Railroad Bridge Inspections for Maintenance and Replacement Prioritization Using Unmanned Aerial Vehicles (UAVs) with Laser Scanning Capabilities

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EXECUTIVE SUMMARY

Railroad Bridge Inspections for Maintenance and Replacement Prioritization Using Unmanned Aerial Vehicles (UAVs) with Laser Capabilities
Safety IDEA Project 32

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IDEA CONCEPT AND PRODUCT

This research focused on the development and implementation of contact-free, reference-free transverse bridge displacement measurements. Recent research had shown that transverse displacements of timber trestle bridges can capture critical changes in bridge serviceability (the ability to safely carry out railroad operations) as a function of railroad loading, speed, and direction. Measuring bridge movement under trains in the field is difficult and expensive because a fixed reference point is not normally available, thus creating the need to erect independent scaffolding to create good reference points near the bridge from where to measure. The research included a concept test for integrating UAVs and laser technologies to assess the structural condition of simply supported spans of conforming steel railroad bridges, which can be instrumental in informing the subsequent prioritization of more detailed inspections. The primary tasks for developing this system was a robust integration of a Laser Doppler Vibrometer (LDV) sensor with a copter-type UAV, optimization of sensor data accuracy, optimization of UAV positioning and movement characteristics, and effective data analysis methods to measure displacements. The main emphasis of this research was freight traffic and transportation, but the application is expected to assist any other type of railroad operation.

PROJECT RESULTS AND FURTHER INVESTIGATION

Initial testing focused on characterizing constituent components of the system: the behavior of the copter UAV, the data from the LDV, and the expected data from current measurements of this type using conventional methods. Researchers compared the data of the LDV sensor to a common tool for linear displacement, the linear variable differential transformer (LVDT), to analyze the relative data outputs before mounting to the UAV. Subsequently, the researchers completed the characterization of the constituent components, and integrated the components into a preliminary testing platform. Finally, researchers collected data to determine their effects on data output of the LDV. The research team collected data outdoors for preliminary validation of the new technology. Results indicated that the prototype was able to monitor movements simulating the vibrations of a train crossing (Figures 1 and 2).

(a) **(b)**

Figure 1. First outdoor laser UAV testing for measuring contact-free, reference-free displacements compared with reference displacements: (a) experiment general view; (b) reference displacement detailed view.

The research team discussed with the Transportation Technology Center, Inc. (TTCI) in Pueblo, CO; the CN railway; and Polytec, Inc. challenges and opportunities to demonstrate that the results can be useful for potential field implementation. Their critical feedback was discussed and included in this report.

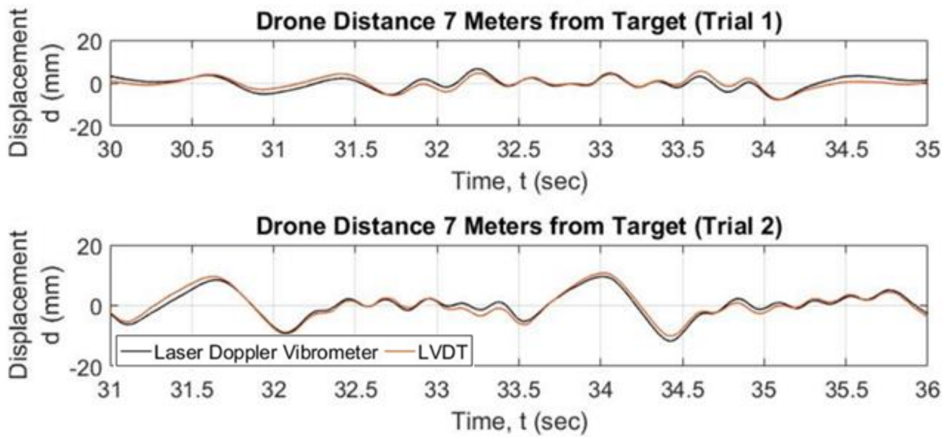


Figure 2. Contact-free, reference-free displacement and reference displacement comparison from field testing.

PRODUCT PAYOFF POTENTIAL

The implementation of this technology allows for more efficient and effective measurements of displacement on railroad bridges during train crossing events, measuring bridges displacements without the need of installing sensors. This data is valuable for assessing safety of bridges at the network level and to inform bridge management prioritization.

PRODUCT TRANSFER

The current implementation was limited by the cable connection from the data collection module to the LDV mounted on the UAV. Current discussions with the sensor manufacturer, Polytec, Inc., evaluated the potential use of a smaller form factor sensor to avoid this cable connection for field implementation. This would allow for measurements to be taken on structures of any height, rather than just those within the height of the cable.

There is one patent filed by the PIs of this research: STC Technology Ref. No. 2016-070: “Assessing the condition of railroad bridges enabled by reference-free, non-contact displacement under revenue service train loads using Unmanned Aerial Vehicles (UAVs) and laser cameras” developed by Fernando Moreu, and Mahmoud Reda Taha. U.S. Utility Application No. 15/477,775 filed on April 3, 2017 (http://www.flintbox.com/public/project/29930/.)

IDEA PRODUCT

The IDEA product integrated UAVs and laser technologies to measure transverse displacements of railroad bridges and compared them with referenced displacements collected using LVDTs (Figure 3). The main goal was to prove to railroads that the use of lasers with UAVs can help collect reference-free non-contact dynamic displacements from railroad train crossing events. The goal of these field measurements was to inform subsequent prioritization of the need for more detailed inspections. This research had identified that measuring dynamic displacement using UAVs and laser technologies is of primary interest for informing decisions in the field. The CN railway provided input throughout the proposed research and agreed to facilitate testing of the concept outlined in this proposal on their bridges in the future. Similarly, the Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the Association of American Railroads (AAR) headquartered in Pueblo, Colorado, provided industry input to the development of this innovation. This included collaborating with the researchers in to outline field test at their facilities in Pueblo, Colorado. This research was consistent with Rail Safety IDEA Topics for Investigation, requesting innovative approaches to improve railroad safety and performance of rail access. The main emphasis of this research was freight traffic and transportation, but the application was anticipated to be applied also to any other type of railroad operation. Researchers added conclusions and findings at the end of this report, as well as a list of additional links for videos of this research. Additional results with other graphics and advancements in this research can be requested from the PIs, not included in this report in order to be concise.

Figure 3. Proposed IDEA Product.

The four primary objectives of this research project were to:

(1) Design and develop the requirements for using UAVs and laser scanning for railroad bridge inspections (with an emphasis on measuring dynamic displacement using 1D laser technology).
(2) Design the software and hardware required to collect these dynamic displacements (through laboratory implementations, programing, and indoor testing).
(3) Develop and test the monitoring approach of this technology on movements of a steel bridge subjected to train loads (field test).
(4) Identify requirements for field validation of this technology in coordination with the CN railway and the TTCI.

CONCEPT AND INNOVATION

CONCEPT OF APPLICATION

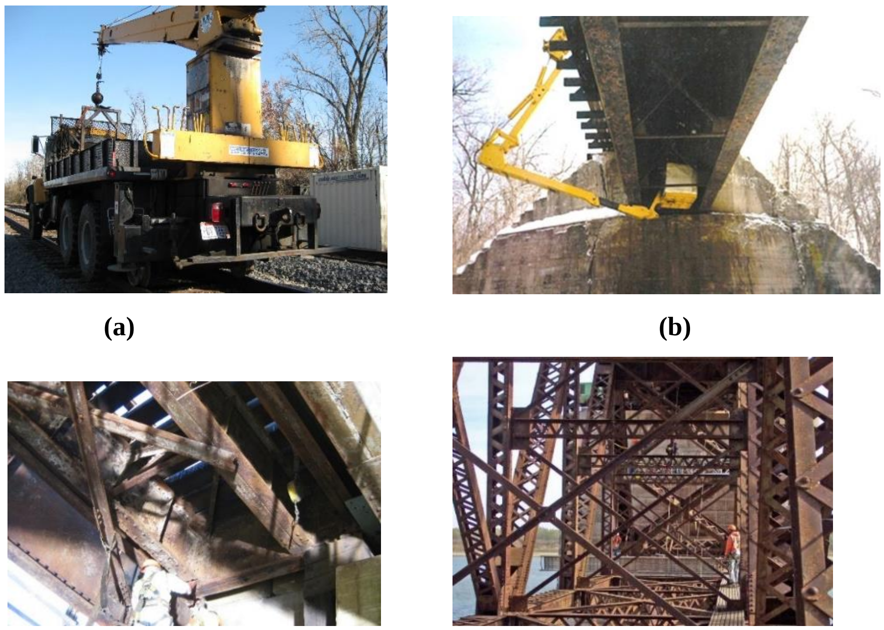
This research team secured the support of the railroad industry. A Class I US railroad, the Canadian National Railway (CN), headquartered in Chicago, Illinois, indicated their strong support for the different research stages described in Section 2: Investigative Approach. The close participation of the CN railway and their willingness to allow access to their bridges validated the applicability of this effort to railroad practice. Polytec, Inc. provided their laser technology to be mounted on the UAV for this research. The CN railway provided input throughout the proposal and facilitated the critical input in order to inform how could this technology be tested on their bridges.

