substances, including lead and asbestos [3,4]. Furthermore, manual blasting is an extremely labor-intensive, time-consuming process [6]. When considering the number of steel bridges that must be maintained, the problem becomes even more apparent.

To solve this problem, there has been increased investigation in robotic systems. Several robotic steel bridge maintenance systems have been developed to automate the blasting process. Examples of these systems include the Robotic Bridge Maintenance System [7], the Automated Abrasive Blasting System [8], and the Autonomous eXploration to Build a Map [4]. Typically, these systems automatically blast the rusted surface areas that are selected manually [5,6,9,10]. A remote operator determines which rusted surface areas need to be blasted, based on an image obtained through sensors mounted on the robotic systems [11]. Because the remote manipulator relies heavily on subjective human vision to select the rusted areas for blasting, its accuracy can be limited [5]. Moreover, such a manual process is repetitive. As a result, it is ineffective in terms of time and cost.

For the effective use of such robotic systems, an automated process for determining the rusted surface areas on a steel bridge to be blasted is an apparent prerequisite. In practice, the determination of the areas to be blasted is accomplished based on the 2012 standard from the American Society for Testing and Materials [12] and the 2000 standard from the Steel Structures Painting Council [13]. According to these standards, both the degree of rusting and the rust distribution type are to be considered to determine the rusted areas that are to be blasted. Therefore, an automated determination process that is not only fast and accurate, but is also in compliance with current standards of practice, is required.

In recent years, several studies have proposed methods to detect rusted areas on a steel bridge automatically [5,14–19]. These studies have shown the potential for automatic detection of either the presence of rusted areas or the rusted areas in a given image via image processing techniques in outdoor environments that are often affected by factors such as weather conditions, variations in illumination, or exhibiting a variety of rust colors. However, further processing is necessary to determine whether blasting is necessary, and if so, where blasting should be performed. In addition, although the detection process should be capable of near-real-time performance, previous studies have focused solely on the accuracy of rust detection, without considering the time needed to detect the rusted areas in an image. In addition, a common limitation in these studies is their lack of consideration of current standards of practice.

This study proposes a method for near-real-time and reliable determination of the rusted surface areas of steel bridges to be blasted, within

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current standards. The proposed method not only determines whether rusted areas are present in an image, along with the amount of rusted areas, but also indicates whether blasting is necessary, and if so, where blasting should be performed. This method is designed for an automatic determination of the rusted surface areas to be blasted which is to be used for various robotic systems. The rest of this paper describes the framework for the proposed method of rusted surface area determination and presents the experimental results obtained with the proposed method. Conclusions and recommendations for future research are then presented.

2. Literature reviews

In recent years, several studies have proposed methods to automatically detect rusted areas on steel bridges for the purposes of steel bridge rust assessment [5,14–19]. These previous studies can be broadly divided into two categories.

The first category includes studies that focus solely on checking whether rusted areas exist in a given color image. Lee et al. [15] proposed a multivariate statistical technique to determine whether rusted areas exist in a given color image. In their study, a total of 20 steel bridge images, including 10 normal state images that do not contain any rusted areas and 10 images containing rusted areas, were used for the validation. The resulting accuracy was 100% for the validation set but the time required for the processing was not reported. Shen et al. [19] suggested a method that combines a Fourier transform method and color image processing to determine whether rusted areas exist in a given color image. The method first determines whether a given image contains a non-homogeneous part caused by rust, non-uniform illumination, or other noises. If the image is determined as containing a non-homogeneous part, the proposed method determines whether or not the part is caused by rust. A total of 25 steel bridge images, including 18 normal state images and 7 images containing rusted areas, were used for the validation. The resolution of each image was 256×256 pixels. In the validation of the proposed method, the resulting accuracy was 100% and the average processing time was 0.11 s/image for the validation set. Although these studies demonstrated the ability to determine the presence of rusted areas automatically, they only indicated whether or not rusted areas were present in a given image.

