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Automatic multi-image stitching for concrete bridge inspection by combining point and line features

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A B S T R A C T

Most of the current techniques for concrete bridge inspection are based on human visual interpretation, which often is dangerous and time-consuming. To address this problem, we introduce in this paper a newly developed vehicle-based robot inspection system that can automatically capture thousands of bottom surface images with a group of high-resolution industrial cameras, which are then stitched into a single composite image. However, traditional image stitching methods generally fail with large drift due to the great number (more than 2000) and sparse texture of linearly distributed images in sequence. Therefore, a novel image stitching method was developed for our robot inspection system, which combines both the 2D image point features and the 3D line features to reduce the drift. First, the bottom surface images are arranged into different strips based on their acquisition order and rough poses, and images in a single strip are divided into several groups. Then, the proposed image stitching method is performed in a bottom-up way, as follows: 1) the images within a single group initially are aligned via their point and line features; 2) the groups within a single strip are then stitched together via a homographic refinement procedure; 3) the strips are aligned into a single composite image that completely covers the bottom surface of the bridge; and 4) after all the stitching procedure are complete, a multi-band blending algorithm is applied to generate the mosaicked panorama as seamlessly as possible. The experimental results on a set of representative images acquired from the bottom surfaces of a real bridge demonstrate the capabilities and the limitations of the proposed approach.

1. Introduction

Concrete and cement are the most widely used man-made materials for constructed systems, especially bridges. Due to excessive usage, overloading, and aging, as well as insufficient maintenance and inspection deficiencies [1], many defects (e.g., cracks) appear on the surfaces of these materials. According to statistics of the National Bridge Inventory (NBI) of the United States Federal Highway Administration [2,3], more than 30,000 bridges on which people rely daily are vulnerable to failure. There is an urgent need to develop more effective approaches for the inspection and evaluation of these bridges. In addition, periodic inspections and maintenance of bridges are necessary to prolong their service lives [4–6]. Although there are many sophisticated nondestructive evaluation methods [7–12] in engineering practice, visual inspection by the human eye [13] is the predominant method still used for the inspection of bridges. However, manual inspection is a labor-intensive task and is also dangerous, qualitative, subjective, and time-consuming [14], especially for the complicated bottom structures of some bridges.

To make the bridge inspection process more effective and safer, various robot systems via remote sensing techniques have been developed in the past decade, which can detect defects (e.g., cracks) more accurately and assess the health status of bridges remotely and easily. Oh et al. [15] designed a robotic system for inspecting the safety status of bridges, which consists of three parts: a specially designed car, a robot mechanism and control system for mobility, and a machine vision system for automatic crack detection. Lim et al. [16] developed a system that used a mobile robot to conduct the inspection, where the robot collected bridge deck images with a high resolution camera. DeVault [17] developed an automated robotic system to enable safe and cost-effective underwater inspections of bridge substructures. La et al. [18] presented a mechatronic system design for an autonomous robotic system for highly efficient bridge deck inspection and evaluation. Yang et al. [19] proposed an innovative approach for conducting bridge inspections by optimizing an unmanned aerial system (UAS) that comprised a rotorcraft prototype and a camera gimbal mechanism. In addition, other robot systems [20,21] have been developed for bridge inspection.

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Cracks are the main defects that appear on the surfaces of concrete materials. Not only in roads [22–24] and buildings [25,26], but also in bridges [1,27,28], crack inspection is an essential task to monitor the health status of these structures. The existing crack detection methods can be classified into two categories: local-feature-based [22,29] and global-feature-based algorithms [30,31]. However, in order to capture high-resolution images of the bottom surface of a bridge, industrial cameras must be placed at close range with a mobile platform which only covers small regions each time. Thus, when using the robotic system to clearly inspect the defects (e.g., cracks) appearing on the bottom surface of a bridge, thousands of images usually are collected. Detecting cracks or other defects on all the images one by one would take a lot of time and cannot represent images as a whole. So, stitching all the images captured from the bridge bottom surface into a single wide-view panorama is necessary in order to comprehensively evaluate the health status of a bridge.

Image stitching technology is widely used in the fields of image processing [32,33], photogrammetry [34,35], and computer vision [36,37], and have been featured in the literature and commercial applications [38,39]. Recently, Brown and Lowe [36] developed a novel method that can recognize multiple panoramas in an unordered image dataset using invariant features for panoramic image stitching. Zaragoza et al. [40] developed an as-projective-as-possible warping method based on a novel moving direct linear transformation (Moving DLT) technique to seamlessly stitch image regions that are inconsistent with the projective model. Jahanshahi and Masri [41] presented novel integrated inspection software based on the use of inexpensive digital cameras, which are appropriately mounted on a structure and can zoom or rotate in three directions (similar to traffic cameras). Rankov et al. [42] proposed an optimized, automated, fast, and reliable method for both image joining and blending that overcame intensity discrepancies and geometric misalignments between the stitched images. Jia and Tang [43] achieved seamless image stitching without producing visual artifacts based on structure deformation and propagation. Although the above studies have solved some key problems in image stitching, which is not suitable for creating a complete single-view image for the bottom surface of a bridge from a large number of high-resolution images.