POTENTIAL PAYOFF FOR PRACTICE

Bridge inspection reports inform maintenance, repair, and replacement (MRR) decisions within the entire network. Bridge inspections have been required annually since 2010 as part of the bridge management program and follow the American

Railway Engineering and Maintenance-of-Way Association (AREMA) recommended practices. Railroad bridge inspections are costly and time consuming. In addition, three significant challenges affect railroad bridge inspections:

(1) Railroad bridge inspectors need to visually evaluate all of the bridge structural elements. This is a major challenge in tall and long steel bridges where elements are difficult to access. At times, inspections need to be scheduled in between regular traffic to allow inspectors visual access to bridge elements (Figures 2 a and b), thereby reducing traffic capacity.
(2) Visual observations without measurements cannot quantify defects; they are generally subjective and depend on the inspector carrying them out (Figures 2 c and d).
(3) Current inspections cannot quantify the dynamic response of bridges to railroad crossing events even though the railroad community is interested in measuring the performance of railroad bridges under live loads.



(a) **(b)**

(c) **(d)**

Figure 4. (a) Cherry picker on track level; (b) Cherry picker during bridge inspection; (c) Bridge inspector inspecting bottom flange; (d) Rating and inspection of a large span steel railroad bridge.

Researchers are interested to collect measurements during train crossing events, hence capturing the bridges' dynamic response to trains. Use of UAVs and lasers to measure transverse displacement can:

1) Increase safety while minimizing direct human interaction with the structure.
2) Provide high quality inspections.
3) Reduce interruptions to revenue service traffic due unneeded cherry picker. The research results increase safety and efficiency of current bridge inspection operations.

TRANSFER TO PRACTICE

The novelty of this research resided in the integration of both UAVs and laser scanning technologies to provide very valuable information about the condition of bridges with relatively inexpensive instrumentation investment. Recent developments with UAVs provided readily available and mature tools that were tested within the context of railroad bridge inspections.

CONCEPT AND INNOVATION

To increase overall profitability, add capacity to rail operations, and comply with new federal regulations on bridge safety, North American railroads are exploring means to improve the management of their bridge networks. Current maintenance, repair, and replacement (MRR) decisions are informed by visual bridge inspections and ratings which recommend Railroads can more effectively allocate their limited resources if MRR decisions cannot be determined using objective data. Researchers concluded from previous research that the methods to collect transverse bridge displacements were of interest and could benefit owners. The use of non-contact sensors are an improvement over the contact method. The research team chose the integration of laser doppler vibrometer and unmanned aerial systems to overcome their respective drawbacks. While an aerial system gave better reachability, more agility, and can be made autonomous, the current onboard technology for displacement measurement did not allow real-time measurements and cannot collect displacements perpendicular to the UAS. Also, the laser doppler vibrometer was able to measure displacements with high accuracy in real-time, yet lacking the accessibility to bridges, so researchers operated it from the ground. This research explored the use of vibrometer advantages to overcome the disadvantage of the aerial system, and vice versa. Table 1 shows the summary of the advantages and disadvantages of both these systems.

Table 1. Summary of advantages and disadvantages of an aerial system and a laser doppler vibrometer

	Unmanned Aerial Systems	Laser Doppler vibrometer
Advantages	• Accessibility • Agility • Autonomous	• Minimal post processing • Large stand-off distance • Real-time output • Non-contact displacement measurement.
Disadvantages	• No real-time output • Cannot measure displacement perpendicular to UAS • More post-processing time	• Requires mounting on ground • Less accessibility

The ideal solution for the dynamic transverse bridge displacement monitoring was to combine the agility and accessibility of the aerial system with the displacement measurement capabilities of a vibrometer. Researchers developed an airborne vibrometer system for dynamic transverse bridge displacement measurement of railway bridges under train loading. This advanced inspection method provided both information about the condition and performance of the bridge from every inspection, thus allowing for the automatic creation of a baseline of the bridge (both condition and performance). The research team narrowed the goal of this research in four tasks (Figure 2-10). These tasks were: (1) displacement sensor selection, (2) development of correction algorithms, (3) UAS-LDV system integration, and (4) field testing using the integrated system. Figure 5 shows the concept and innovation associated with this research and the different concepts that were implemented.

INVESTIGATION

The different steps and accomplishments are listed in the following sections, corresponding to the different tasks listed for this SAFETY IDEA project.

TASK #1: PREPARATION: PRESENT RESEARCH PROJECT TO THE RAILROAD BRIDGE COMMUNITY AND COLLECT EARLY FEEDBACK

The task was to prepare a detailed schedule for the project and present it to the panel review board. Researchers made changes based on suggestions and prepared the final project plan. The detailed discussion with TRB members took place during the TRB conference in January in Washington. During this meeting, researchers discussed the detailed scope of the project. At the IMAC conference of the Society of Engineering Mechanics, researchers met and discussed in detail laser sensors options with OMS and Polytech. After this discussion with experts, the research team narrowed the project scope to focus on displacements using 1D Lasers.

TASK #2: SELECT AND DEVELOP UAV FOR RAILROAD BRIDGE INSPECTION IN CONJUNCTION WITH THE LASER CAMERA

The next task was to prepare the basis of the project and to shortlist and to acquire the drone and laser sensor for the project. The research team prepared and tested a small bridge using train data with an actuator to excite the bridge. The research team selected the company for drone operations as DJI, a leader in the market of non-expensive drone operations. The research team selected Polytec, a leader in laser measurement systems, for the laser component. The following sections explain the rationale of these selections.

EQUIPMENT

DRONE SELECTION

The team did a preliminary selection of the drone taking into consideration the weight of the sensor, the flight time depending on the train passing event (15 to 20 minutes at full payload carrying capacity), wind endurance, and range of operation. Since the sensor head and sensor assembly weighed around 10 pounds, the industrial drones were better suited for this application. The list of drones' candidates is in Table 2. For this project, the research team selected Drone Matrice

Pro 600 by DJI, with a payload carrying capacity of 15 pounds, able to endure winds up to 40 MPH, flying time of about 20 minutes at full load, and a programmable function to make it autonomous. This was the best suited drone for the application.

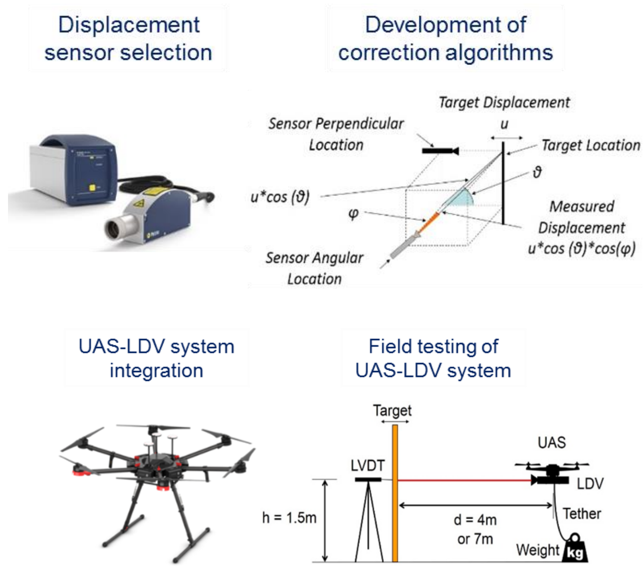


Figure 5. Integration of LDV and UAS for dynamic transverse displacement measurement.

Table 2. Drone candidates.

Product	Company	Image	Website
X4-P	DragonFly		http://www.draganfly.com/products/x4-p/specs
Pelican	AscTec		http://www.asctec.de/en/
Matrice 600 Pro	DJI		http://www.dji.com/products/industrial
Ad2	Action Drone		http://actiondroneusa.com/systems/ad2/

LASER SELECTION

The research team shortlisted Polytec OFV-534 Laser Doppler Vibrometer for the project. These lasers were selected based on their weight, range from the target, and sensitivity. Table 3 lists all laser candidates.

TASK #3: DEVELOP THE APPLICATION OF LASER IN UAV FOR BRIDGE DISPLACEMENT MONITORING

After the successful completion of tasks 1 and 2, researchers tested the laser sensor for accuracy and field operation. The team conducted various tests for measuring the output from stable to progressively moving the vibrometer. The experiments were divided into four sections depending on the position and motion of the vibrometer:

a. Fixed Vibrometer with Laser Signal Perpendicular to the Target
b. Fixed Vibrometer with Laser Signal at an Angle to the Target
c. Dynamic Angular Motion of the Vibrometer
d. Random Dynamic Angular and Lateral Motions of the Vibrometer

Table 4 describes the different states of motion for each setup. Figure 6 shows the experimental layout of all the above configurations. Figure 7 shows the laboratory setup.

Table 3. Laser candidates.

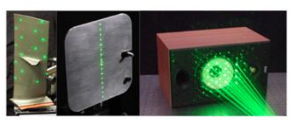
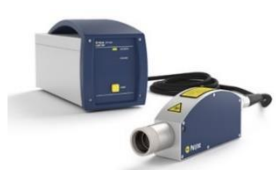
Product	Company	Image	Website
LP 01	OMS		http://www.omscorporation.com/products/laser-point/
Multipoint	OMS		http://www.omscorporation.com/products/multibeam-vibrometer/
IL2000	Keyence		http://www.keyence.com/products/measure/laser-1d/il/specs/index.jsp
OFV-50x	Polytech		http://www.polytec.com/us/products/vibration-sensors/single-point-vibrometers/modular-systems/ofv-50x-vibrometer-sensor-head/
OFV-534	Polytech		http://www.polytec.com/us/products/vibration-sensors/single-point-vibrometers/modular-systems/ofv-534-compact-sensor-head/

Table 4. State of motion of vibrometer for the four experimental setups.

