CIAMTIS

U.S. DOT Region 3 University Transportation Center

Automated Path Tracking and Mapping for Economical, Real-Time, and Knowledge-Based Roller Control in Pavement Compaction Operations: Phase I: Algorithm Development

April 20, 2020

Prepared by:
Fei Dai, John P. Zaniewski, and Linjun Lu
West Virginia University

r3utc.psu.edu

PennState
College of Engineering

LARSON
TRANSPORTATION
INSTITUTE

Technical Report Documentation Page

1. Report No. [UTC assigned]	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Automated Path Tracking and Mapping for Economical, Real-Time, and Knowledge-Based Roller Control in Pavement Compaction Operations: Phase I: Algorithm Development	**5. Report Date** April 20, 2020
	6. Performing Organization Code
7. Author(s) Fei Dai, John P. Zaniewski, Linjun Lu	**8. Performing Organization Report No.**
9. Performing Organization Name and Address West Virginia University Department of Civil and Environmental Engineering Morgantown, West Virginia 26506-6103	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. [Enter contract number here]
12. Sponsoring Agency Name and Address U.S. Department of Transportation Research and Innovative Technology Administration 3rd Fl, East Bldg E33-461 1200 New Jersey Ave, SE Washington, DC 20590	**13. Type of Report and Period Covered** Draft Final Report xx/xx/20xx – xx/xx/20xx
	14. Sponsoring Agency Code

15. Supplementary Notes

[Enter sponsor contact's Name, Email, Phone]

16. Abstract

Compaction is considered as the last and possibly the most important phase in construction of asphalt pavement. It densifies the paving mat and affects the performance properties of the constructed pavement to a great extent. Inspired by recent advances in visual odometry, this research developed a thermal-based technology carrying an infrared camera (IR) for roller path tracking and mapping in the pavement construction process. Especially, a novel calibration method using a special symmetric circular pattern was created for IR camera calibration, and a visual odometry algorithm leveraging computer vision knowledge, i.e., vanishing points and optical flow technique, was developed for roller path tracking and mapping. The technology can provide real-time roller locating and a continuous recording of color-coded plots of the roller path, which may assist operators to control their rolling operations in real time. Initial field experiments were conducted in order to test the performance of the developed algorithm. The visual results demonstrated that the developed technology is a promising alternative to intelligent compaction (IC).

17. Key Words Pavement Construction; Intelligent Compaction; Infrared Images; Computer Vision; Path Tracking and Mapping	**18. Distribution Statement** No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** XXX	**22. Price**

Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

BACKGROUND

Asphalt mixtures, a major industrial product, has been adopted worldwide in various applications. Every year, over five hundred million tons of Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) are produced and placed on roadway across the United States by federal, state, and local governments (Gallivan et al. 2011). HMA and WMA are defined as the combination of aggregates (92%-96%), asphalt (4%-8%) and air, whose behavior directly based on the level of compaction. Pavement compaction refers to a process that uses external forces to reduce the volume of air in an HMA/WMA mixture to aggregate the particles into mire closely spaced arrangement. During the pavement construction, compaction is considered as the last and possibly the most important phase in quality control, which affects the performance properties of the constructed pavement to a great extent.

With technological advancement in recent years, intelligent compaction (IC) has been extensively studied. Typically, IC refers to an improved compaction process that using roller equipped with an intelligent measurement system that consists of a highly accurate GPS, accelerometers, onboard computer reporting system, and infrared thermometers, which can assist the roller operators to improve the construction quality (Gallivan et al. 2011). During compaction, the IC technology can maintain a continuous record of color-coded plots of rolling path that can provide roller operator with the real-time location of roller and the number of roller passes. According to the feedback, the roller operator can adjust the roller direction in real time to meet the correct compaction pattern.

However, due to the fact that retrofitting the IC technology to an existing roller is costly (up to $100,000), the industry is reluctant to its adoption, which hinders the implementation of this technology in extensive field applications (Nieves 2013). Therefore, there are great opportunities for development of new technologies to achieve economical yet viable pass mapping for roller operators to use in the field. Inspired by the recent advances in visual odometry (VO), this study developed the thermal-based system carrying an IR camera for roller path tracking and mapping in pavement construction.

OBJECTIVES

The objective of this research was to create and validate new algorithms that exploit thermal imaging modality to automatically track and map paths for economical, real-time, and knowledge-based roller control in pavement compaction operations. In comparison to regular imaging modality, due to the thermal difference between the fresh hot asphalt and the surrounding environment, applying the thermal imaging modality works equally well during the day and night.