This paper introduces a specially designed bridge inspection system to automatically detect the bridge defects (e.g., cracks) from a complete single-view image of the bridge bottom surface, which is obtained via stitching thousands of high-resolution images. The remainder of this paper is organized as follows. The new bridge inspection system is briefly introduced in Section 2. Section 3 describes the proposed automatic multi-image alignment and stitching approach in detail, which consists of image alignment within a single strip, image alignment between neighboring strips, and image warping and blending. Experimental results on a large set of images acquired from the bottom surface of a real bridge are discussed and evaluated in Section 4. Conclusions and future work are provided in Section 5.

2. System overview

The designed bridge inspection system can inspect the bottom structure of a bridge remotely by controlling a specially designed truck with a huge and flexible mechanical arm and an intelligent inspection robot system with various sensors as shown in Fig. 1. The shape of the intelligent inspection robot mounted on the terminal of the multi-linkage arm looks like a cube box with holes in the surface. In total, there are two high-resolution industrial CCD cameras, two 3D cameras, one near infrared line laser and one ultrasonic range finder mounted on the top side of the "cube box", as shown in Fig. 2.

In this paper, a novel approach also is introduced to stitch the images of the concrete bottom surfaces of a bridge using the designed robot system. In the practical application, at least two CCD cameras are used to capture the images of the bottom surfaces of a bridge. With the slow moving trunk, each CCD camera collects a large set of images at the low frequency of 6 Hz as shown in Section 4, and each 3D camera acquires 3D cloud points with each profile of 2048 points at a high frequency of 339 Hz. The operation and data acquisition procedures of the bridge inspection system can be summarized as follows. The operator first pulls the trunk to the side of a bridge and then the multi-linkage arm system carries the intelligent inspection robot to the bottom of the bridge. Next, the laser range finder (LRF) mounted on the inspection robot starts to scan the bridge via the rotation device. The LRF scanning data are then used to estimate the geometric information (e.g., the width, height, and length of the various object elements) of the bridge bottom structure via point cloud segmentation [44]. This bridge information then is utilized in the acquisition task planning for the truck and the intelligent inspection robot. Next, the images together with metadata (i.e., the poses of the cameras estimated by the LRF and high-precision incremental encoder (HPIE)) of the bridge bottom surfaces are collected by the sensors mounted on the intelligent inspection robot close to the surfaces with the slow moving of the trunk at a low speed of around 1 m per second. Fig. 3 shows the processing flow of the proposed image stitching approach, which is as follows. First, based on the rough pose information of each image obtained from both the LRF and the HPIE, the acquired images are divided into several strips. Second, images in a single strip are divided into multiple groups. The poses of each image in the same group are first optimized using point features extracted from 2D images and line features extracted from 3D point clouds, which then are used to project the image to the 3D bridge model, which is represented by a set of 3D planes extracted from the LRF scanning data. Next, a homographic refinement procedure is applied to increase the global consistency between different groups of images in a single strip. Third, the point features are used to align the multiple strips for generating a composite wide-view image covering the whole bottom surface of a bridge. Finally, a multi-band blending method [45] is applied with an open-source software called Enblend [1] to make the single-view composite image as seamlessly as possible, which can greatly eliminate both the luminance differences and the color deviations between images and further conceal image parallax.

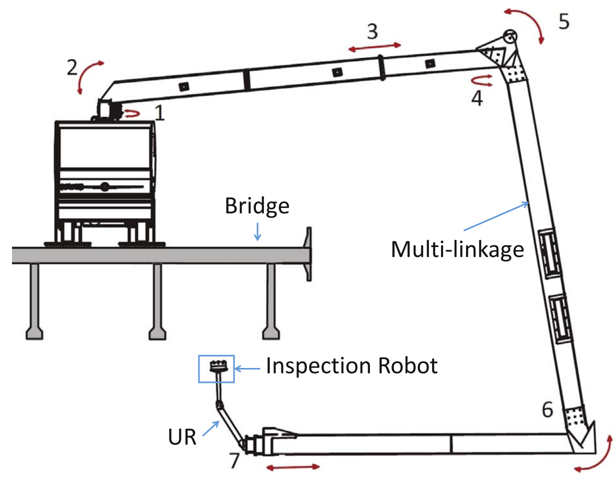

Fig. 1. An overview of the whole mechanism for the designed bridge inspection system. The arcs with double arrows refer to the rotation operation and the lines with double arrows refer to the elongation and shortening of each joint of the multi-linkage arm.

3. Multi-image alignment and stitching

Image alignment and stitching, which mosaics a number of geometrically aligned images into a single-view composite image, is becoming increasingly popular in computer vision. It is widely used in

[1] Available at http://enblend.sourceforge.net/.