Experiment	States of Motion					
	X direction	Y direction	Z direction	Roll	Pitch	Yaw
a	No motion	No motion	No motion	0º	0º	0º
b	No motion	No motion	No motion	0º	Fixed αº	Fixed θº
c	No motion	No motion	No motion	0º	Δαº	Δθº
d	Δx	No motion	No motion	0º	Δαº	Δθº

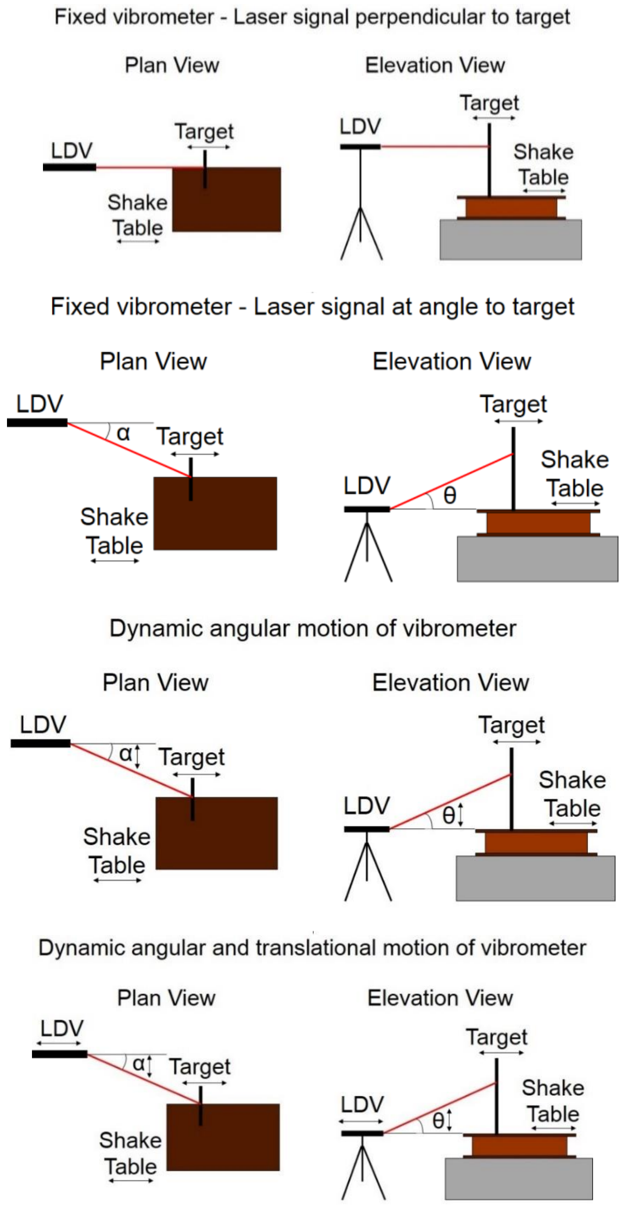


Figure 6. Experimental layout for different vibrometer for (a) vibrometer signal perpendicular to the target, (b) vibrometer at an angle to the target, (c) dynamic angular motion of the vibrometer, and (d) dynamic angular and translational motion of vibrometer.

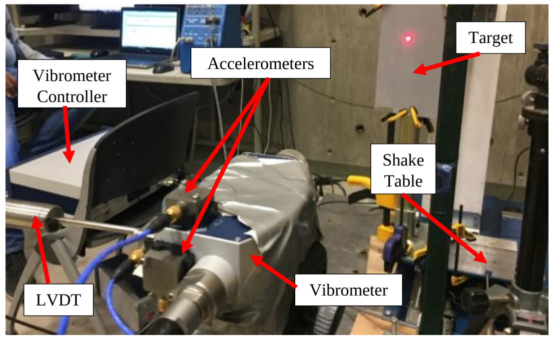
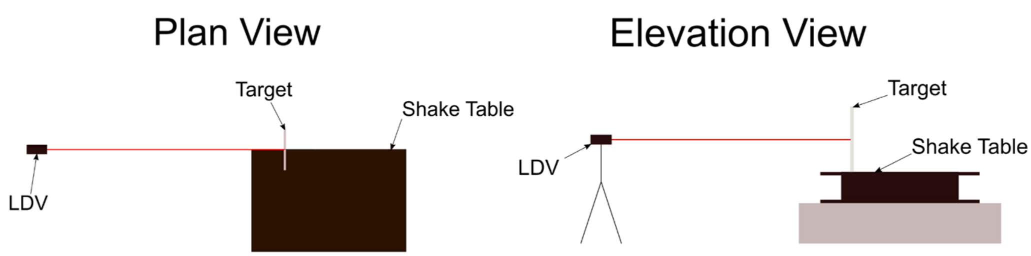


Figure 7. Laboratory setup.

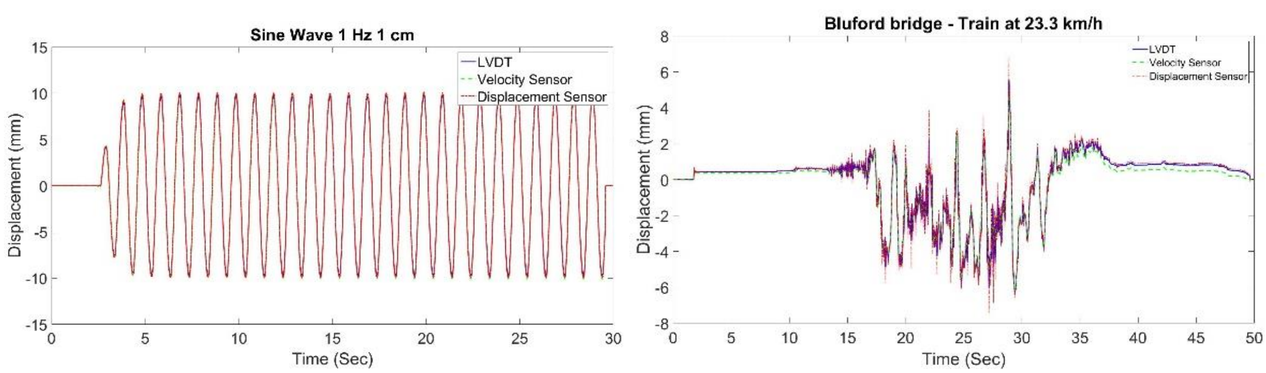
MEASUREMENT OF DISPLACEMENT SUBJECTED TO SINUSOIDAL SIGNALS AND TRAINS (PERPENDICULAR, STATIC)

The research team validated through a set of sinusoidal signals the reliability of laser doppler vibrometer (LDV). Figure 8 shows the setup for the first test. Figure 8(a) shows the plan view, Figure 8(b) the elevation view. The research team placed a target on the shake table and pointed the LDV laser to the target. Researchers also added an LVDT on the other side of the target providing the reference displacement. The shake table simulated the sinusoidal displacements. Figure 9 shows the results of this test where the output of velocity as well as the displacement decoder of the vibrometer were exactly in phase with the LVDT measurements. Figure 9(a) shows the signal of a sine wave of 1 Hz and 1 cm amplitude, and Figure 9 (b) shows the signal from a train crossing event in one railroad bridge under a test train of six cars in central Illinois. The measurement differences between the vibrometer sensors and LVDT for the sine wave with the velocity decoder were about 4% peak and about 1.6% RMS, while for the displacement decoder, the same measurements were about 2.5% peak and about 0.9% RMS. Similarly, researchers simulated a bridge displacement from a train traveling at 23.3 km/h using the shake table. The difference in the measurement by the velocity decoder was about 12% peak and about 3% RMS, while that of the displacement decoder was about 15% peak and 1.5% RMS.



(a) **(b)**

Figure 8. Test setup for laser perpendicular to the vibrating plane: (a) Plan View, and (b) Elevation View.

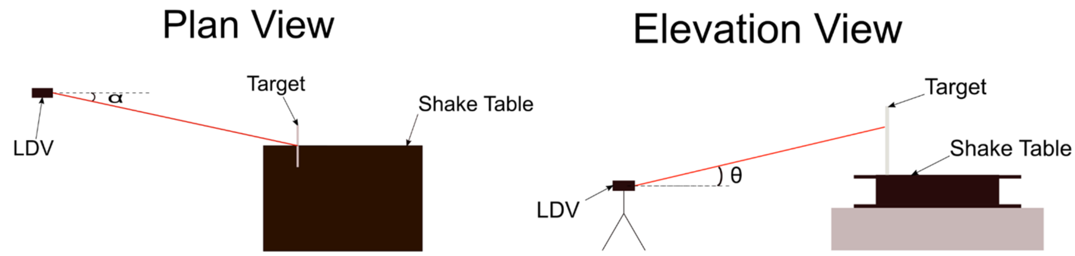


(a) **(b)**

Figure 9. Results for laser perpendicular to vibrating plane: (a) Sine Wave, and (b) Train Data.