DATA AND DATA STRUCTURES

In order to test the performance of the proposed algorithm, thermal data have been collected from different construction sites. Except for the raw thermal data, the recording information includes: 1) the location of construction sites; 2) whether the data has been collected during the day or night; 3) the start time and end time of compaction tasks; 4) ingredient proportions of asphalt mixtures. This information is important for later algorithm performance evaluation, as in IR vision, on freeways due to the wider right of way, there are fewer features in the background compared to county roads. Furthermore, different materials have different capacities in reflecting/absorbing heat. Thus, in IR vision, there are more features in the background during the day compared to night, when the temperature is more uniform.

CHAPTER 2

Methodology

INTRODUCTION

In this research, a thermal-based system that is capable of producing roller locations and pass maps with acceptable accuracy and affordability was developed. In this chapter, the hardware selection, the algorithm development, and the software are presented in detail.

OVERVIEW OF PROPOSED SYSTEM

Figure 1 illustrates the overview of the proposed compaction system installed on a roller. It consists of an infrared camera, a digital video recorder, a display screen, and a laptop running the proposed automatic locating and mapping algorithms. The IR camera is mounted on the top of the roller with the help of a triple suction cup camera mount, which is in corresponding to the center of rotation of the roller in order to precisely record the motion of roller. The thermal video stream data captured from the IR camera are continuously transferred to the digital video recorder-Safety Vision DVR Model SVR 4100, which is wirelessly linked to a laptop for further data processing in a real-time manner. After data processing, a color-coded plot that contains the location of the roller and the number of roller passes is back-transmitted and displayed on the display screen in front of the operator.

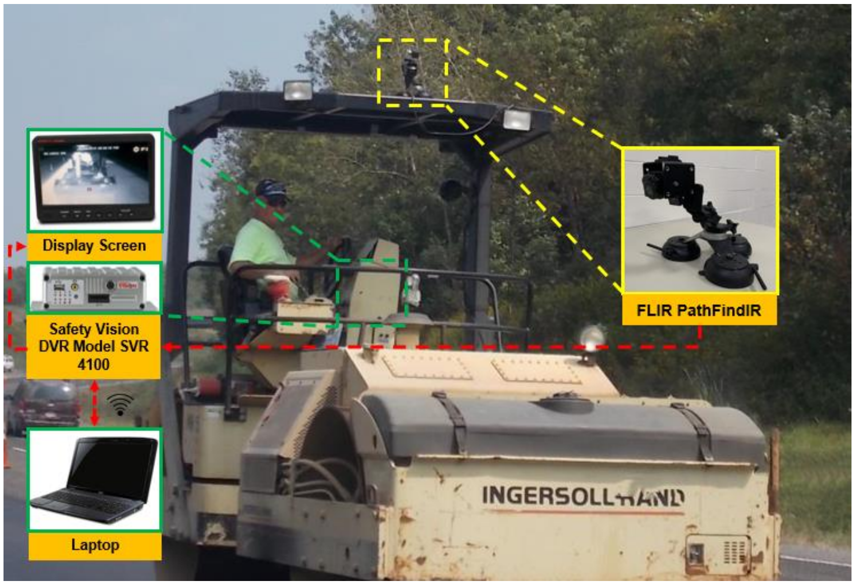


Figure 1. Vision-based roller system.

HARDWARE

Rollers

Through collaboration with their industry partners, the researchers collected IR image data using the IC camera installed on two types of rollers, namely DD-110 Vibratory Asphalt Compactor, and DYNAPAC CA1400D Vibratory Asphalt Compactor. The DD-110 has dual 78 inch (1980 mm) wide drums and provides high-performance capability for highway and other large paving jobs. In a cycle of compaction (two side-by-side passes), this rolling width of the roller can permit coverage of pavement panels up to 12 feet 6 inches (3.8 meters). Large 54 inches (1.4 meters) drum diameter reduces rolling resistance and produces unsurpassed pavement surface smoothness. This roller possesses a static weight of twelve and one-half tons (11.4 metric tons), which can meet DOT static roller requirements for increased machine utilization. The DYNAPAC CA1400D is a single-drum vibratory compactor with a 66-inch roller and a static linear load of 12 pli (1 pli = 175.1268 N/m). It has two amplitudes: 0.067 and 0.032 inch. The roller has a differential lock and drum drive traction both forward and reverse, and offers dual speed.

