IDEA

Innovations Deserving
Exploratory Analysis Programs

Rail Safety IDEA Program

Measuring Behavior of Railroad Bridges under Revenue Traffic using Lasers and Unmanned Aerial Vehicles (UAVs) for Safer Operations: Implementation

Final Report for
Rail Safety IDEA Project 37

Prepared by:
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March 2022

TRB TRANSPORTATION RESEARCH BOARD
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This IDEA project was funded by the Rail Safety IDEA Program.

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- The Rail Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
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Measuring Behavior of Railroad Bridges under Revenue Traffic using Lasers and Unmanned Aerial Vehicles (UAVs) for Safer Operations: Implementation

IDEA Program Final Report

For the Period January 2019 through December 2021

Rail Safety IDEA Project 37

Prepared for the IDEA Program

Transportation Research Board

National Academies of Sciences, Engieering, and Medicine

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Glossary

AAR	Association of American Railroads
AFRL	Air Force Research Laboratory
AR	Augmented Reality
AREMA	American Railway Engineering and Maintenance-of-Way Association
ASCE	American Society of Civil Engineers
BNSF	Burlington Northern Santa Fe Railroad
CN	Canadian National Railway
DAQ	Data Acquisition System
DoF	Degree of Freedom
EMI	Engineering Mechanics Institute
ERP	Expert Review Panel
FVP	First-Person View
GPU	Graphics Processing Unit
IR	Infrared
LANL	Los Alamos National Laboratory
LDV	Laser Doppler Vibrometer
LVDT	Linear Variable Differential Transformer
MAHRES	Multi-Agent, Robotics, and Heterogeneous Systems Lab
PM	Program Manager
RMS	Root Mean Square
SHM	Structural Health Monitoring
TTCI	Transportation Technology Center, Inc.
ToF	Time of Flight
UAV	Unmanned Aerial Vehicles
UP	Union Pacific Railroad
USDOT	United States Department of Transportation

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Investigator Profile

Fernando Moreu is an Assistant Professor at the Department of Civil, Construction, and Environmental Engineering (CCEE) at UNM. He holds courtesy appointments in the Departments of Electrical and Computer Engineering Department (ECE), Mechanical Engineering (ME), and Computer Science (CS). He is the founder and director of the Smart Management of Infrastructure Laboratory (SMILab) (http://smilab.unm.edu/). SMILab's research interests include structural dynamics and control, structural health monitoring, wireless smart sensor networks, cyber-physical systems, computer vision, earthquake engineering, augmented reality, unmanned aerial systems, bridge engineering, and aerospace structures monitoring and reusability. Prof. Moreu has published 38 journal papers and several conference proceedings. Prof. Moreu received his MS and PhD degrees in structural engineering from the University of Illinois at Urbana-Champaign (2005 and 2015, respectively). In 2019, Prof. Moreu received the CCEE Stamm Teacher of the Year award. His projects are funded by the National Science Foundation, Department of Energy, Department of Defense, National Academy of Science, Federal Railway Administration, US Department of Transportation, NASA, Transportation Research Board, and the commercial sector. He is a Member of ASCE, ASME, SPIE, and AREMA. Prof. Moreu is a registered Professional Engineer since 2010.

Executive Summary

Measuring Behavior of Railroad Bridges under Revenue Traffic using Lasers and Unmanned Aerial Vehicles (UAVs) for Safer Operations: Implementation

Safety IDEA Project 37

Research Agency:	University of New Mexico
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Completed:	Scheduled to be completed December 2021
IDEA Contract Amount:	$98,997