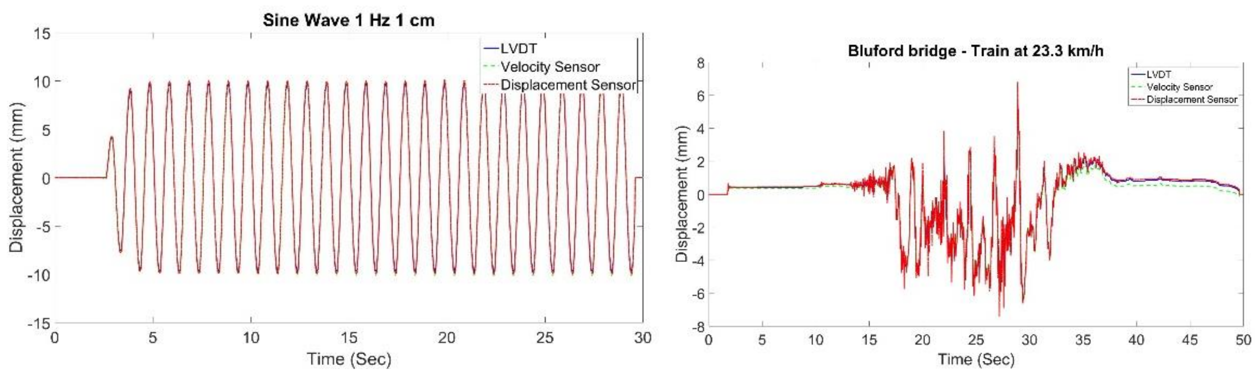
MEASUREMENT OF DISPLACEMENT SUBJECTED TO SINUSOIDAL SIGNALS AND TRAINS (NON-PERPENDICULAR, STATIC)

This setup tested the reliability of the vibrometer when pointed at the vibrating surface at an angle. As seen in Figure 10 the vibrometer was at a yaw angle 'α' (plan view) as well as pitch angle 'θ' (elevation view). Figure 11 shows the results when the pitch and yaw angles were 30^0. Again, both the output of velocity as well as the displacement decoder of the vibrometer were exactly in phase with the LVDT measurements. The difference in sensor measurements for the sine wave with the velocity decoder was about 3.1% peak and about 1.5% RMS, while for the displacement decoder, it was about 3% peak and about 1.4% RMS (Figure 10 a). Researchers simulated a bridge displacement for a train traveling at 23.3 km/h with the shake table, and measured 10% peak and about 2.5% RMS by the velocity decoder, and about 15% peak and 1.5% RMS by the displacement decoder (Figure 10 b).



(a) **(b)**

Figure 10. Test setup for laser at yaw and pitch angle to the vibrating plane: (a) Plan View, and (b) Elevation View.



(a) **(b)**

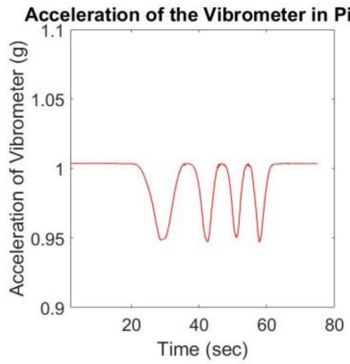
Figure 11. Results for laser at yaw and pitch angle to vibrating plane: (a) Sine Wave, and (b) Train Data.

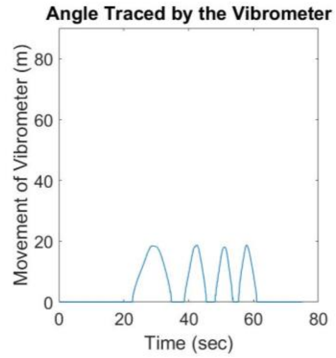
MEASUREMENT OF DISPLACEMENT SUBJECTED TO SINUSOIDAL SIGNALS (PITCH ANGULAR MOVEMENT, DYNAMIC)

The 3rd test compared the output of a dynamically pitched vibrometer to the LVDT output. Researchers measured the pitch angle of the vibrometer with the help of an accelerometer. Figure 12(a) shows the reading of the change in acceleration with the pitching motion of the vibrometer. Researchers used this acceleration reading to calculate the dynamic angle of the vibrometer. Figure 12(b) shows the measured angle of the vibrometer. Researchers corrected the measured output using the angle read (Figure 13).

MEASUREMENT OF DISPLACEMENT SUBJECTED TO TRAINS (RANDOM MOVEMENT, INCLUDING ROTATION AND DISPLACEMENT, DYNAMIC)

The final test was to measure and correct the output of the vibrometer for a random motion. The research team measured the output and corrected it for change in distance from the target, as well as the change in angle to the target. The result of test 4 can be seen in Figure 14.





(a) **(b)**

Figure 12. Reading of the accelerometer for dynamic pitching motion; (a) Acceleration; (b) Angle.

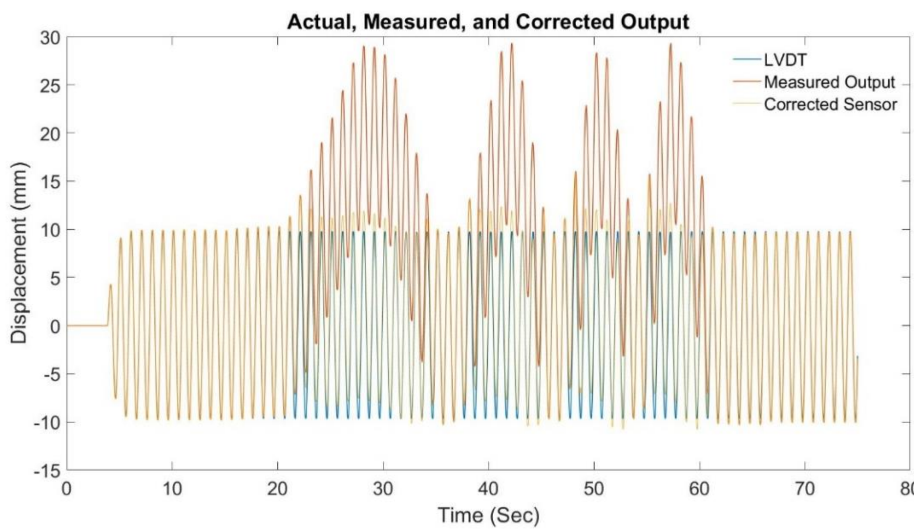


Figure 13. Measured output of the vibrometer and corrected output using the angle calculated from acceleration readings vs LVDT output.

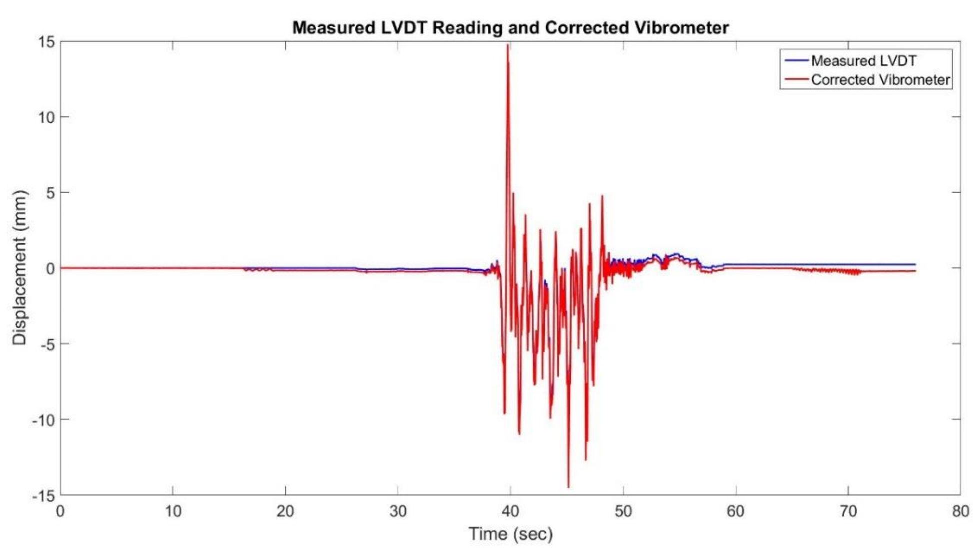


Figure 14. Result for the corrected random motion of the vibrometer vs LVDT.

This task focused on designing the framework for transverse displacement using an LDV in moving condition. The author selected the LDV OFV-534 by Polytec, with small dimensions and weight for these experiments so the results can be carried forward to the UAS implementation. All tests in this section were carried out in the laboratory with a vibrometer measuring the displacement of a target on the shake table simulating harmonic waves, earthquakes, and transverse bridge displacements under train loading. The authors conducted the initial tests and validated the output response of the vibrometer compared to the LVDT. Authors developed algorithms to correct for various configurations of the vibrometer in moving and stationary conditions. The research team tested algorithms and validated them in the laboratory. Table 3-3 shows the summary of the measured and corrected signal differences.

Table 5. Summary of the LDV measured and corrected readings for different experimental setup.

Vibrometer State	Measured Output		Corrected Output	
	Peak	RMS	Peak	RMS
Static Perpendicular	4%	1%	-	-
Pitch 30^0	12%	5%	2%	1%
Pitch 30^0 and Yaw 30^0	22%	10%	2%	1%
Dynamic Pitching	200%	22%	10%	5%
Random Motion	22%	12%	10%	2%

From the results, the researchers concluded that the vibrometer measured the pseudo-static displacement of the railroad bridges, and that the algorithms developed for correction of movement of the vibrometer worked for all the configurations described. Based on these tests and results, the research team demonstrated that that the selected vibrometer can be used to measure transverse dynamic displacements accurately. This was possible as long as the movement of the LDV was accurately measured and tracked, as demonstrated in the laboratory.

TASK #4: LAB BRIDGE TESTING USING UAV

The first part of this task consisted of running bridge displacements in the laboratory that correspond to different bridge conditions. The second part of the task was to measure the values of similar displacements using the UAV system, as well as several LVDTs in outdoor environments. The research team measured displacements of the UAV system. Subsequently, researchers could correct the motion recorded by the UAV from the total measurement to get the final measurement. This final measurement was compared to the LVDT readings.

