CIAMTIS

U.S. DOT Region 3 University Transportation Center

Unmanned Aerial Vehicles for Inspection of Tack Coats and Ancillary Highway Structures

November 20, 2022

Prepared by:

F. Dai, A. da Silva, West Virginia University; D. Lattanzi, M. Ghyabi, George Mason University; L. Wang, Virginia Tech

r3utc.psu.edu

PennState College of Engineering | LARSON TRANSPORTATION INSTITUTE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CIAM-UTC-REG28		

4. Title and Subtitle Unmanned Aerial Vehicles for Inspection of Tack Coats and Ancillary Highway Structures	**5. Report Date** November 20, 2022 **6. Performing Organization Code**
7. Author(s) Fei Dai, Aida da Silva, David Lattanzi, Mehrdad Ghyabi, and Linbing Wang	**8. Performing Organization Report No.**
9. Performing Organization Name and Address West Virginia University, Wadsworth Department of Civil and Environmental Engineering, Morgantown, West Virginia 26505-6103 George Mason University, Sid and Reva Dewberry Department of Civil, Environmental, and Infrastructure Engineering, Fairfax, Virginia 22030	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** 69A3551847103
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 12/2/2020-1/20/2022 **14. Sponsoring Agency Code**

15. Supplementary Notes

Work funded through The Pennsylvania State University through the University Transportation Center Grant Agreement, Grant No. 69A3551847103.

16. Abstract

Unmanned aerial vehicles (UAVs), also known as drones, have emerged as a non-destructive sensing technology in the construction industry for many inspection practices. Compared to other non-destructive inspection technologies, using UAVs offers benefits ranging from accelerating data collection to accessing hard-to-read surfaces and locations. With the broad camera field of view and its affordable cost, UAVs have been actively explored by the research community and industrial practitioners to enhance transportation infrastructure and community inspection practices. This project investigated the feasibility of applying the UAV technology to enhance the inspection operations of tack coats and ancillary highway structures. Proper selection of techniques and algorithm development were carried out to quantitatively assess the coverage uniformity of tack coats applied on pavements and ancillary structural performance through measurements conducted on UAV-captured images. Conduct of experiments showed promising results for use of UAVs in the inspection tasks of tack coats and ancillary highway structures, which could serve as a supplementary method for the current inspection practices.

17. Key Words	18. Distribution Statement
Tack coats, ancillary highway structures, drones, unmanned aerial vehicle, UAV, computer vision applications	No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	25	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER

Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

BACKGROUND

Tack coat is a thin layer of asphalt that ensures the bonding between an existing pavement and an asphalt overlay. It is typically used for renovation of asphalt pavement to achieve better bond strength. Poor application of tack coats may result in inadequate bonding between the existing pavement surface and the overlay [1]. This can cause slippage, shoving, and rutting of the overlay, whose direct results are an uncomfortable driving experience and reduced service life of the pavement structure [2], [3]. To ensure the construction quality during the process of asphalt pavement renovation, state agencies (e.g., West Virginia DOT, Virginia DOT, and Pennsylvania DOT) actively send inspectors to perform visual inspection of the operation at the jobsite. One of their ultimate goals is to ensure uniform coverage of the applied tack coats before the overlay is applied. Nevertheless, the current practice of tack coat inspection done manually is somewhat inefficient. The process is tedious and time-consuming and points to a need for new technologies that can allow state pavement inspectors to rapidly assess the quality of tack coat operations and make accurate, timely decisions about actions needed to control the quality in construction.

Departments of transportation (DOTs) and other managing highway agencies have long been legally obligated to routinely inspect and assess critical assets such as bridge structures and roadway pavements. What has historically received less attention are the many ancillary structures along roadways such as luminaires, high-mast light poles (HMLTs), and sign structures. Over the last decade, these structures have experienced premature failure stemming from corrosion, fatigue, and installation irregularities [4]. As a result, many DOT agencies have increased the required frequency and rigor for inspecting ancillary structures. While ancillary structures are usually much smaller in scale than a bridge, their inspection often requires expensive rigging, and inspections can be disproportionately time-consuming relative to their size and quantity [5], [6]. This has resulted in major cost pressures for DOTs. For example, in Virginia ancillary structures now account for 20% of the overall inspection budget. There is a need to develop new inspection methods for ancillary structures that are faster and more economical than the primarily manual visual inspections in widespread use.

This project investigated the feasibility of applying unmanned aerial vehicles (UAVs) to accelerate and improve the inspection and management of tack coats and ancillary highway structures. UAVs can potentially provide a platform for comprehensive, high-resolution, and high-frequency imaging of pavements and structures without the need for excessive rigging and traffic control. Combined with computer vision and other techniques for interpretation of the recorded images, using UAVs may provide unique measurements of coverage uniformity of tack coats and ancillary structural performance. The goal was to consider the problem as an integration of hardware and software, comprising a complete UAV-based solution system.