Figure 2 and Table 1 show the DD-110 Vibratory Asphalt Compactor and its technical specifications.

Source: Ingersoll Rand

Figure 2. DD-110 Vibratory Asphalt Compactor.

__Table 1. A typical technical specification of DD-110 Vibratory Asphalt Compactor.__

Machine Dimensions		
Overall length	222.5 in.	(5650 mm)
Overall Width	87.2 in.	(2215 mm)
Overall Height	20	21
Drum		
Drum Width	78 in.	(1980 mm)
Drum Diameter	54 in.	(1370 mm)
Shell Thickness	0.75 in.	(19 mm)
Vibration		
Frequency		
High	2500 vpm	(42 Hz)
Low	1850 vpm	(31 Hz)
Centrifugal Force		
Max/drum	30,000 lb.	(133.4 kN)
Min/drum	8,030 lb.	(35.7 kN)
Amplitude Settings	Eight	
Nominal Amplitude		
Max	.037 in.	(0.94 mm)
Min	.018 in.	(0.46 mm)

Figure 3 and Table 2 show the DYNAPAC CA1400D single drum vibratory roller and its technical specifications.

Source: GYNAPAC

__Figure 3. DYNAPAC CA1400D single drum vibratory roller.__

Table 2. A typical technical specification of DYNAPAC CA1400D single drum vibratory roller.

Messes		
Operating mass (incl. ROPS)	14,350 lb.	(63.8 KN)
Module mass (front/rear)	7,500/6,850 lb.	(33.3/30.5 KN)
Max. operating mass	15,900 lb.	(70.7 KN)
Traction		
Speed range	0-6.2 mph	(0-2.8 m/s)
Tire size (16 ply)	400/60-22.5 flotation	
Theor. gradeability	56%	
Vertical oscillation	±9º	
Compaction		
Static linear load	114 lbs/in	(19 KN/m)
Nominal amplitude (high/low)	0.067/0.032 in	(0.17/0.08 cm)
Vibration frequency (high/low amplitude)	1,920/1,920 vpm	(32/32 Hz)
Centrifugal force (high/low amplitude)	25,600/12,400 lbf	(113.9/55.2 KN)

IR camera

Since one of the objectives of this project was to deliver a low-cost solution, after studying the IR cameras available in the market, the researchers chose the FLIR PathFindIR (black and white) as the cheap but feasible camera that met the project’s requirements. The main criteria for camera selection were a minimum frame rate of 15 fps and an industrial design that allows using the camera in harsh environments. The specification for FLLR® PathFindIR (black and white) is listed below:

- Frame Rate: 30-Hz Standard
- Sensor Type: 320×240 uncooled microbolometer
- Field of view: 24º h×18º v
- Resolution: 324×256 pixel
- Focal Length: 19 millimeters
- Operation Temperature: -40ºC + 80ºC

Data logger and laptop

The data logger used in this study was Observer™ 4100 User Guide, which can collect and store the thermal data from the IR camera. The user can adjust the record setting to control the framerate and resolution of recording. Select for D1 (704×576), HD1 (704×288), or CIF (354×288). The laptop used for all data processing had 8 Gigs of memory and Intel Core i5 CPU.

ALGORITHM DEVELOPMENT

In this study, the researchers developed a thermal-based odometry algorithm for roller path tracking and mapping. This algorithm is within the scope of the monocular odometry method. In order to ensure the accuracy of visual odometry, camera calibration is an essential and indispensable step, which should be conducted before a visual odometry task. However, traditional optical camera calibration is not suitable for IR camera, since the corners of the calibration plane cannot be captured by IR camera. Therefore, a feasible and practical camera calibration needs to be developed for IR camera calibration. To this end, this study proposed a novel camera calibration method, which employs a special symmetric circular pattern. Following this, the development of the visual odometry algorithm for roller pass tracking and mapping was presented. The details of the development process were described in the following sections.

IR camera calibration

Originally, a checkerboard similar to the typical pattern was used for calibration. To make the pattern visible in long wavelengths (LWIR) spectrum range, magnet squares were placed on the black squares. The whole pattern was uniformly heated with a heat lamp, as shown in Figure 4. In Figure 4, the square edges and corners in the image taken by the IR camera were fuzzy (the image was inverted). This was due to the fact that heat disseminates into the air from the heated magnets. Thus, key point extraction for the heated chessboard pattern using IR camera was less precise compared to the calibration process for regular optical cameras. A review of the literature in this area indicated that using a heated chessboard pattern alone, and the same calibration algorithm as used for optical cameras would result in a projection error greater than 1 pixel. In this study, re-projection error for FLIR PathFindIR camera using a heated chessboard was found to be between 1.2-1.5 pixels after multiple repetitions.