IDEA CONCEPT AND PRODUCT

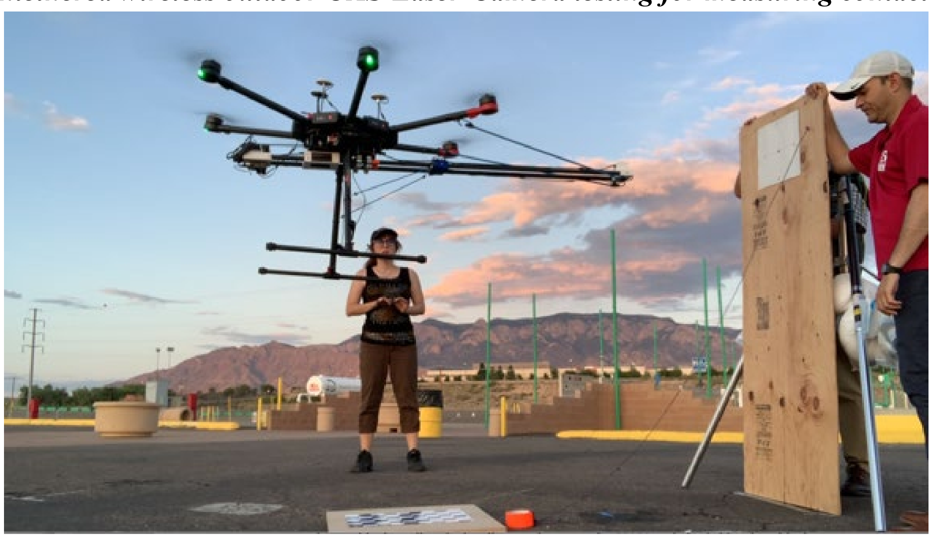
This research focused on developing an Unmanned Aerial Vehicle (UAV)-Laser-Camera system that was economic and reliable so the railroad industry can adopt it. Specifically, this IDEA product was directed towards development of a product that can assist railroad bridge managers to obtain total transverse displacement of railroad bridges under trains. This research project designed a new system by integrating aUAV equipped with lasers, sensors, and other hardware to measure total transverse displacements in the field. The new system was tested to demonstrate that the system could fly near bridges and measure bridge displacement in a new non-contact and reference-free method. The intellectual innovation of this project resided in the integration of measurements from two sensors of different natures: laser and camera. A new algorithm was developed to collect various signals from the UAV sensing platform and obtain the desired total transverse displacement values. The new system was tested in outdoor environment to prove its accuracy and outdoors performance while being untethered. The results obtained were validated to be repeatable. Feedback from the railroad industry ensured its readiness for field use.

PROJECT RESULTS AND FURTHER INVESTIGATION

Initially, the hardware and software development were conducted in parallel. The two main sensors, laser and camera, were selected in consideration to their accuracy, range, and price. Researchers developed a preliminary algorithm and tested the accuracy of the methodology in 1 Degree of Freedom (1 DoF). Once their results were deemed satisfactory by the railroad, the research team improved the algorithm to obtain the 6 DoF motion using the video collected by a camera and computer-vision techniques. The camera and laser signals were subsequently integrated to obtain the total displacement. Following that, indoor laboratory experiments were conducted to validate the algorithm prior to field implementation.

For field implementation, the research team used a DJI Matrix 600. Additionally, the team used Arduino based data loggers to to ensure the affordability of this innovation using low-cost sensors. Several test flights were conducted in the Balloon Fiesta Park at Albuquerque, New Mexico. These experiments were aimed to identify challenges of the methodology and inform future steps to help create a robust integration between the algorithm and hardware outdoors. Access to real bridges was possible due to COVID-19 restrictions in 2020 and 2021. The railroad recommended to test the system in any type of bridge to ensure the system was scalable for bridge enviroments. One local pedestrian bridge in Albuquerque of similar size than timber railroad bridges was chosen to conduct large-scale bridge experiment. The aim of the field experiment was to show that of the proposed approach was feasible for similar bridge elevation settings. The possible uncertainties and challenges of the field experiment have been investigated and addressed prior to the test. The field test provided valuable information about the uncertainties than can be expected in real railroad bridge monitoring.

Figure 1: First untethered wireless outdoor UAS-Laser-Camera testing for measuring contact-free,



reference-free displacements (Albuquerque, New Mexico).

PRODUCT PAYOFF POTENTIAL

The emphasis of this research was the measurement of bridge displacements under freight traffic, but the application can be extended to displacement estimation in other structures. This research provided a new method using an optimum integration between a computational algorithm and low-cost hardware that can provide information to affect decisions of prioritizing bridge repair and replacements without the need for bridge access by inspectors, specifically, for bridges located at inaccessible locations. Inspectors can use the product of this research to collect data remotely and without the need to climb the bridge to install sensors.

PRODUCT TRANSFER

This method can measure total displacement composed of both pseudo-static and dynamic components under freight load which was previously not possible. Future improvements in cost and accuracy can be expected with progress in the UAV, sensors, and laser market.