TASK 4, PHASE 1: LABORATORY TESTING OF BRIDGE DISPLACEMENTS USING LDV

Researchers designed a test to analyze the reliability of the Laser Doppler Vibrometer under field conditions and in natural lighting. Researchers conducted multiple tests with varying distance d from 3 m to 7.5 m to determine the optimal operating distance for the drone (Figure 15 and Figure 16). The signal output of the displacement decoder DD900 of the LDV had a maximum sensitivity of 5mm/V. The range of the VibPilot DAQ was +/- 10V, giving the maximum range of data acquisition +/- 5 cm. If the displacement exceeds this range, there could be a loss of signal information. The displacement decoder worked in Return to Zero (R2Z) and Clip modes. By selecting R2Z the signal was forced to return to zero and continued recording in case of the range being exceeded. The signal was post processed to remove the return to zero-state and a continuous signal was be obtained (Figure 17). The corrected signal of the vibrometer had the exact same frequency spectrum as the LVDT output (Figure 18). It was observed that the RMS difference between the LVDT and the LDV signals were between 1% and 3% and did not increase with distance (Figure 19).

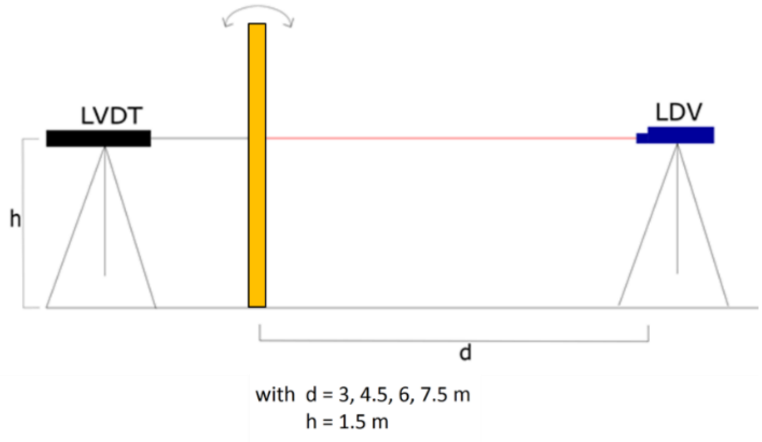


Figure 15. UNM laboratory railroad bridge monitoring experiment.

Figure 16. Laboratory testing of railroad bridge displacements using laser (outdoor measurements).

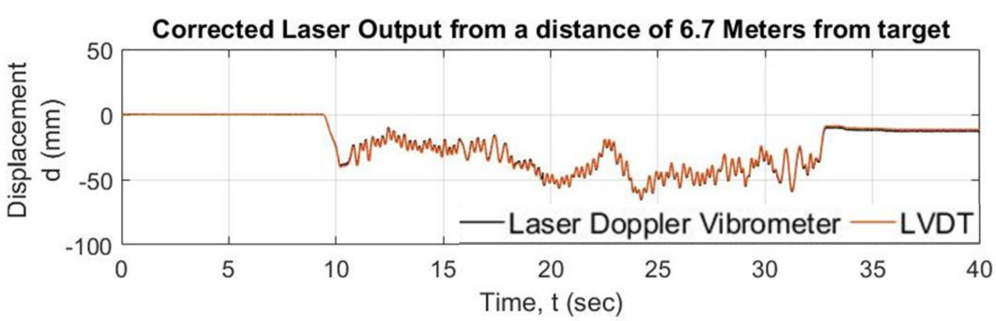


Figure 17. Laser and LVDT data in the laboratory of railroad bridge displacement.

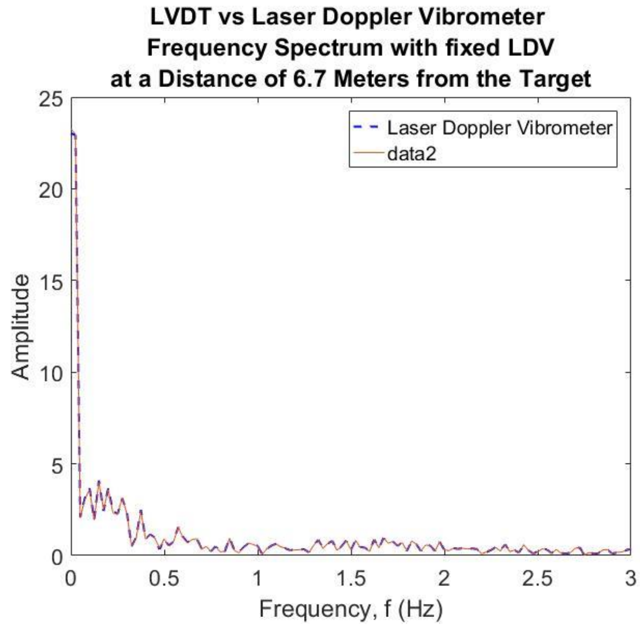


Figure 18. Frequency domain comparison between LVDT and LDV.

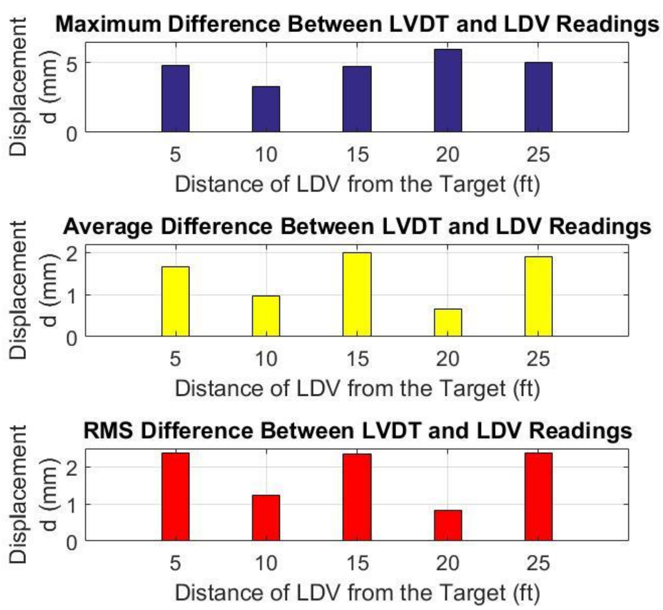


Figure 19. Comparison between LVDT and LDV readings for railroad bridge monitoring.

TASK 4, PHASE 2: FIELD TESTING OF BRIDGE DISPLACEMENTS USING LDV AND UAV

During the preliminary validation of this UAS for LDV integration researchers had some drone crashes. Researchers learned lessons from these mistakes to develop the research framework for the integration of the system. Table 6 shows the summary of important mistakes and lessons from this research stage. The author and the pilot of the UAS observed that the flight in confined space causes weak GPS signal and learned the importance of configuring GPS antenna and system. They also learned that during imbalanced landings it was important to abort the landing and make a fresh landing attempt.

The research team included the generation of checklists and failsafe methods for the remaining research steps. Additionally, researchers added tethering from the drone to the ground to avoid damage to the vibrometer assembly or any injuries during the flight of the two integrated systems. Researchers designed a test to analyze the reliability of operations using the LDV and the UAV (Figure 20 and Figure 21). To date, this was the first measurement of the dynamic displacement of bridges using lasers attached to drones (Figure 22). The movement of the board was to represent different bridge vibrations under train crossing.

Table 6. Failures and Lessons from the UAS test flights.

Failures	Causes
Drone flight and crash against the wall	• Return to home function failure due to GPS signal
Drone flight and crash at George J Maloof Airpark	• Landing on uneven surface • Improper GPS configuration

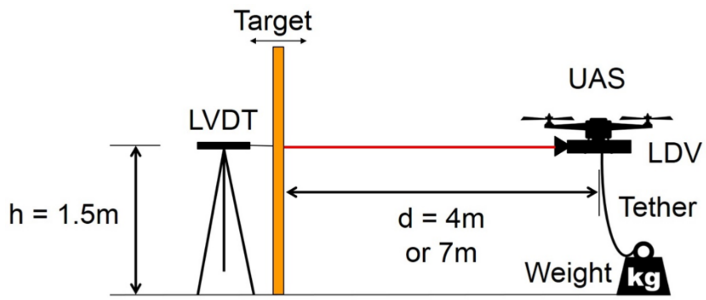


Figure 20. Field testing layout.

Figure 21. First UAV laser displacement measurement in the field (Albuquerque, New Mexico).

Figure 22. Testing of the UAV using the LDV laser for dynamic displacement in the field.

The data collected from the drone is summarized in Figure 23. Three different experiments were conducted. Researchers observed that the drone moved during the experiment with low frequencies, and researchers could obtain the dynamic displacements of the bridge by filtering both LDV and LVDT displacements with a high pass filter of 0.5 Hertz (Figure 24). Figure 25 shows the frequency spectrum of the vibrometer and LVDT filtered data. Figure 26 shows the displacement measurement of the bridge under trains for dynamic responses. Figure 27 shows successful results of dynamic displacement of railroad bridges using a laser mounted on a UAV.

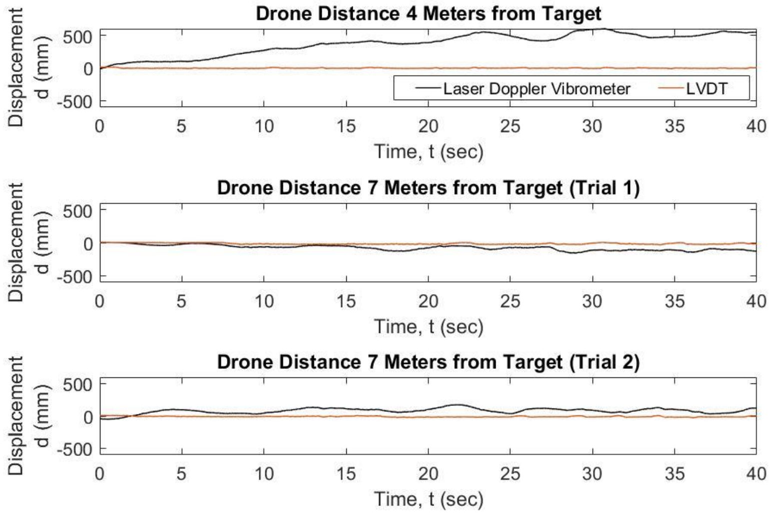


Figure 23. Data from three different railroad bridge displacements.