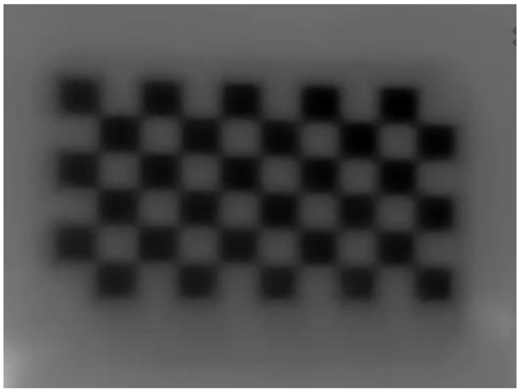


Figure 4. Thermal image of a heated chessboard pattern.

To reduce the re-projection error, a symmetrical circular calibration pattern was developed in this study, which was displayed in Figure 5. When IR camera captures the special pattern after heating, however, there are ellipse features not circular ones displayed in the thermal image. It is because the calibration pattern is not parallel to the image plane. Therefore, the ellipses detection algorithm was employed for feature detection, and the center of ellipses can be identified afterwards. An example of ellipse detection was shown in Figure 6. For the camera calibration purpose, multiple thermal images should be captured from the calibration plane with different orientations. As recommended by OpenCV manual, a minimum of 10 shots of a pattern from different angles could help get satisfactory camera calibration result. In order to obtain the camera parameters, a popular camera calibration method proposed by Zhang (Zhang 2000) was employed in this study.

Figure 5. The symmetrical circular pattern for IR camera calibration.

Figure 6. Thermal image of the symmetrical circular pattern.

Algorithm for roller tracking and mapping

The overview of the algorithm development for roller tracking and mapping was presented as follows.

Since the camera configuration was set to 15 fps (frame per second) for data collection, the time interval between two consecutive frames was 0.067 s. During this tiny interval, it was reasonable to consider the roller's motion as a linear motion, and therefore, the corresponding motion could be decomposed into two main motion components, i.e., the change of heading direction and the linear translation. To estimate the change of heading direction, the information of the vanishing point of the pavement boundaries was utilized. An example of the vanishing point of the pavement boundaries was shown in Figure 7. According to the geometric theory, the vanishing point represents the direction of a bunch of parallel lines on the same plane. On the other hand, it was also practically reasonable to consider the compaction pavement in the vicinity of the roller as a plane. Under this condition, if the roller moves precisely along the pavement boundary, the vanishing point is supposed to be stable in the image plane. Otherwise, the location of the corresponding vanishing point will change if there is a deviation between the heading direction of the roller and the direction of the pavement boundaries. Therefore, the change in roller direction contributes to the change in the location of vanishing point in the image plane. In light of this, the heading direction of the roller could be inversely identified from the dynamic information of the vanishing point. The derivation details can refer to *Multiple View Geometry in Computer Vision* (Hartley and Zisserman 2003).

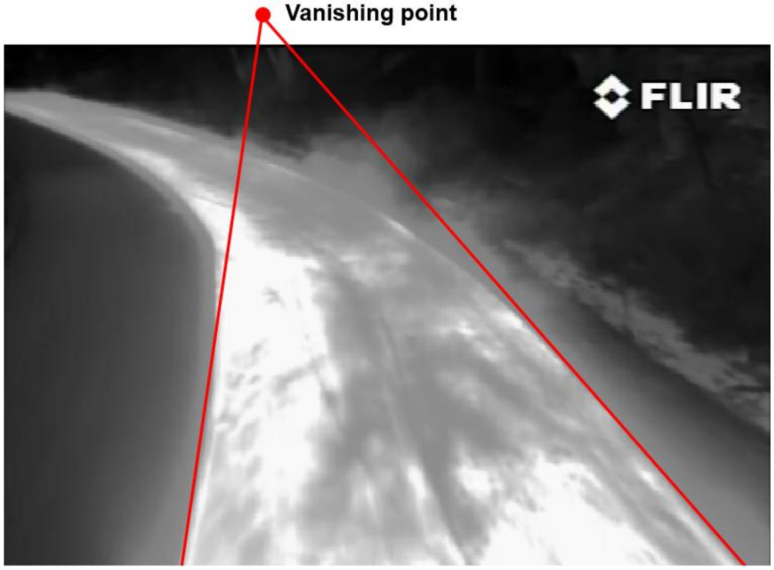


Figure 7: Two pavement boundaries and the corresponding vanishing point.