OBJECTIVES

The objectives of this research project were to:

1. Identify the most viable implementation scenarios for UAVs in tack coat and ancillary structure inspections;
2. Construct data products that support development of inspection technologies for tack coats and ancillary structures via UAVs;
3. Create algorithms and analytical methods that leverage these data products to accelerate assessments;
4. Identify key UAV hardware parameters necessary to optimize the solution; and
5. Evaluate the overall approach through realistic field testing.

DATA AND DATA STRUCTURES

Data Generation for Tack Coat Uniformity Inspections

In order to assess the adequate uniformity for tack coat, the level of uniformity was referenced through examples of tack coat uniformity provided by the Virginia Asphalt Association [7], as shown in Figure 1, and their grading levels were leveraged to facilitate this research. The Virginia Asphalt Association's supplemental information on Section 310 - Tack Coat for the tack coat inspection and verification process has stated that inspectors from VDOT are required to actively inspect the coating distribution to ensure that grade "A" should be achieved to maintain the adequacy of bonding. Otherwise, recoating is necessary if the "B" and "C" level of uniformity are being spotted. To facilitate the development of algorithms that enable the UAV-based solution to recognize a wide variety of uniformity levels for tack coat inspection, a set of image data with respect to tack coat layering on pavements were collected from pavement construction sites and the internet. The data were carefully evaluated to ensure that no other objects were presented in the segmented images and labeled with the assistance of a DOT field expert.

Source: Virginia Asphalt Association

Figure 1. Tack coat uniformity criteria used by VDoT inspectors.

A series of UAV test flights were performed on the pavement construction sites in order for collecting appropriate data. Figure 2 shows one example of a video frame captured by the UAV. The research team identified the height to be approximately over 30 ft to operate the UAV so that the field of view of the camera fully covered the region of interest (tack coat in this case). A series of 4K recording videos of milled road covered with tack coats were collected from a DJI Phantom 4 Pro+ V2.0. Two batteries were used, and each battery could hold up to about 18 minutes of recording in the air. During videotaping, the optical axis of the camera on the UAV was set to around 90 degrees to the road surface. The sample rate was 30 frames per second. A total of 2,699 seconds of video were recorded, and the longest recorded video was

327 seconds. In total, 17 video files were collected, and only 9 files were used based on the test flight results. For the inspection algorithm development, a total of 2,896 frames were selected from the extracted frames, together with 684 images collected from the internet, to form the dataset.

Figure 2. An example of inspected tack coat uniformity layering, as viewed at 90° by a UAV during inspection.

Data Generation for Ancillary Highway Inspections

A review of prior work in ancillary structures indicated that most relevant structures, for instance lightpole masts, act as cantilever beams under the wind loads that drive their structural response. A series of laboratory-scale specimens were designed to simulate this behavior in a controlled environment. To create the test specimens, a cantilever structure was fabricated out of aluminum framing. The structure was designed so that various masses could be applied to change the dynamical system properties of the specimen (Figure 3). Since the aluminum beam had negligible mass in comparison to the weights used for loading, the behavior of the system could be simplified to that of a lumped mass-spring-damper model (single degree of freedom). These test specimens were evaluated under laboratory conditions, and then under field conditions. UAV field testing on full-scale ancillary structures was also performed, as will be discussed.

Figure 3. Experimental test frame with camera and laser displacement sensor.

For both the laboratory and field testing of the aluminum frame, the specimen was excited under a variety of dynamic and static loadings. The structural response was recorded in digital videos as well as ground truth sensor measurements. In the laboratory tests an Edmund Optics EO-2323 industrial camera was used to record the videos. This is a monochrome machine vision sensor, with a sensor size of 9.22x5.76 mm (1920x1200 pixels). To achieve higher data sampling rates, only a region of interest (ROI) containing the tip of the cantilever beam was recorded. By recording this 444x160 pixel area, and setting the pixel clock and exposure time to 200 MHz and 1.19 ms respectively, a frame rate of 1,000 fps was achieved. For the field testing of the specimen, a Panasonic GH5 camera recorded the videos. The GH5 has a sensor size of 17.3x13 mm (5184x3888 pixels), though only a portion of that resolution was accessed during video recording (following specifications for 4K and 6K video standards). The GH5 recorded test data at 60 fps.

In the laboratory setting, a Micro-Epsilon optoNCDT 1320-10 laser sensor was installed above the cantilever beam. The precision of this device is 10 μm, and the measuring range of this model is 10 mm, sufficient for the range of displacement of the cantilever beam in this experimental setup. The laser displacement meter is able to record data with acquisition frequency up to 2 kHz. However, to improve synchronization with the video recording, the data sampling frequency was set to 1 kHz. In the field setting, the known and calibrated properties of the structural system, as determined through prior laboratory testing, served as ground truth.

In addition to the testing on the structural test frame, a series of UAV test flights were performed on the George Mason campus. The research team identified a series of lightpole masts that were representative of ancillary highway structures, and that could be safely navigated by a UAV. A DJI Phantom 4 Pro V2.0 recording in 4K was used for all piloted UAV tests. A total of 654 seconds of video were recorded in 9 files, at 30 fps sampling rate. Out of nine files, eight were recorded for the purpose of video-based displacement measurement. The longest recorded video of 317 seconds was recorded for the purpose of creating a point cloud of the light pole, though this ultimately was not used during the research program. Out of eight recorded displacement measurement videos, three were too noisy to work with due to environmental disturbances during the test flights. A total of 10,110 image frames were available for the task of video-based displacement measurement.