There was one patent filed by the PI and the RA of this research: STC Technology Ref. No. 2020-122: “Monitoring reference-free contact-free total displacements and movements with a UAS equipped with lasers and computer-vision” developed by Fernando Moreu, and Roya Nasimi, disclosure date June 2nd, 2020.

IDEA Product

The idea project developed a brand-new hardware system accompanied by a computer-vision based computational methodology to provide UAV enabled infrastructure inspection. The physical system comprised multiple sensors: laser, camera, accelerometer, all integrated on a UAV system. The algorithm processed the data collected during a dynamic bridge response event at above 20 feet from the ground. The objective of this IDEA research was to monitor infrastructure and to develop a method that can be applied to obtain non-contact total transverse displacement of railroad bridges. The product of the project was a safe and cost-efficient alternative to replace the traditional methods of collected displacements from inaccessible regions. During the project, the input from the CN railroad ensured that the priorities for the railroad managers are considered, such as the low-cost of the proposed system. The research focused on the railroad bridges, but the system was applicable to other inaccessible infrastructure’s inspections.

Concept and Innovation

Objective data can help railroad managers to make informed decisions and properly regulate their budgets. Transverse component of railroad bridges’ displacement under train loading is critical in bridge condition assessments. Inspectors are interested in quantifing changes in bridge responses over the time, on addition to their visual inspections to bridges. Transverse displacement can be an indication of bridge performance and need for maintenance prioritization. When the transverse displacement of a railroad bridge increases over time, the bridges managers adopt safety measures such as repairing the bridge or decreasing the train speed to avoid excessive displacements that could eventually cause derailments. Traditionally inspectors conduct manual inspections or touch the bridges’ surface to feel their transverse displacement. In order to collect displacements from bridges, sensor are added to bridge components. However, sensor installation cost money, has safety concerns, and involve track time. This Rail SAFETY IDEA project provides a new UAV system that can collect displacement data without the need for bridge sensor deployment. The use of UAV for inspections has previously been investigated but most of them collect image-based data. New UAV studies measuring displacement values have focused on static responses but were unable to collect transverse/out-of-plane displacement components using camera. The innovation of this IDEA project resides in the integration of collecting transverse displacement integrating a low-cost laser with an available consumer -based camera.

Investigation

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

TASK #1: Project kick-off meeting and railroad industry feedback

a. TRB kick-off meeting

The kickoff meeting was held by the PI and research group on a web conference with the Project Manager and members of the Expert Review Panel (ERP) on January 22nd, 2019. During this meeting, potential ideas, and innovative methods were introduced. A detailed schedule for the project was discussed and approved.

b. Railroad industry feedback

The TRB Annual Meeting was used to collect inputs from industry (railroads, Government experts, private industry). Phone conversations with the railroad suggested the use of low-cost sensors and to explore their accuracy for cost reduction. The research group attended the Association of American Railroads (AAR) Annual Research in March 25-27 (Colorado Springs and Pueblo, Colorado). Railroad industry members attending provided specific feedback. The various individuals were members of AREMA C-7, C-8, C-10 and C-15 (http://aar.com/2019AnnualReview_register.php.) Throughtout the project, the bridge departments of both CN and BNSF railroads and their bridge inspection/testing teams provided input on the value of testing a large scale laser/camera UAS system to measure transverse displacements. Additionally, the research team has presented this work on AREMA Committee 10 and AREMA Committee 15, to ensure the level of testing achieved in this report is of value to bridge managers as a proof of concept on large scale bridges. Additionally, it is worth noticing that the research team has shared the results with TRB and the New Mexico Department of Transportation (NMDOT) who have indicated their appreciation of the difficulty of combining laser and cameras in a moving object to collect total displacements and displacement compensation. The railroad industry indicated that the value of collecting data from a pedestrian bridge due to COVID is a good proof of concept of this technology since the size/elevation of the bridge is comparable to timber railroad bridges and the lessons learned from flying outside near a bridge are sufficient to evaluate given the limitations to access bridges during COVID.

TASK #2: Embedded algorithms for flying and filming and hardware development needs

This task focused on hardware and software development. The team used different methods to choose the most appropriate hardware and software solutions. The following section explains the different options for physical hardware system, their pros and cons, and the final selections.

The team developed a new algorithm and validated with experiments. Using these results the team improved the preliminary algorithm.