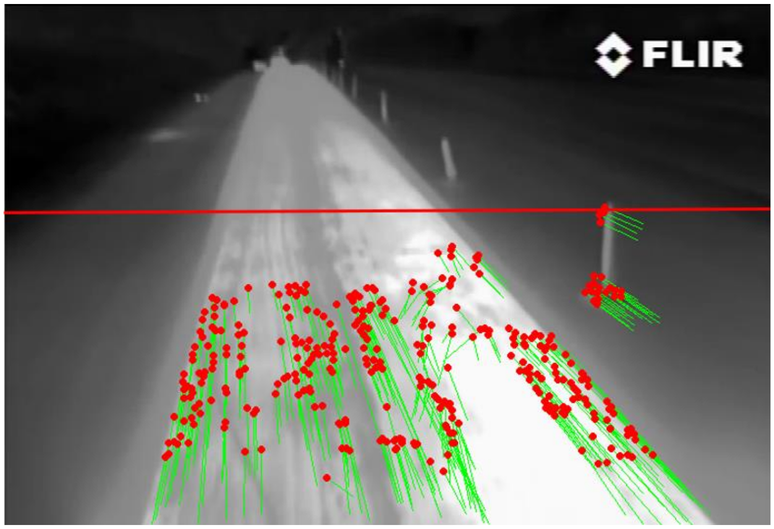


Figure 8: Optical flow estimation.

In terms of the translation component, the optical flow technique (Bouguet 2005) was employed in this study. An example of optical flow estimation was shown in Figure 8. Once the flow vector in the image plane was obtained, it would be projected onto the ground plane using the projection relationship between the image plane and the ground plane. The corresponding projection relationship could be determined from several sets of point correspondences (known physical distance between each two targets and targets' coordinates in the image plane), as shown in Figures 9 and 10. After that, the motion vector of the roller could be obtained, as an example shown in Figure 11, which is related to the translation of the roller on the ground plane. Finally, the translation of the roller within two consecutive frames can be determined by averaging the components in the motion vector.

Figure 9: Calibration setup in the field.

Figure 10: Thermal image of the calibration setup.

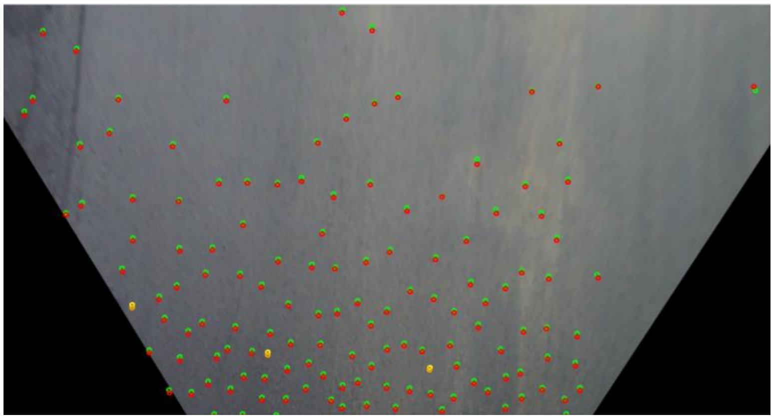


Figure 11: Motion vector on the ground plane between two consecutive frames.

After obtaining the change of the heading direction and the linear translation of the roller from two consecutive frames, the position of the roller on the ground plane in the current frame could be derived based on its location in the previous frame. Finally, the global position of the roller could be determined by cumulating the frame-by-frame motion.

SOFTWARE

The prototype of the proposed algorithm was developed in Visual Studio 2015 with OpenCV. OpenCV is an open and free source library for both computer vision and machine learning. It was built to facilitate a common infrastructure for CV applications, and it is free for both academic and commercial use. In addition, OpenCV design was based on computational efficiency with a strong emphasis on real-time application. Perhaps the most useful part of OpenCV is its architecture and memory management. It also provides users with a framework in which one can work with images and videos using OpenCV's algorithms or user-developed algorithms, without worrying about allocating and de-allocating memory for the image. Figure 12 shows the developed software in Visual Studio 2015.