Figure 4. Examples of inspected lightpole masts, as viewed by a UAV during inspection.

CHAPTER 2

Methodology

INTRODUCTION

The overall goal of this project was to develop a UAV-based solution for augmenting the inspection of tack coat uniformity and ancillary highway structures that would otherwise require expensive rigging and manual labor for assessment. Achieving this required an operational assessment of both tack coat and ancillary inspection practices, as well as the available UAV technologies and potential data products. These were used to prototype UAV inspection workflows and inform the development of analytical methods for assessing the resulting data products.

Proposed Methodology for Tack Coat Coverage Uniformity Inspection

The proposed setup of the UAV use in tack coat inspection is illustrated in Figure 5. The airborne UAV captures video frames after application of the tack coats on milled pavements. The appropriate height should be selected to have sufficient coverage of the region of applied tack coats as well as to avoid unnecessary coverage of too much irrelevant surrounding objects in the pavement scene. The UAV should be operated along the pavement until the desired tack coat region is thoroughly covered and inspected. The UAV's speed should be controlled between 4 ft/s and 10 ft/s to avoid distortion or blur in the video frames. Once the video frames are collected, they are transferred to a computer workstation for uniformity assessment using the developed algorithm detailed in the following subsection.

Figure 5. Overview of proposed setup of the UAV used for tack coat uniformity inspection.

Algorithm Development

The collected data were sent to a computer workstation for further processing in this research using the developed algorithm, which primarily consists of two main steps. Considering that flying the drone to purely film the tack coat region without capturing the surroundings from the UAV's field of view would be impractical for the operator to handle, the first step was extracting the boundary lines and segmenting the coating area in the captured image frames. The boundaries are detected to locate the coating region that would allow for tack coat uniformity assessment performed only within this region in the following step. The second step was to measure the coating coverage and provide a grading scale based on pre-defined criteria.

Extracting the tack coat boundary lines from video frames

Techniques for boundary line extractions were considered to narrow the focus to only the tack coat regions for image processing. Two main features of the tack coat were considered. The first feature was the color of tack coat. Despite the type of tack coat materials [8], it was assumed that the tack coat is composed of a single color. So the algorithm was designed firstly to capture the pixels belonging to a single object using a defined histogram threshold for the color [9]. By converting the RGB (red, green, and blue) image to an HSV (hue saturation value) color scale, the image is represented with a numerical measurement in degrees that correspond to different colors contained in the image. When viewing the tack coat region in the HSV space, three important pieces of information on the color can be retrieved. The first is the true color value of the tack coat which, is defined by H (hue). The second piece of information is S (saturation), which provides the chromatic information of the tack coat color. The last piece of information is V (value), which represents how bright the color is, and it changes the color intensity from light to dark. Defining the minimum and maximum thresholds to establish a range of HSV values allows for capturing tack coat pixels by abandoning pixels of the neighboring objects. However, this is excluding the non-uniformity pixels in the segmentation.

Therefore, the second feature was considered, which was the tack coat boundary edges in the images. The result of the color thresholding led to a region in which the boundary detection operation was performed. To detect the boundary lines, one of the most used methods called Hough transform [10] was applied. This method discretized the edge points map generated from a Canny edge detector into Hough Space using angle-radius parametrization. A voting scheme and minimum distance threshold were used to filter the potential detected lines down to the local maxima and further reduce redundancy in line fitting [11]. From the detected straight lines, the 2D image points' coordinates were then calculated where the lines intersect the x-axis of the image. There were four points' pixel coordinates extracted. The first two were extracted at the origin where the height was 0, while the other two were extracted at the height equal to the height of the image. The obtained four points formed the tack coat region for subsequent uniformity analysis.

Measuring the coating uniformity

The texture analysis was applied to measure the coverage uniformity at the pixel level. The surface texture was measured in 256 grey tonal levels using the grey-level co-occurrence matrix (GLCM). The GLCM matrix is formed from the frequency of grey level variations between two pixels known as a reference and neighboring pixels [12]. To establish the GLCM matrix, the relationship between reference and neighboring pixels was defined by two parameters: angle and distance. The angle refers to the direction along which neighboring pixels are selected and processed. The distance is the offset distance between the reference and neighboring pixels. For the matrix, six different texture metrics were computed – namely, contrast, correlation, homogeneity, energy, dissimilarity, and angular second moment. To compute these texture metrics, the two parameters of angle and distance were set as: 0°, 45°, 180°, 135°, 225°, 315°, and 5 pixels, 10 pixels, respectively. The discriminative patterns in the obtained texture metrics were used to determine the level of uniformity, and the identification was based on the pre-defined uniformity criteria defined by the field expert.