Hardware needs/development/results

The team looked for the best options for a distance measuring and a motion tracking sensor that could be operated on the drone, following recommendations from the ERP panel during the kick-off meeting.

ZED Camera

A ZED stereo camera was selected and purchased for testing based on feedback from the kick-off meeting. The ZED camera can capture depth and motion information on a 3D platform. This camera has a range of 0.5 to 20 meters with the sampling rate of 100 FPS, and a weight of 159 gr. Figure 2 shows the ZED camera 3D point cloud and the trajectory during movement. To operate the ZED camera, an SDK system and Nvidia graphics processing unit (GPU) was required. Due to the weight of the camera and required costly motherboard to operate it remotely (over $1000) the team decided to look for other options such as lasers/camera integration.

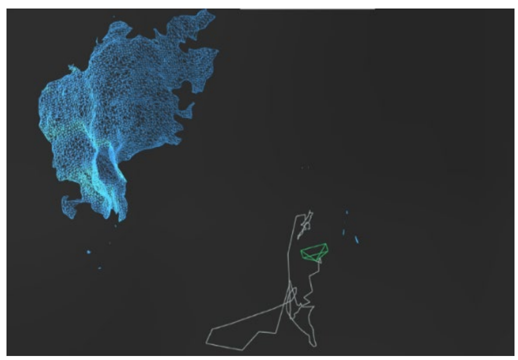


Figure 2: ZED camera track motion on a point and surface mapping of environment.

TFMini-Micro LiDAR module

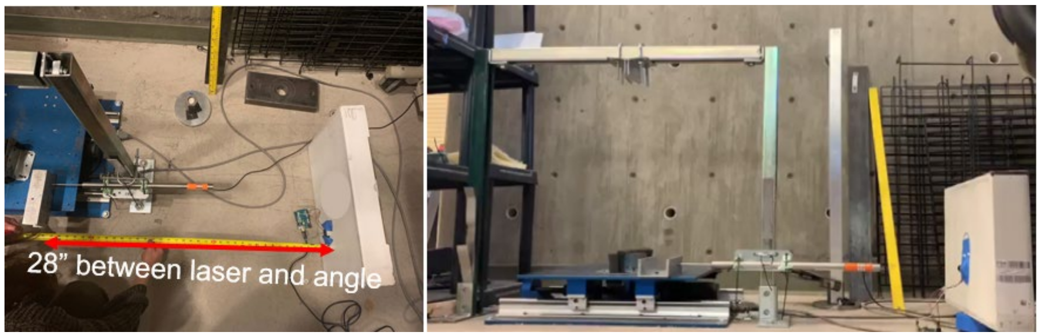
Various dynamic measurement sensors were considered for collecting the dynamic transverse displacements. All these sensors were time-of-flight sensors, which have been used on drones for different purposes such as obstacle detection.

Of the available options, TFMini Lidar distance measurement sensor was the cheapest and lightest one and was selected as a first step to test its viability for this project.

The team selected this sensor for preliminary tests to collect displacements data in laboratory environments. Important advantages of this laser are its low cost, small size, and negligable weight. The sensor has an accuracy of +/- 5 mm within 30 cm to 12 m. This sensor uses a 5V micro controller with an Arduino Uno micro controller.

Experiments on TFMini-Micro LiDAR module (TFMini)

As discussed, this off-the-shelf laser has several advantages: low price, small size, and low weight. The disadvantage of this sensor was its accuracy of +/- 5 mm. For railroad bridges with large displacement ranges, it would be of interest, however it was limited for railroad bridges with small displacements. The research team tested the accuracy of the TFMini sensor designing a shake table test. The measurements from the TFMini displacement were compared with measurements gathered with an LVDT. Figure 3(a) and Figure 3(b) show the plan and elevation view of the experiment layout, respectively.



(a) **(b)**

Figure 3: TFMini-LVDT test's experimentl; (a) plan view; (b) elevation view.

Railroad managers are interested in measuring nonsymmetric displacements like those collected on railroad bridges under freight cars. The research team focused their effort in collecting total nonsymmetric signal from the literature. Figure 4 shows the results of the experiments using LVDT and the TFMini. The results show that with the low sampling rate of the TFMini, around 70-80 Hz, and the high level of quantization, the TFMini can detect displacement with an error of 10 mm and 20 mm in pseudo-static and total displacements, respectively. For large displacements, TFMini can be a good low cost, low weight, and low size dynamic displacement laser that can be added to the UAV. For this project the TFMini was discarded, and new lasers of higher accuracy were pursued.