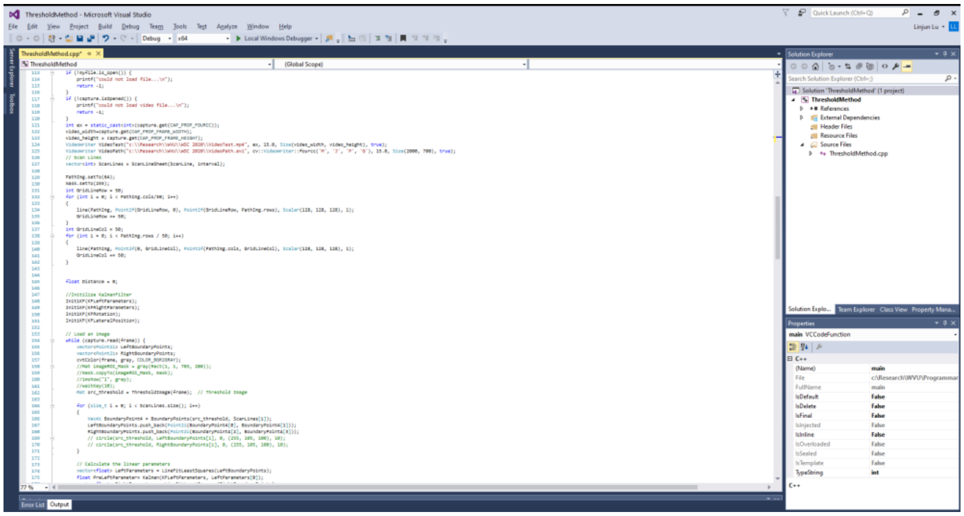


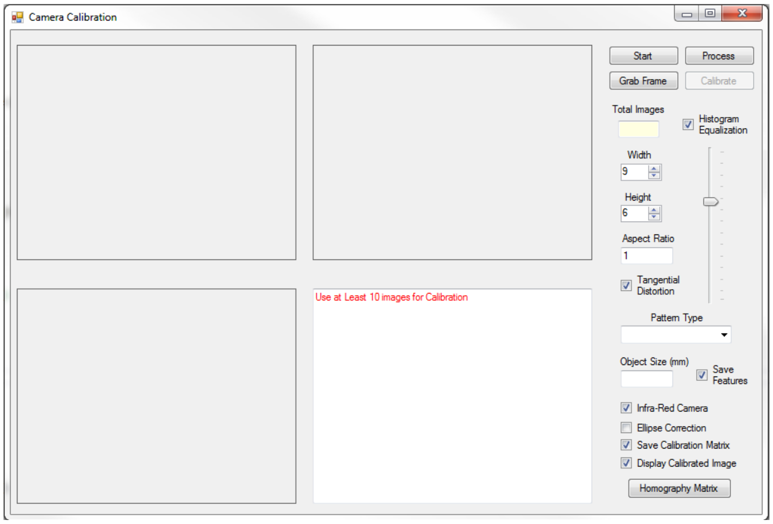
Figure 12: Developed software in Visual Studio 2015.

CHAPTER 3

Findings

INTRODUCTION

The graphical user interface (GUI) of this prototype was shown in Figures 13 and 14. In order to evaluate the performance of the proposed algorithm, qualitative and quantitative tests were performed, respectively. In terms of the qualitative performance, it was mainly based on the visual result associated with the continuous recording of color-coded plots of the roller path. As for the quantitative performance, the accumulative position error after a long run was used as the metric for accuracy validation. As this was the first phase (year 1) of the proposed study, only the initial visual result with respect to the qualitative performance was illustrated here.



Use at Least 10 images for Calibration

Total Images
☑ Histogram Equalization
Width: 9
Height: 6
Aspect Ratio: 1
☑ Tangential Distortion
Object Size (mm)
☑ Save Features
☑ Infra-Red Camera
☐ Ellipse Correction
☑ Save Calibration Matrix
☑ Display Calibrated Image

Figure 13: Camera calibration module.