Proposed Methodology for Ancillary Structures Inspections

The project initiated with an assessment of ancillary structural inspection practices and prior work using UAVs and imaging methods for structural assessments. The primary finding was that fatigue cracking due to cyclical wind vibrations was the primary concern for most inspections [13], [14]. While UAVs are capable of collecting a wide variety of data, the focus on structural dynamics and fatigue meant that high-speed video recording was the most suitable data product for the project. Ancillary structures experience their primary vibrations below approximately 20 Hz, and so the UAV camera needed to record high-resolution 4K video at higher than 40 Hz to avoid signal aliasing [15]. Additionally, high-resolution imaging capable of resolving fatigue cracks in images was deemed to be an important data product for UAVs.

The flight plan for the UAV field testing was designed to position the UAV in a location where the camera sensor plane would be adjacent to the primary plane of structural vibration. The UAV would then fly to an altitude matching that of critical structural elements in order to minimize the ground sample distance (GSD) for the target element and thereby maximize the relevant image resolution.

Analytical Methods

The operational assessment identified two critical challenges for using UAVs to perform dynamic assessments of structures. One technical difficulty is that a UAV is constantly in motion during any given flight, and even small motions need to be corrected for in order to capture accurate structural motions. The second difficulty is that the motion of ancillary structures under wind loads is small, on the order of millimeters, and requires highly accurate computer vision methods and signal post-processing for viability.

Removing UAV motion from videos

The research team considered two methods for eliminating UAV camera motions. The first approach was to consider the problem as a reframing of the classic camera pose estimation problem in computer vision [16]. The concept is that if the global position of the camera can be found in any given image, the image can be adjusted to account for small UAV camera motions [17], [18]. There are a variety of ways to find this global position, but a well-established method is using the coordinates of at least six known locations in a global 3D coordinate system as well as their coordinates in the 2D image coordinates system. This method leads to solving eigenvalue problems iteratively to estimate the fundamental camera matrix for any given pose. The fundamental matrix can be used to estimate the location of the camera center in the 3D coordinate system. To test the viability of this approach, a 3D target was designed and fabricated (Figure 6).

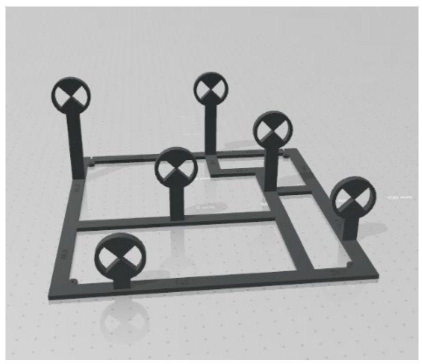


Figure 6. Designed calibration target.

Another approach considered for removing UAV motions was frequency domain signal processing. An advantage of using UAVs as displacement sensors is that the frequency range of UAV movements due to wind currents is much lower than that of conventional light poles. This creates a gap in the frequency spectrum of the unfiltered signal between UAV frequency and the frequency of the structure. The existence of this gap allowed for the use of frequency filters in the Fourier domain representation of a signal.

Measuring structural displacements

One of the most well-established methods for measuring displacements of objects in video frames is phase-based motion tracking [19]. This technique is specifically efficient when object surfaces include edges perpendicular to the direction of motion, as is the case for ancillary structural vibrations. That is because the process uses a complex filter with a real part that is a Gaussian filter and an imaginary part that is a Hilbert wavelet. The result is strong amplitudes on or near the directional edge that result in a reliable phase measurement proportional to the structural displacement. Another benefit of using the phase-based approach is the availability of computationally efficient matrix operations. Unlike many other approaches, in phase-based analysis it is not necessary to analyze each video frame sequentially. The frames of the video are considered as a single 3D signal, and so all Fourier transformations can be performed at once for all frames. This means that phase-based displacement measurements are relatively efficient, computationally.

CHAPTER 3

Findings

PERFORMANCE EVALUATION FOR THE TACK COAT INSPECTIONS

Evaluation of Boundary Lines Detection

The performance of the boundary lines detection algorithm was evaluated on the collected image set. The Intersection over Union (IoU) metric was selected to measure the overlapping between the detected boundary lines of the tack coat region and ground truth. The ground truth boundary lines were manually labeled using VGG Image Annotator (VIA). The IoU reflects that the closer the value is to 1, the higher the accuracy is. Figure 7 shows the result of the evaluation performance for the developed algorithm. The algorithm has an average of 0.9 accuracy (represented by the straight line in Figure 7) in detecting the tack coat region boundary lines. Figure 8 shows two representative detection results from images collected in the field. In these detection results, the boundaries of the tack coat region were successfully retrieved and are annotated in red.