The second category includes studies that aim to detect not only the presence of rusted areas but also the rusted areas in a given color image. Chen et al. [17] suggested a box-and-ellipse-based and adaptive-network-based fuzzy inference system (BE-ANFIS). The average processing time was 200 s/image for 40 color images, each with a resolution of 256×256 pixels. But the quantitative and statistical results necessary to evaluate the accuracy of the method were not reported. In their later study, the most recent investigation on rust detection, Chen et al. [18] proposed a method that combines the Fourier transform method and a support vector machine. A total of 50 steel bridge images, each with a resolution of 256×256 pixels, were used for the validation. The results of the performance evaluation showed that the average processing time was 7.55 s/image and the average value of the F-measure for the 50 images was 0.82, which ranges from 0 to 1.

The previous studies that focused on the detection of rusted areas have shown the potential for automatic detection of either the presence of rusted areas or the rusted areas in a given image via image processing techniques. However, further processing is necessary to determine whether blasting is necessary, and if so, where blasting should be performed. In addition, there is still a need to improve the processing speed presented in the previous studies so that the method could be used for robotic steel bridge maintenance systems, because the sizes of steel bridges can vary from several hundreds of meters to a few kilometers in length and several tens of meters wide. Furthermore, a common limitation of these studies is the lack of consideration for current standards of practice. According to the ASTM [12] and SSPC [13] standards, both the degree of rusting and the rust distribution type are to be considered when determining the rusted areas that need to be blasted.

3. Proposed method of rusted surface area determination

This study proposes a method to rapidly and reliably determine which rusted surface areas of a steel bridge need to be blasted for robotic steel bridge maintenance systems. The proposed method not only determines whether rust is present in an image, along with the amount of rust, but also indicates whether blasting is necessary, and if so, where blasting should be performed (see Fig. 1). This method is targeted toward steel bridges painted in a variety of colors (gray, white, brown, red, khaki, green, blue, and yellow colors). The method presented here is extended from our previous work [20], where the method was limited only to brown or red steel bridges.

This study uses color to detect the rusted areas in the input image based on pixel-level classification. Among the various possible features, the color feature is more practical than the texture or shape features because it is more robust against the shape of objects, changes in scale, or camera focusing [21]. By using the simple color feature, objects of interest can be quickly and easily detected via pixel-wise classification if their inherent color is sufficiently distinguishable from the color of their surroundings [22].

As the first step, a color space conversion transforms the input image from the red/green/blue (RGB) color space to the hue/saturation/intensity (HSI) color space. Then, pixel-level classification is performed to detect the rusted areas. For this process, we needed to choose the most appropriate classifier to use, in terms of both speed and accuracy. In this study, the best classifier was selected by computing and comparing the performance of rust classification models from six different classifiers, via 10-fold cross-validation. The classifier selection process was performed only once. After that, the areas to be blasted were determined by verifying whether the detection results satisfied the criteria specified in current standards of practice. The standards are based on the degree of rusting, on a scale of 0 to 10, and the rust distribution type (i.e., spot rusting, general rusting, or pin-point rusting). The standards are defined by ASTM [12], referred to in Chen et al. [18], and SSPC [13]. A detailed description of the process is provided in later sections of this paper.

4. Determination of rusted surface areas to be blasted

4.1. Color space conversion

The robotic systems for steel bridge maintenance acquire color images in an outdoor environment, where the color of objects is affected by changes in illumination and can cause false detection [20]. The values of colors in the RGB color space, the most prevalent choice for computer graphics, are particularly subject to deterioration owing to changes in illumination [23]. Such variations caused by factors in outdoor environments may considerably affect color properties, potentially impacting detection performance [24].

To deal with these potential artifacts, it is important to represent color in a way that minimizes the effect of variations in illumination. In this study, to represent color in an appropriate form, the color values in the RGB color space were converted to those in the HSI color space, which separates chrominance information from luminance information, for details, see Wesolkowski [25] and Zou and Kim [26]. Hue and saturation are related to color, or chromaticity, and are illumination-independent components. The three components (hue, saturation, and intensity) were used as input feature vectors to detect the rusted areas. The RGB color space can be converted to the HSI color space using the following formulas [27]:

$$H = \arctan\left(\frac{\sqrt{3}(G-B)}{(R-G)+(R-B)}\right) \tag{1}$$