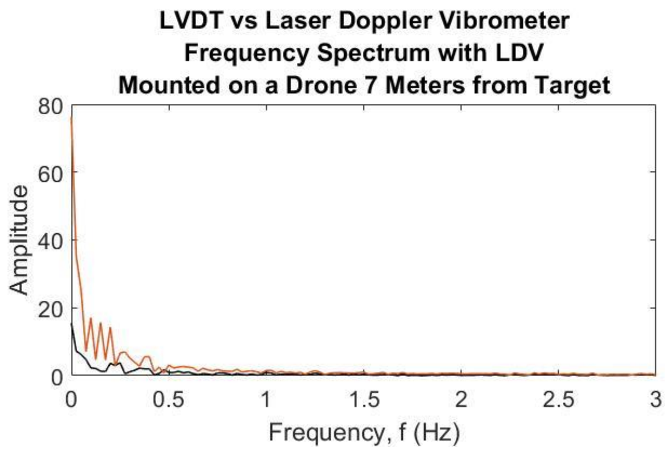


Figure 24. The frequency content of both LVDT and LDV during drone operations.

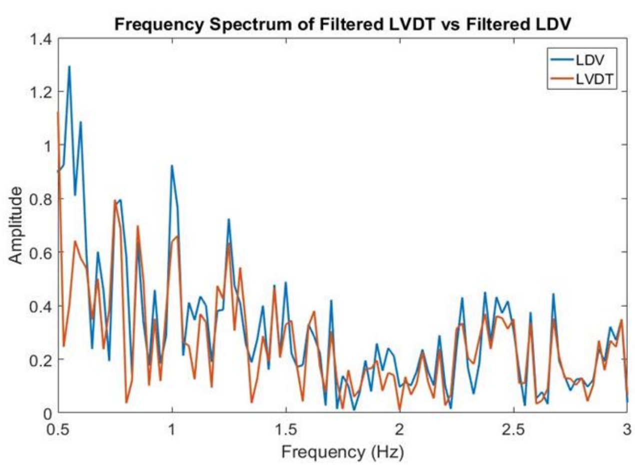


Figure 25. Spectral output of filtered LVDT and LDV signals.

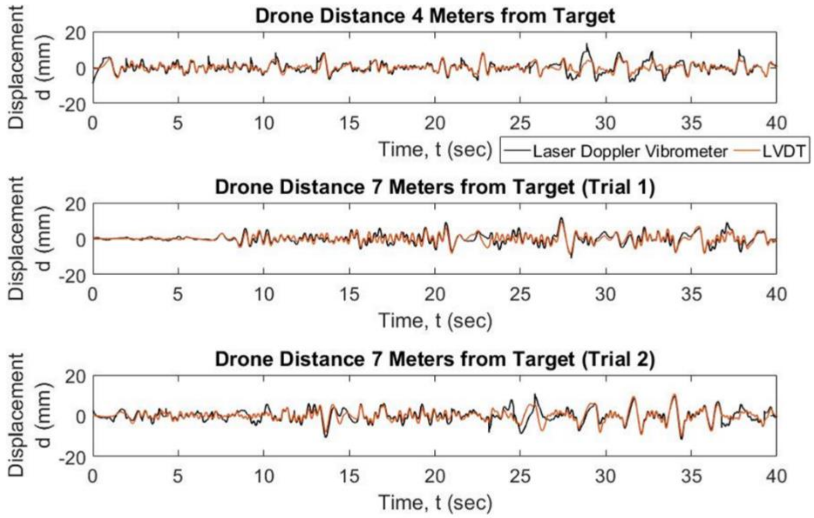


Figure 26. Displacement measurement of railroad bridges using lasers and UAV.

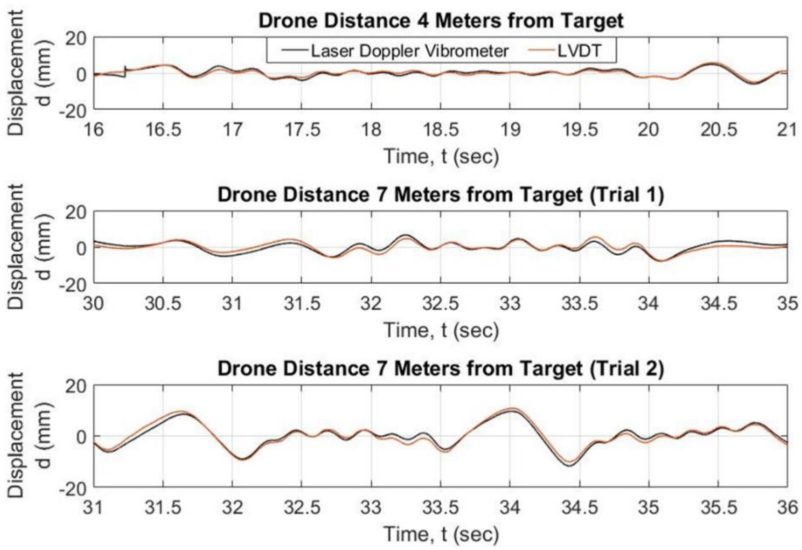


Figure 27. Dynamic displacement measurement of railroad bridges.

The research team compared the signals for peak and RMS differences and observed that both the peak as well as the RMS difference was less than 2 mm (Figure 28). Figure 29 shows that the average output peak error of the three tests was about 10% and the average RMS difference was around 8%. These results proved that an LDV mounted on a UAS could be used for monitoring the dynamic transverse bridge displacements under the discussed considerations.

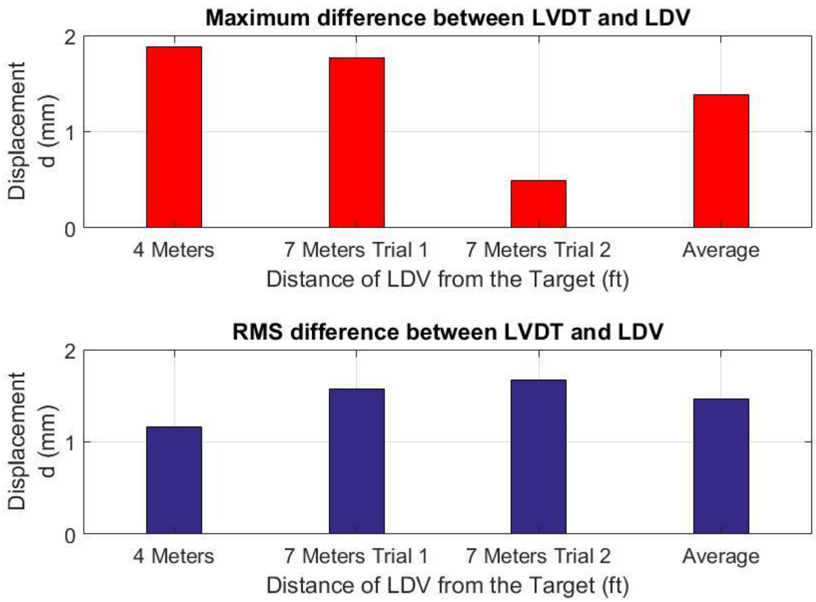


Figure 28. Peak and RMS signal difference comparison between filtered vibrometer and LVDT signals.

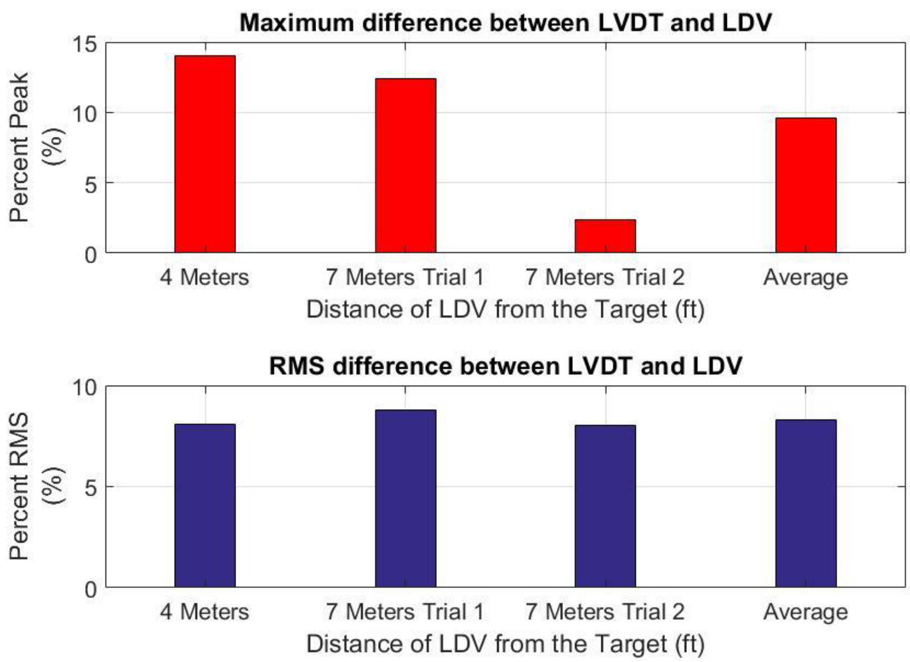


Figure 29. Percentage peak and RMS signal difference comparison between filtered vibrometer and LVDT signals

PLANS FOR IMPLEMENTATION

TESTING

The most immediate task following the success of this project was to design how to conduct a field measurement of a railroad bridge under train crossing using UAV and laser displacement (LDV). The field testing was scheduled for October/November 2018, but the team will test earlier if possible (see Figure 30).