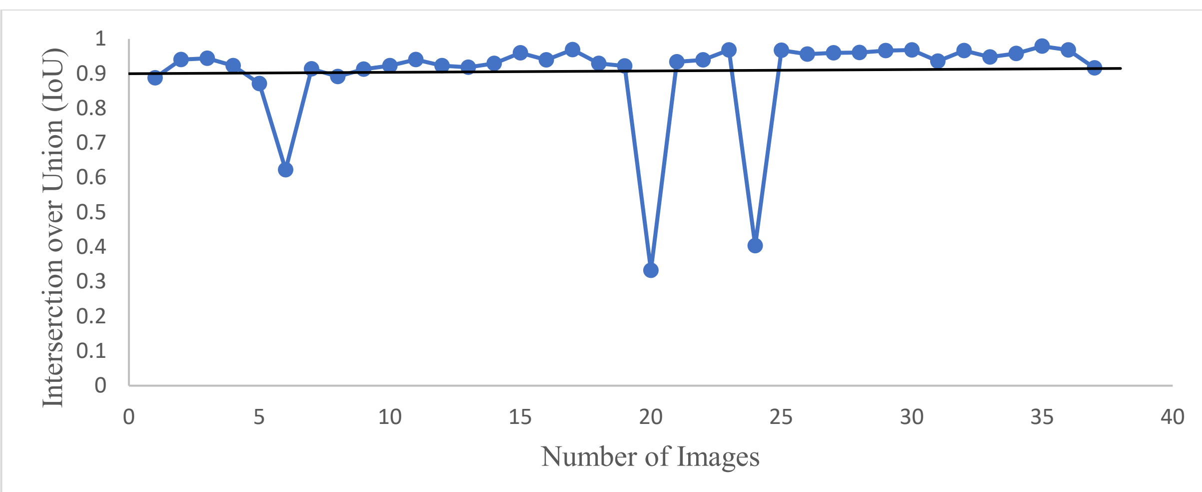
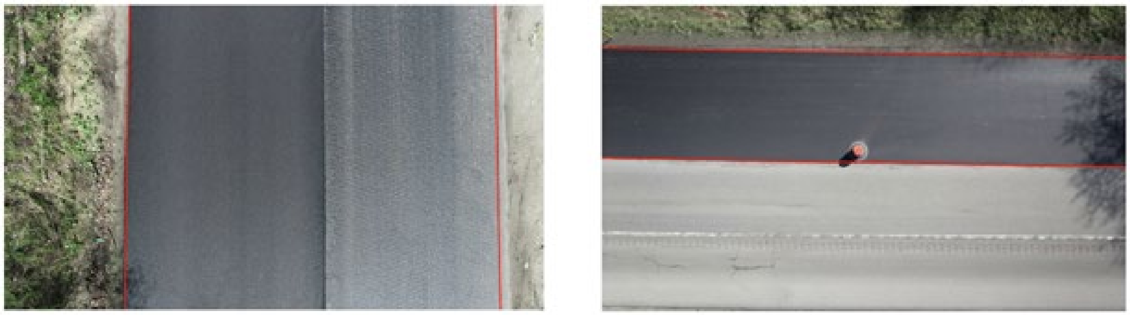


Figure 7. Intersection over Union between the ground truth and the detected boundary lines.



(a) (b)

Figure 8. Examples of boundary lines detection of layered tack coat regions.

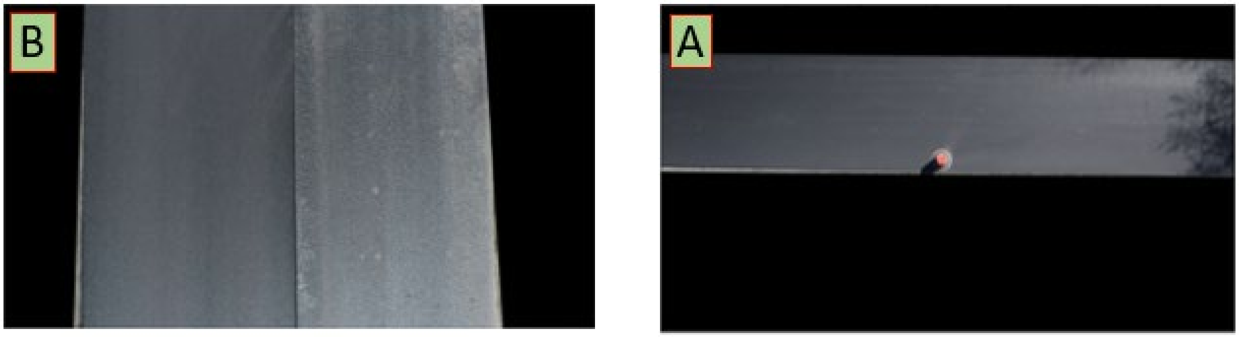
Evaluation of Coverage Uniformity Measurement

Given the ground truth data manually labeled with the help from a subject matter expert, the performance of the coverage uniformity measurement was evaluated using the precision and recall metrics; the evaluation results are presented in Table 1. Here, precision is expressed as TP/(TP + FP), where TP is the true positive that represents the number of correctly detected target objects (tack coat coverage uniformity levels: A, B, and C), and FP is the false positive that denotes the number of falsely detected target objects (e.g., a tack coat coverage uniformity level is falsely detected as A, but actually it is B or C). The recall is defined by TP/(TP + FN), where FN is the false negative that denotes the number of target objects not being successfully detected (e.g., a tack coat coverage uniformity level should have been detected as A, but actually it is wrongly detected as B or C). High precision indicates that most of the detected uniformity levels are the actual target objects. High recall shows that most of the target uniformity levels are successfully detected.

Table 1. Performance evaluation for the measurement algorithm of the tack coat coverage uniformity.

