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3D reconstruction of road surfaces using an integrated multi-sensory approach

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Abstract

In this paper, we present our experience in building a mobile imaging system that incorporates multi-modality sensors for road surface mapping and inspection applications. Our proposed system leverages 3D laser-range sensors, video cameras, global positioning systems (GPS) and inertial measurement units (IMU) towards the generation of photo-realistic, geometrically accurate, geo-referenced 3D models of road surfaces. Based on our summary of the state-of-the-art systems for a road distress survey, we identify several challenges in the real-time deployment, integration and visualization of the multi-sensor data. Then, we present our data acquisition and processing algorithms as a novel two-stage automation procedure that can meet the accuracy requirements with real-time performance. We provide algorithms for 3D surface reconstruction to process the raw data and deliver detail preserving 3D models that possess accurate depth information for characterization and visualization of cracks as a significant improvement over contemporary commercial video-based vision systems.

Keywords: Road surface reconstruction; Multi-sensor integration; 3D geometric mapping; Laser range scanning

1. Introduction

Every year a substantial amount of maintenance costs occur for collecting and evaluating road distress data. The inspection procedure that involves personnel walking or driving slowly over asphalt and concrete pavements and subsequently observing surface defects and degradation, is not only cumbersome and time consuming, but is also susceptible to human subjectivity, error, and inefficiency. With the safety of the personnel and the passengers that use the roadways in mind, this functional and important process of inspection can be significantly improved using a formalized imaging system. Several companies have hence worked towards the production of automatic commercial inspection systems to meet the specific requirements in assessing distress on the road surfaces using video cameras and image processing algorithms. With limited success using the 2D image-based systems, and with the advent of 3D laser scanners, the next logical improvement appears to be the use of accurate 3D maps for road distress analysis.

Towards that end, we propose a mobile laser scanning approach to acquire 3D data and implement surface reconstruction techniques to create 3D geometric models. The output 3D models from our two-stage acquisition and processing methodology brings together 3D laser scanning from the field of optics and surface reconstruction techniques from computer vision and graphics research areas into the engineering for road distress inspection. Though our experiments with a simple prototype in this paper are targeted towards road surface mapping, our approach should impact inspection work for airport runways and highways with minor modifications like deploying high-speed laser scanners. The detailed geo-referenced road surface models from our system can also be used to enrich available 3D databases embedded in geographical information systems (GIS). In describing such

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a system and processing pipeline, we list the following two contributions of this paper:

- *Multi-sensor integration for road surface mapping*: We propose an integrated multi-sensor approach for efficiently and automatically capturing 3D road surface data and demonstrate the methods involved using a prototype data acquisition system.
- *Multi-stage processing system*: We list a set of processing algorithms, which combine methods from computer vision and computer graphics for creating coarse models as a precursor to constructing detailed piecewise smooth surfaces from scattered point cloud data. The coarse model is obtained by first gridding and interpolating the data, while the detailed model is the output after smoothing and denoising using algorithms that preserve sharp features and geometric details.

We have organized this paper to emphasize the above contributions in the construction of a multi-modal integrated imaging system that is capable of real-time data collection and processing. In Section 2, we summarize existing commercial systems targeting road surface inspection. The literature survey emphasizes the design methods implemented thus far and also serves as a reference to understand the difficulty in building systems for real-time deployment. We introduce our prototype system and explain the idea behind using multi-modal sensors in Section 3. After explaining data acquisition, we discuss the integration and processing algorithms on the multi-modality data. The integration involves the representation and reconstruction of range data into a spatially meaningful visualizable form using the information from position and orientation sensors. We show the 3D models generated using our system driving a van along a test area containing different types of cracks in Section 4 and conclude with recommendations for possible improvements and reproducibility of our system in Section 5.

2. Related work

The key to successful road surface evaluation lies in identifying different types of distress and linking them to the cause. In particular, the interest in standard practice is on cracks and debris as dominant distress data [1]. Targeting such a goal of being able to detect road distress, the most popular method for automatically acquiring road data is through digital imaging using vision cameras. Some examples of commercial imaging systems include Pathview [2], ARAN [3], and Digital Imaging System [4]. As a significant next step using digital cameras, video logging is also adopted as a common technique in storing and processing continuous image data. VIASAT [5], GeoVAN [6], and L.C.P.C [7] are some recent commercial systems that are based on video logging. The common feature between these commercial systems is that one or more cameras are mounted along with archival equipment for recording 2D images of the road surface. Another configuration requires the placement of two cameras separated by a baseline distance to acquire stereo images. From the two stereo images and with the calibration information of the cameras, 3D information is estimated using epipolar geometry. However, the accuracy from 3D reconstruction has not been sufficient for distress analysis. In addition to multiple cameras, some of these systems like GPS Vision [8] use position sensors such as the GPS for global location information. The integration of GPS information with the video to create GIS-like databases of road surfaces claims to improve road network identification and pavement inspection for better maintenance and data management. Part of the success for these imaging-based systems can be attributed to the ease of using the acquired images and processing them to analyze distress information, such as crack patterns, width, length, counts, areas, and in some cases even depth [9].

One major issue with pure video-based systems is their inability to discriminate dark areas not caused by pavement distress such as tire marks, oil spills, shadows, and recent fillings [10]. Moreover, the 3D geometric information, in particular the depth, is difficult to derive from 2D images at the required scale of accuracy. Shadows and poor illumination are also major problems for daytime operation though they can be overcome using additional lighting systems or by acquiring data in the night after sunset [11].

The introduction of laser scanning techniques is only a recent trend in support of the image-based techniques. The advantage of using laser scanners is that the 3D information of the road surface acquired at high speed can aid in detecting cracks that were not detected by traditional imaging approaches. The maps produced by DistressVIEW 3D [12] representing the left and right ruts in a 2D color image is an example of 3D sensors that support the image data.

We briefly explain some 3D methods used for road surface reconstruction before presenting our system in Section 3. Javidi et al. [13] have proposed a phase shifting digital interferometry-based technique as an improvement for ARAN [3] towards measuring 3D depth. The basic principle behind using interferometry is to project multiple laser beams to a CCD camera and then observe the diffraction patterns to reconstruct 3D coordinates using holography. Though their system is able to derive crack depth and integrate with 2D images, the system is too sensitive to the vibrations of a moving van. Laurent et al. introduced a multi-scanner synchronized system for measuring dense 3D coordinates [14]. This system is efficient when mounted on a mobile vehicle driving at high speed and is able to output a binary image with 255 (bright) denoting non-distress areas and zero (dark) denoting distress areas in near real time. Bursanescu [15] introduced a similar system consisting of six sensors for high-speed and high-resolution scanning. Their system outputs binary crack maps along with longitudinal road parameters. Abuhadrous [16] also scans road surfaces together with