Figure 30. TTCI bridge in Pueblo, Colorado.

DISPLACEMENT CORRECTION

In this report it was agreed that future displacement correction for total displacement includes the use of video cameras to estimate the 6-DOF of the drone using a fixed target while compensating for the movement of the drone. The first step in the proposed approach will be camera calibration, intended to remove distortion to get accurate displacement measurements using consumer-grade cameras. Calibrating the camera will also obtain the Intrinsic Matrix, which includes unique parameters of the camera lens independent of the location of the scene. These parameters are essential in the latter part of the proposed method to calculate 6-DOF motion of the camera. The camera calibration process can be conducted by taking pictures of known geometry points, in this case a checker board, from different points of view.

Once the camera is calibrated and the image distortion is removed, the points on the checker board are determined by analyzing the video frame-by-frame. To achieve reliable tracking, distinct features are selected from the objects of interest. These features should be invariant to changes in illumination, scale, and pose (rotation and affine), as well as able to characterize the local proximity of the points of interest. Several feature detection methods can be used for this purpose. In this work, the corner detection method suggested by Harris and Stephens (1988) will be used to extract the features within the region of interest (ROI) in the initial video frame.

After the features are selected for the initial frame, the KLT algorithm will be adopted to track the point features for the entire duration of a video. Assuming small motions between consecutive frames, the optical flow vector can be obtained by minimizing the residual of the difference between the intensity of the previous and the following frames. The accuracy of the displacement result can be enhanced by applying Image Pyramids and outlier removal methods, such as RANSAC. Finally, the projected 2D motion of the camera to the image coordinate can be obtained and resolved to 6DOF motion using the equation shown in Figure 31.

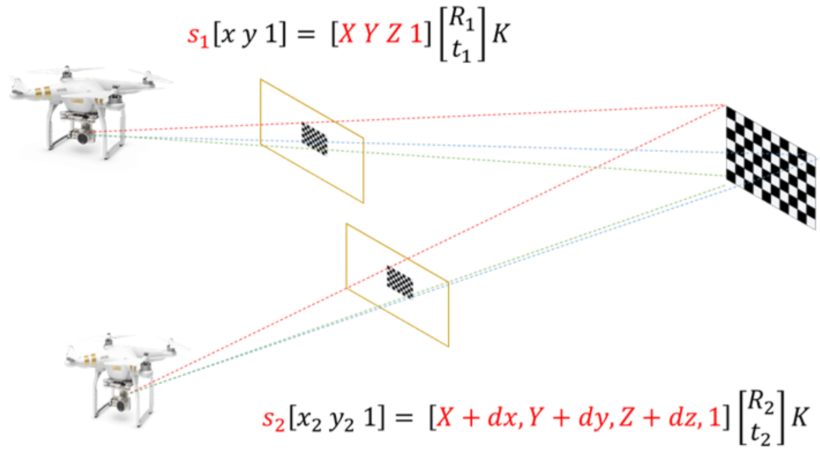


Figure 31. Drone location using the camera and a fixed target in the field.

PRELIMINARY TESTING PLAN AT TTCI

The UNM team has already started conversations with different personnel of TTCI in charge of safety, drone activities, and bridge testing at TTCI. This is not the final testing plan but it was included in this report showing the maturity of this research and the progress in demonstrating the practical application of the developed product up to the date the report was completed.

Objective

The objective of this proposed testing will be to gather the displacement data on the DPG bridge structures to determine the characteristics of LDV data on real bridges as well as to determine any variables introduced into the flight behavior of the UAV. The data collected from the LDV will be cross-referenced with the other displacement sensors for validation. The test results will be used to assess the efficacy of the data collection methods and data analysis models for characterizing the serviceability of railroad bridge structures.

Span description

The plan is to collect measurements on one of the steel DPG bridges at the TTCI testing facility. The bridge to be measured will be determined by TTCI, depending on their availability. Data collection using at least two different bridges would be optimal to identify any variance present between bridges.

Measurements

Prior to the testing, a training course will be completed to ensure safe testing practices as instructed by TTCI. Measurements will be taken alongside the DPG structures of service train bridges. The goal will be to monitor 10 crossings, to provide sufficient data to identify outlier behavior. If feasible, two bridges will be monitored.

Figure 32 shows the general testing layout in the plan view. The LDV measurements taken with the drone will be compared with other sensors installed in the bridge. The location of the UNM personnel is shown in the plan view and can be modified to follow TTCI recommendations. The drone will fly approximately 5 feet from the ground. The sensors will be placed on the bridge prior to the drone operations. The pilot of the drone will follow the direction of the TTCI safety staff during the entire testing operation. Figure 33 shows the elevation view and sensor layout with labeling and connections to the web and flange. The next section describes the plan for sensor installation in the bridge.

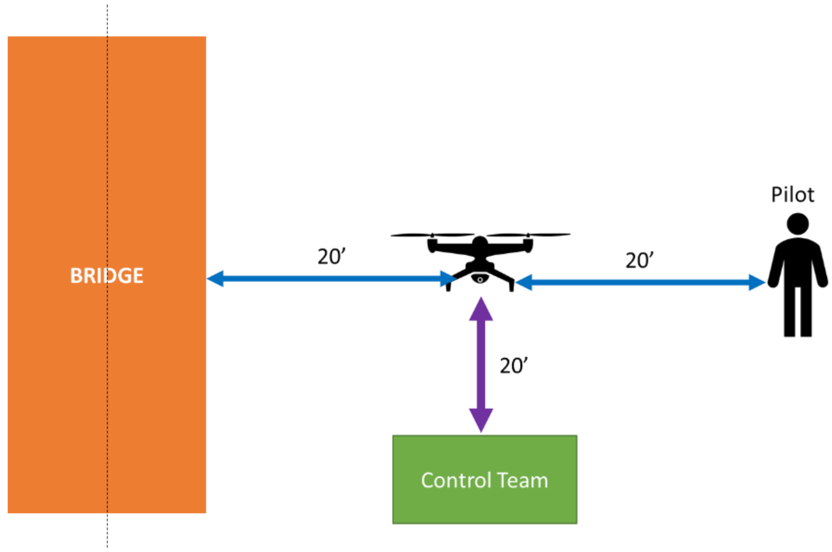
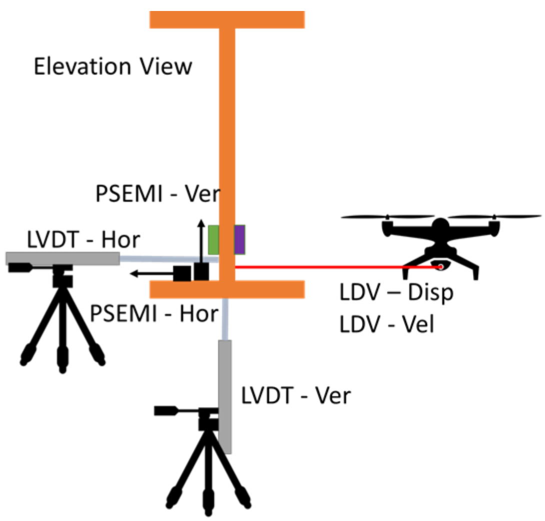
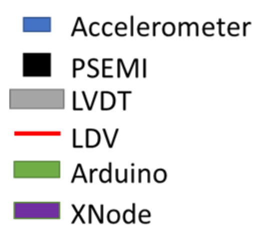


Figure 32. General testing layout (plan view).





Channel	Sensor
1	LDV - Disp
2	LDV - Vel
3	LVDT - Hor
4	LVDT - Ver
5	PSEMI – Hor
6	PSEMI – Ver
7	Accelerometer - Log
8	Accelerometer - Ver

Figure 33. Elevation view and sensor layout.

Sensor Installation

The laser signal will be collected using a reflective tape that will be added to the web of the bridge ahead of time. The other sensors will be in contact with the bridge and will be either glued or clamped before the testing. Specific details of the glue and clamp will be submitted for final approval prior to the visit to TTCI. The entire list of sensors and description is listed in Table 7. The function details are listed in Table 8.

Table 7. Equipment list (tentative).

Channel	Sensor	Equipment
1	LDV - Disp	Drone; LDV Sensor+Controller; Digital Controller; 1 100' BNC Cable
2	LDV - Vel	Drone; LDV Sensor+Controller; Digital Controller; 1 100' BNC Cable
3	LVDT - Hor	LVDT (Red); Tripod; Power Supply; 1 100' BNC Cable (cut at one end); Breakout Box;
4	LVDT - Ver	LVDT (Red); Tripod; Power Supply; 1 100' BNC Cable (cut at one end); Breakout Box;
5	PSEMI – Hor	PSEMI Sensor; PSEMI Signal Conditioner; 1 100' BNC Cable; 1 100' BNC Cable; 1 20' BNC Cable;
6	PSEMI – Ver	PSEMI Sensor; PSEMI Signal Conditioner; 1 100' BNC Cable; 1 100' BNC Cable (from DAQ to SC); 1 20' BNC Cable (from SC to Sensor);
7	Accelerometer - Hor	PCB Sensor; Breakout Box; 1 100' BNC Cable; Blue Acc Cable
8	Accelerometer - Ver	PCB Sensor; Breakout Box; 1 100' BNC Cable; Blue Acc Cable

Table 8. Equipment list function.