Uniformity Level	Ground Truth	TP	FP	FN	Precision	Recall
Level A	147	128	10	19	92.8%	87.1%
Level B	38	33	11	5	75.0%	86.8%
Level C	43	35	11	11	76.1%	81.4%
Average	-	-	-	-	81.3%	85.1%

Examples of field experiments on coverage uniformity measurement are shown in Figure 9. The results of the measurement show that the coverage uniformity in Figure 9(a) was scored as a B level, while the coverage uniformity in Figure 9(b) was rated as an A level. The B level of uniformity was taken after a few days of coating without applying overlay due to rain, and the layer had been covered with dust later, thanks to the traffic movement. It can also be observed in Figure 9(a) regarding the non-uniform pattern. As shown in Figure 9(b), the tack coat is layered uniformly throughout the region.



(a) (b)

Figure 9. Examples of extracted and measured tack coat regions.

PERFORMANCE EVALUATION FOR ANCILLARY HIGHWAY STRUCTURE INSPECTIONS

Evaluation of Camera Motion Corrections

Initial testing of the camera target system was performed in a laboratory setting. To test the effectiveness of the targeting system, the target was installed on the structural beam specimen. Static loads were then applied sequentially to the test specimen and the position of the calibration target was tracked throughout the quasi-static loading process. The measured error in target position was computed using the ground truth laser displacement measurement (Figure 10). As the figure shows, the target tracking approach yields very low errors, though error did accumulate as loading increased. Overall, the laboratory experiments showed that 3D positional targeting is an effective method for isolating motions. Unfortunately, logistical restrictions at the field testing sites prevented full-scale field testing of the targeting system.

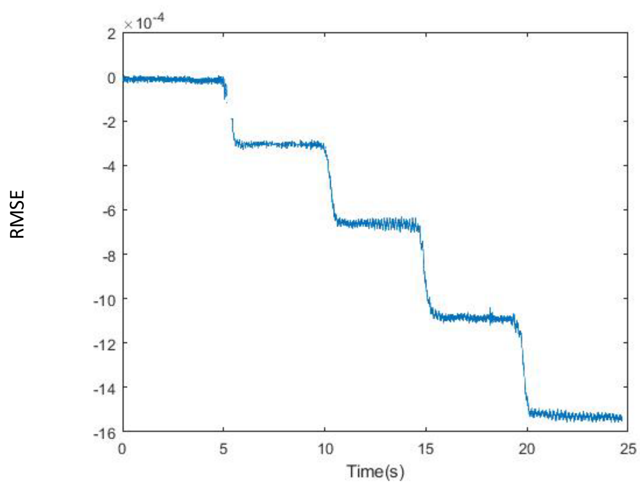


Figure 10. Error analysis for camera calibration testing, static load test results.

Evaluation of Structural Motion Detection

The laboratory and field tests on the fabricated test specimens indicated that phase-based motion detection is a viable approach to structural displacement tracking. The exhaustive set of tests are not reported here for clarity. Figure 11 shows a representative set of measurements for both a laboratory and field environment. What these results illustrate is that moving from a laboratory to a field environment degraded measurement accuracy by an order of magnitude. In both cases, the ground sample distance (i.e., the pixel metric) is roughly equivalent. But environmental effects such as atmospheric distortion clearly degrade measurement capabilities and must be considered when designing field applications for computer vision systems.

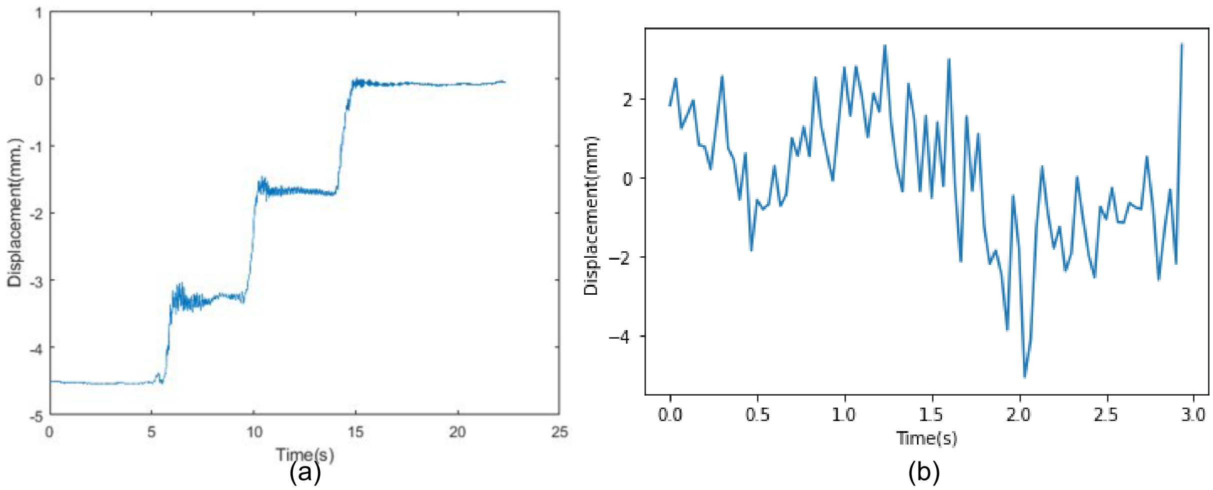


Figure 11. Phase-based displacement measurements in (a) laboratory setting and (b) field setting.