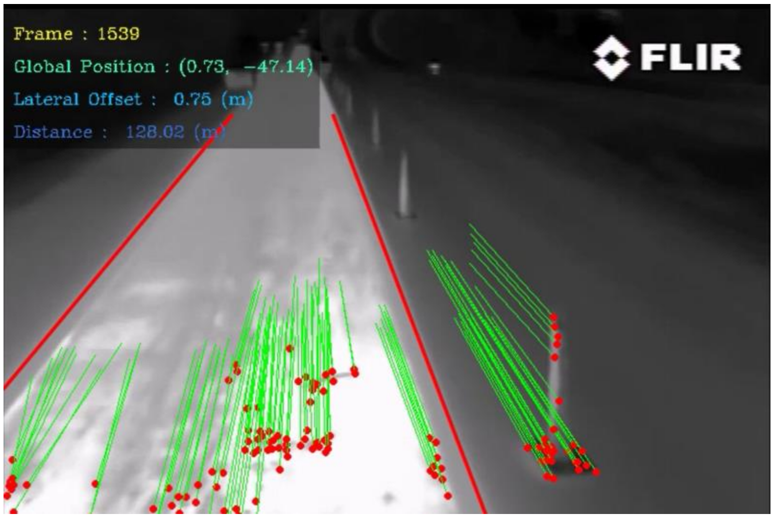


Figure 14: Roller tracking module.

PERFORMANCE EVALUATION

Using the developed prototype, experiments were conducted separately in two different pavement construction sites as listed in Table 3. As a result, 19 sets of thermal video datasets have been collected, as listed in Figure 15. As for initial stage of evaluation, only two sets of thermal video datasets were used here.

Table 3. Summary of field demonstrations.

Site	Location	Date	Materials/Construction
1	I-68E MP 24	09/10/2019	HMA new construction
2	US 50W, WV	10/14/2019	HMA new construction

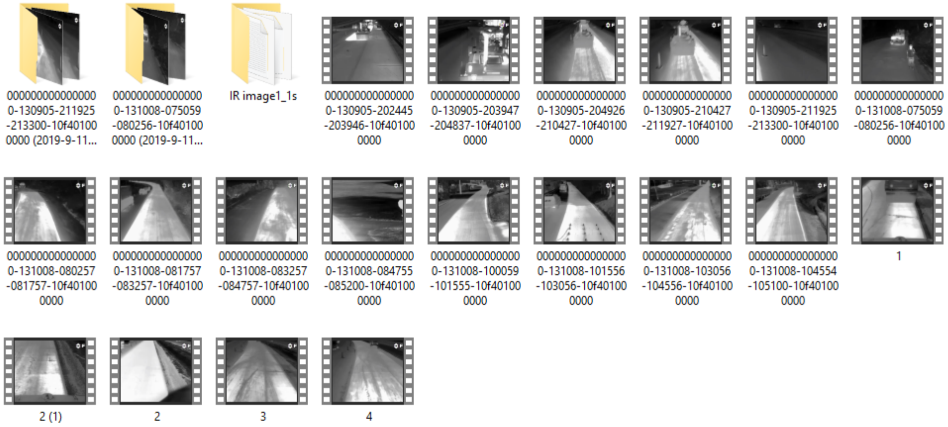
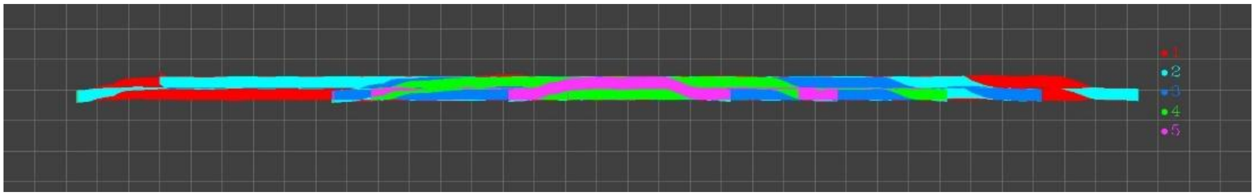
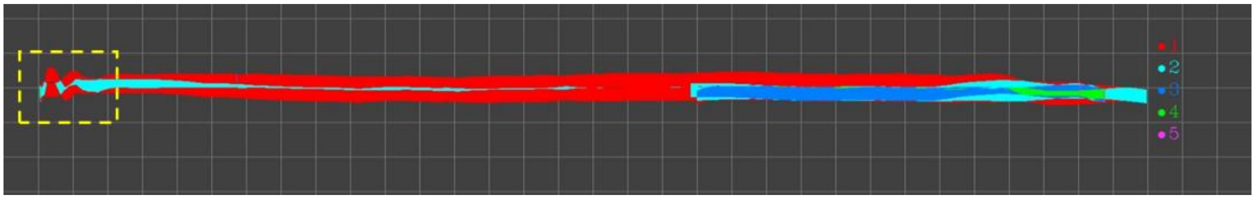


Figure 15: Thermal video datasets.