Channel	Sensor	Location	Duty
1	LDV - Disp	20' away from midspan Pointing to midspan	UAV's capability in measuring displacements during operation
2	LDV - Vel	20' away from midspan Pointing to midspan	Complimentary measurement for better displacement measurement
3	LVDT - Hor	3' away from midspan Pointing to midspan	Reference transverse displacement
4	LVDT - Ver	3' away from midspan Pointing to midspan	Reference vertical displacement
5	PSEMI – Hor	1'' away from web transversally On the flange	Proof-of-Concept sensor for measuring dynamic displacement
6	PSEMI – Ver	1'' away from web transversally On the bottom flange	Proof-of-Concept sensor for measuring dynamic displacement
7	Accelerometer - Log	1'' away from bottom flange vertically 5'' away from support, on the web	Rotation measurement to compliment PSEMI sensors
8	Accelerometer - Ver	1'' away from bottom flange vertically 5'' away from support, on the web	Rotation measurement to compliment PSEMI sensors

TTCI Support

TTCI agreed to provide required instructions and training. The UNM team will bring the following equipment for the testing phase:

1. Power generator for sensors and data collection station
2. Tripods and attachment materials for our sensors
3. LVDT, accelerometers, UAV and LDV sensor, data acquisition and analysis hardware
4. PPE (hard hats, steel toe boots, reflective clothing, eye protection)

It was anticipated that TTCI help will not be needed during the process of data collection since the instrumentation and data collection will be under and to the side of the bridge and will not interrupt the train crossing operation.

Schedule

It was anticipated that field test could be completed in one single day in the months of September or October before the train operations cease in November 2018. If possible, the team will measure bridge crossings during the day.

CONCLUSIONS

Synopsis of the Study

The main outcome of this IDEA concept was a novel method to measure dynamic transverse bridge displacement using an LDV with a UAS. The research team introduced the problems of bridge transverse displacement measurement using contact and non-contact sensors. Following this introduction, researchers described a new method for transverse bridge displacement measurement using a moving laser doppler vibrometer to be mounted on a drone. The first step in this approach was to find the operation capabilities of a vibrometer subject to different motions. Researchers developed algorithms based on trigonometry to compensate for the motion of the vibrometer. These algorithms included correction of the static angular positioning of vibrometer, the dynamic angular motion of the vibrometer, and the random motion of the vibrometer. The research team then used these algorithms to test different test scenarios. The research team tested the vibrometer for accuracy from different distances, frequencies and amplitudes, and signal properties. The errors in these tests were found to be less than 10% peak and 2% RMS. Researchers also tested the vibrometer for accuracy at different angles to the target while stationary, with 5% peak and 2% RMS errors.

The correction algorithms were analyzed for dynamic pitching motion and random motion of the vibrometer. The differences for the dynamic pitching were less than 10% peak and less than 5% RMS. The difference between the proposed method and measured transverse displacements for random motion were around 12% in peak and 1% in RMS. The research team concluded that the vibrometer accurately measured the target vibration from all these different configurations under the described testing conditions.

The research team designed a test setup to measure simulated displacements of a railroad bridge under dynamic loading using an LDV mounted on a UAS. The test setup also described how the tethering of UAS was used for protection of the vibrometer cables and assembly. The team analyzed the results in the frequency domain, and found that the low frequency components of the vibrometer readings matched the movements of the drone. Researchers filtered both signals for this low frequency component with a 3^{rd} order high pass Butterworth with a 0.5 Hz cut-off frequency compared the performance of the results in the same frequency range, which matched closely to each other. The displacement captured by the vibrometer was around 10% with an RMS difference around 8%. The research team proved that an LDV mounted UAS was suitable for dynamic transverse displacement measurement of railroad bridges.

The major contributions of this project included the following: (1) selection of a laser sensor to be integrated with the UAS system. (2) design algorithms to correct the errors introduced due to the movement of the vibrometer, and successful testing of transverse displacement measurement using a moving vibrometer platform, as well as of the correction algorithms, (3) selection of a UAS suitable for lifting the vibrometers, and (4) first attempts to use an LDV mounted on a UAS for collection of dynamic transverse displacement data, and successful testing and analysis of the data collected by the integrated UAS-LDV system.

The proposed technology reduces the efforts, risk, time, and cost involved in acquiring transverse displacements under loading operations and can be implemented for efficient infrastructure monitoring across various industries. The progress of the innovation described and the proof of concept in the field has exceeded the expectations due the ability of the drone and laser to collect dynamic displacement outdoors, instead of just in the laboratory.

There was one patent filed by the PIs of this research: STC Technology Ref. No. 2016-070: "Assessing the condition of railroad bridges enabled by reference-free, non-contact displacement under revenue service train loads using Unmanned Aerial Vehicles (UAVs) and laser cameras" developed by Fernando Moreu, and Mahmoud Reda Taha. U.S. Utility Application No. 15/477,775 filed on April 3, 2017 (http://www.flintbox.com/public/project/29930/.)

Planned Next Steps for this Research

This work was completed with constant guidance and suggestions from the project review panel and industry experts. As per their feedback, the future work on this project included suggestions for benchmarking the UAS based LDV operations for different operating and environmental conditions, such as benchmarking the operation of the UAS system on various types of steel reflective surfaces, measurements on old rusty bridges with chipped paints, operating LDV based UAS in various lighting conditions, and in different weather. The other tasks suggested were to set standards for this system including the distance of operation from the target (25ft, 50ft, 75ft, 100ft, 125ft, 150ft) while flying to collect transverse target displacement. This was suggested to improve the safety of UAS and infrastructure while operating next to a structure.

In the next step of this research, a third system was planned to be added to the LDV and UAS. A localization based on image processing was studied to be implemented for tracking the movement of the UAS based on technology developed by Yoon, H. et.al. 2016. The movements of the UAS will be calculated using this approach, and these movements will be used for obtaining the horizontal movement of the UAS and the LDV for 3D displacement monitoring.

On future research steps, the UAS will be programed to fly next to the railroad bridge and collect transverse displacements autonomously. This will save human effort involved in structural inspection. The automation of the UAS will have the capabilities to compensate for its movements under various environmental and mechanical conditions.

Future Areas of Development

The future implementation phase includes the adaption of the following technical considerations for field implementation:

1. Smaller size and weight of the laser, longer battery, and non-tethered application.
2. Integration of both laser and video techniques to allow 3D displacement measurements.
3. Exploring the use of multiple lasers mounted in one drone.

The research team discussed future developments from these integrated systems, including simultaneously measuring the transverse displacement of the bridge at multiple points under dynamic loading, as well as collecting the transverse train displacement during normal operations, automatically. To make this possible, a swarm system needs to be developed with multiple UAS-LDV systems for measuring the transverse bridge displacement such that the UAS work with each other and compensate for each other's movements. Also, the goal is to have these system housings in the train car itself for easier deployment and data acquisition for all the bridges along the path of the train for continuous monitoring. Additional implementation considerations include the requirement of UAS staff to communicate with the train engineer approaching the bridge to avoid field surprises while operating the flight/inspection. Table 9 summarizes the various aspects of implementation as recommendations for future developments:

Table 9. Future Developments.

Future Development	Description
Reflectivity-Proven	The field applicability of the LDV on the drone regarding the reflectivity of the surface may affect its implementation. Some bridges may have old painting chipping. The change in the reflectivity could affect the results greatly. Future field implementation should discuss the effect of the reflective tape effect in the quality of the displacement and on different surfaces (Steel, Rust, Concrete, Colored walls, etc.). This research tested LDV with the drone on the field under varying light condition without a reflective surface. The results shown in the presentations belong to these tests. The effect of steel reflectivity, lack of continuity in old bridges, materials, has not been tested and should be address in future research for implementation.
Drone Stability	Eventually, it is desirable for the laser beam to be pointed to the same location but drones can drift away. The octocopter could in the development of this technology provide more stable flight. A custom stable controller to be programmed into the guidance system which will facilitate for better stability. Field implementation should discuss stabilization approaches that enhance the controlled operations in the field.
Vertical Measurements	Vertical displacements should be eventually measured with the proposed system, even adding a mirror at 45 degrees such that drone can still measure vertical displacement while still next to the bridge instead of underneath the bridge.
Laser Safety	The laser used for this research is a class 2, i.e. safe for the eyes, but new lasers or developments in the future should include the eye safety during field operations, as well as the compatibility of the power level with FAA enforcements. The effect of temperature in the accuracy of the laser reading should be studied in future research and implementation limitations (both cold and warm environments). There is a need to check on the laser safety issues relative to OHA regulations and special pilot permits for specific railroad environments and FAA requirements, or others.
Steel Interference	For substantial steel spans, researchers need to make sure the span does not interfere with the navigation system of the drone. If the drone uses any sort of magnetic compass, the drone might have problems with the navigation system when close to the span. TTCI operators have noted this close to the girder spans at FAST.
Visibility	Check the signal and data quality under low light conditions, and interference from ambient lighting. Check for effects of various environmental conditions (heat, humidity, fog, wind, rain) on the laser properties and the signal and data quality. Benchmark for testing in night or low visibility conditions.
Train-laser Interference	Benchmark the effect of dynamic shadowing from the train during the measurement. Benchmark the ability of the new system to measure different bridge members during train-crossing events of several minutes.

REFERENCES

- Youtube video links of drones in operation:

  1. Small drone (hovering) https://www.youtube.com/watch?v=P0aUXTYLb70&feature=youtu.be
  2. Midsize drone (recording hovering with laser) https://www.youtube.com/watch?v=9wTpHidbEMM&feature=youtu.be
  3. DJI 600 Matrice drone (flying) https://www.youtube.com/watch?v=JKfLLvb0O_c&feature=youtu.be
  4. DJI 600 Matrice drone (measuring displacement with laser outdoors) https://www.youtube.com/watch?v=5E8YKF75Ug0&feature=youtu.be

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