Evaluation of Camera Motion Corrections

The results from the field testing of the UAV platform were promising but also served to highlight the many practical challenges associated with complex robotics field applications. Due to the nature of the testing environment, the calibration target could not be safely installed onsite. It remains an open question whether or not such a target could be implemented by practitioners performing field tests and is an avenue for future work. As a result, signal processing of the phase-based signals was the only method available to remove the UAV motions, estimated to be in a frequency band below 1 Hz. An example of the resulting displacement measurement for a full-scale lightpole mast is shown in Figure 12.

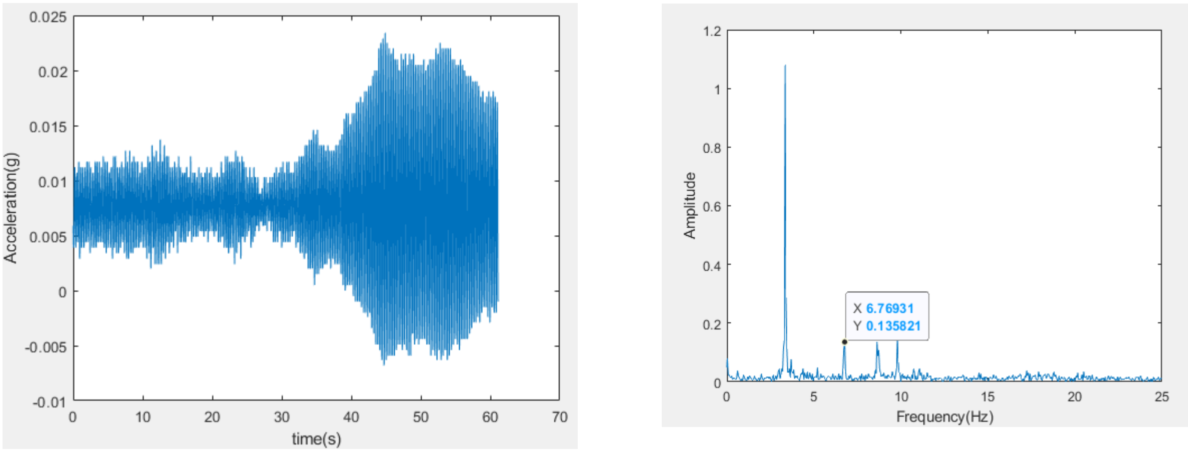


Figure 12. Time domain and frequency domain representation of lightpole mast vibrations, as captured through UAV imaging.

The resonant frequency response of the lightpole masts was clearly captured through the phase-based analysis, though further study is warranted to validate whether or not the observed frequency content matches the true structural response of the lightpole systems. The biggest difficulty faced by the research team was that the video motion approach was reliant on the camera sensor being roughly co-planar with the plane of motion of the lightpole masts, a limitation shared among almost all monocular computer vision methodologies. However, actual structural vibrations were clearly observed to be fully three dimensional, a fact that likely degraded performance significantly. In a 2D image analysis problem, 3D motions are typically miscomputed as unrealistic motions, as shown in Figure 13.

Figure 13. Example of 3D lightpole motion, manifested as unrealistic motion vectors.

CHAPTER 4

Recommendations

SUMMARY AND CONCLUSION

This project considered how UAVs could be used to enhance the inspection of tack coats and ancillary highway structures and reduce the time and cost of those inspections. The result of existing inspection practice, which has relied on subjective judgement and experience, was the principal driver for the development of the proposed techniques.

For tack coat inspections, the main purpose is to ensure uniform coverage in applications of tack coats. To enhance the existing inspection practices, the main idea here was to harvest the power of image processing to provide automatic and objective measurement of coverage uniformity of tack coats. The designed technique involves combination of a UAV with computer vision techniques. The UAV is applied to record videos of tack coats within controlled speed, and the videos are further processed to provide a quantitative measurement of coverage uniformity.

The development of the measurement algorithm was guided by the technical challenges addressed in the steps detailed in the methodology. The developed technique was tested with UAV-collected images from pavement construction sites, and the accuracy of the technique in detecting the boundary and measuring the coverage uniformity was promising. However, more comprehensive evaluations are still needed to challenge the technique in different conditions associated with factors such as lighting, shadows, and occlusions. The improvement will be made based on the collected evaluation performance to further enhance the technique's practicality.

For most ancillary structural inspections, an assessment of existing inspection practices indicates that fatigue analysis is the primary motivation. In particular, the ability to quantify the dynamic response of an ancillary structure in-situ and then associate that response with a statistical estimate of remaining fatigue life became the driver for the developed technical approach. That approach was designed to use a UAV to record structural vibrations of an ancillary structure through video recordings, followed by a series of computational analyses that quantify the dynamic time history response of a structure through computer vision, while also accounting for the motion of the UAV itself.