The roller tracking result identified from the developed algorithm was shown in Figure 16, which recorded the all-passes and color-coded data through the entire construction period. Moreover, the different colors shown in Figure 16 corresponded to the different number of passes. Intuitively, the result of rolling paths obtained from the developed algorithm was satisfactory, except for a small portion located on the left side of the rolling pattern, as annotated by a dashed box in Figure 16 (b). After checking the raw thermal data, this abnormal phenomenon mainly occurred when the roller was reaching the end of the layout of the pavement, namely the boundary information disappeared in the FOV of the camera. Consequently, the motion component, i.e., the heading direction, was invalid during this period. During the time when the IR camera could continuously capture the boundary, the roller tracking process remained stable and satisfactory. It visually helped validate the accuracy of the developed algorithm.



(a) I-68E MP 24



(b) US 50W, WV

Figure 16. Color-coded pass coverage and counts.

The pavement road in Pavement Construction I-68E MP 24 has two lanes with a width of 2000 mm for each one. According to the pavement requirement, the DD-110 Vibratory Asphalt Compactor roller was used in this compaction task, whose drum width is 1990 mm. Following the designed rolling pattern, the roller operator was required to drive straightly along one working lane and turn to the other lane when the operator was planning to change the movement from a back-or-forth rolling motion. The rolling operation kept up with such a paving operation pattern until a required number of roller passes had been achieved. Under this situation, it is expected that there are a proper number of roller passes that uniformly along with the mat. This expected result was observed in Figure 17, which shows the detailed information of the rolling pattern from a selected layer. Therefore, the performance of the developed algorithm was validated again.

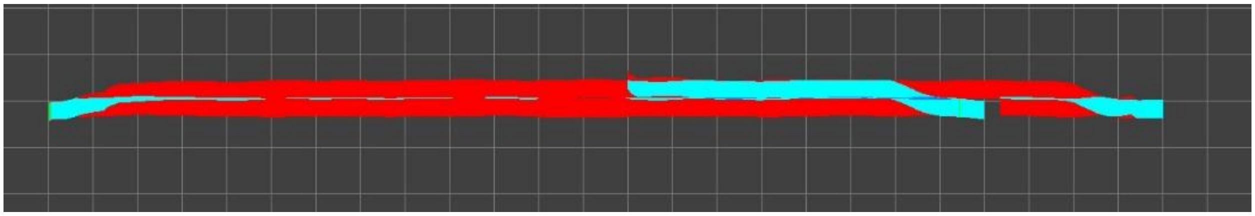


Figure 17. A typical proof-mapping from the first pavement construction.

CONCLUSIONS

In this study, the researchers developed a thermal-based algorithm for roller path tracking and mapping in pavement constructions. The visual result of the rolling pattern from two different pavement construction sites initially demonstrated the performance of the developed algorithm.

CHAPTER 4

Recommendations

Some recommendations were summarized as follows.

1. The thermal-based algorithm developed in this study demonstrated great potential for automatic roller path tracking and mapping in pavement construction in a cost-effective manner, which could be a promising alternative to existing expensive IC technologies.

2. Further experiments are still needed in order to test and improve the performance of the proposed algorithm. These will be conducted in the years two and three study. In specific, the tasks in years two and three will include: 1) testing the individual components of the system in the PI's laboratory; 2) testing the whole system in PI's laboratory to ensure functionalities and performance of the system to meet the minimum operational requirements developed; 3) testing the system as a whole in an operational environment; 4) based on the documented performance, the PI will further improve the developed algorithm to make it field-deployable.

References

Bouguet, J.Y. (2005). Pyramidal Implementation of the Lucas Kanade Feature Tracker Description of the algorithm. *Trends in Microbiology 13*(11):505–509.

Gallivan, V.L., G.K. Chang, and R.D. Horan (2011). Practical Implementation of Intelligent Compaction Technology in Hot Mix Asphalt Pavements. *Journal of the Association of Asphalt Paving Technologists*, *81*:1-32.

Hartley, R., and A. Zisserman (2003). Multiple View Geometry in Computer Vision. Cambridge University Press: Cambridge, UK.

Nieves, A. (2013). *Intelligent Compaction*. Report No. FHWA-HIF-13-051, Federal Highway Administration, Summer 2013.

Zhang, Z.Y. (2000). A Flexible New Technique for Camera Calibration. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *22*(11):1330-1334.