The key technical challenges addressed in this work were the development of approaches for compensating for the UAV motion and for measuring structural response through video motion analysis. These methods were tested under laboratory and field conditions. The project concluded with a series of UAV-based experiments on resurfacing jobsites and full-scale lightpole masts. The resulting measurement accuracy was promising, as was the effectiveness of the target-based camera motion correction method. However, the complexities of full-scale 3D structural dynamics and the logistics of the field environment pose a variety of technical problems that must be addressed prior to implementation.

AVENUES FOR FUTURE WORK

Despite the achievements, the proposed technique for tack coat inspection still has room for improvement. Further research can be done in creating additional functions to locate the non-uniformity regions in the images and provide percentage of coverage for the spotted regions. Also, more comprehensive evaluations are suggested to evaluate the technique in different conditions associated with factors such as lighting, shadows, and occlusions to enhance the technological practicality.

The most critical avenue for future work is the need to extend the measurement process to fully three-dimensional structural vibrations. Without such developments, UAV-based vibration analysis will not be practical for ancillary structures. Potential technical approaches could include exploring stereo-vision UAV systems or monocular computer vision approaches for depth map estimation. Additionally, more robust methods of camera motion estimation are warranted, as is an operational assessment of the implementation feasibility of the designed 3D calibration target.

References

1. Transportation Research Board (2012). *Optimization of Tack Coat for HMA Placement*, National Cooperative Highway Research Program: Washington, DC.
2. Federal Highway Administration (2016). *Tech Brief: Tack Coat Best Practices*. Office of Asset Management, Pavements, and Construction: Washington, DC.
3. Allen, G. (2016). *Poor Tack Coats Are Killing Our Roads: Why?* [accessed 11/12/2022]; https://blacklidgeemulsions.com/interlayer-bonding-part-iii/].
4. Ward, B.R. (2009). The Falling Sky: Aging High-Mast Light Towers a Growing Concern in US. *Roads & Bridges*, 47(1):52-55.
5. Starnater, P., and C. Eric (2007). Inspection, Repair, and Rehabilitation of Ancillary Highway Structures to Enhance Fatigue Performance. Transportation Research Board 86th Annual Meeting.
6. Foley, C.M., R. Fournelle, S.J. Ginal, and J.L. Peronto (2004). *Structural analysis of sign bridge structures and luminaire supports*. Wisconsin Highway Research Program, Report No. WHRP 04-03.
7. Hobson, R., and H. King (2016). *Supplemental Section 310 - Tack Coat: Tack Coat Inspection and Verification Process,* Virginia Asphalt Association [accessed 11/11/2022]; Available from: https://www.vaasphalt.org/wp-content/uploads/2016/03/Pres4_Tack-Coat-Inspection-and-Verification.pdf.
8. Mohammad, L.N., M. Raqib, and B. Huang (2002). Influence of asphalt tack coat materials on interface shear strength*. Transportation Research Record*, 1789(1):56-65.
9. Abeid Neto, J., D. Arditi, and M.W. Evens (2002). Using colors to detect structural components in digital pictures*. Computer-Aided Civil and Infrastructure Engineering*, 17(1):61-67.
10. Pratt, W.K. (2007). *Digital image processing: PIKS Scientific inside.* Wiley-Interscience: Hoboken, N.J .
11. Fernandes, L.A., and M.M. Oliveira (2008). Real-time line detection through an improved Hough transform voting scheme*. Pattern recognition*, 41(1):299-314.
12. Haralick, R.M., K. Shanmugam, and I.H. Dinstein (1973). Textural features for image classification*. IEEE Transactions on Systems, Man, and Cybernetics*, SMC-3(6):610-621.
13. Singh, J., and M.H. Hebdon (2021). Investigation of Anchor Nut Loosening on Highway Ancillary Structures*. Journal of Structural Engineering*, 147(4):04021026.
14. SoleimaniBabakamali, M., A. Moghadam, R. Sarlo, M.H. Hebdon, and P.S. Harvey, Jr. (2021). Mast arm monitoring via traffic camera footage: A pixel-based modal analysis approach*. Experimental Techniques*, 45(1):329-343.
15. Garlich, M.J., and E.T. Thorkildsen (2005). *Guidelines for the installation, inspection, maintenance and repair of structural supports for highway signs, luminaires, and traffic signals*. Federal Highway Administration, Report No. NHI 05-036.
16. Hartley, R., and A. Zissernan (2004). *Multiple view geometry*. Cambridge University Press, Cambridge.
17. Khaloo, A., and D. Lattanzi (2017). Pixel-wise structural motion tracking from rectified repurposed videos*. Structural Control and Health Monitoring*, 24(11):e2009.
18. Pollefeys, M., L. Van Gool, M. Vergauwen, F. Verbiest, K. Cornelis, J. Tops, and R. Koch (2004). Visual modeling with a hand-held camera*. International Journal of Computer Vision*, 59(3):207-232.
19. Gautama, T., and M. Van Hulle (2002). A phase-based approach to the estimation of the optical flow field using spatial filtering. I*EEE Transactions on Neural Networks*, 13(5):1127-1136.