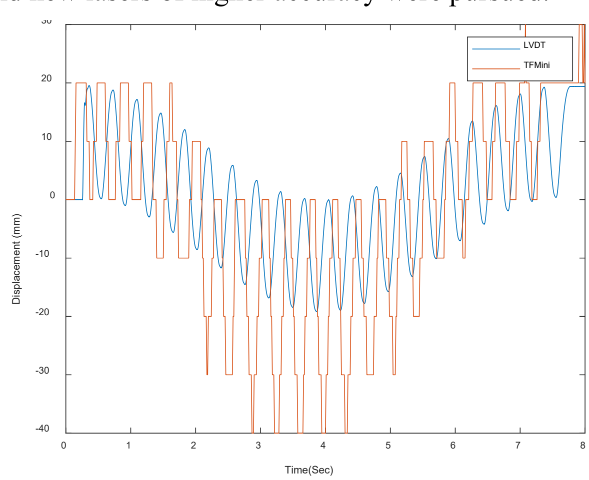
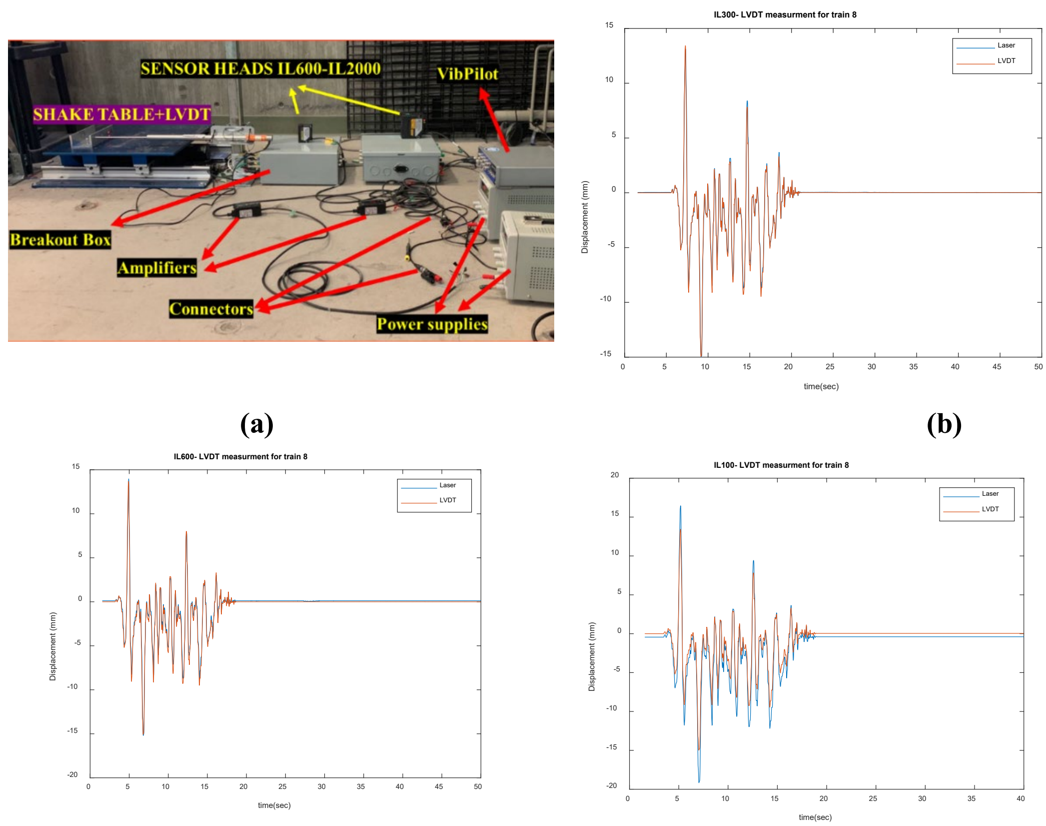


Figure 4: LVDT-TFMini measurement for non-symmetric signal.

High accuracy lasers:

For higher displacement accuracy, the team tested three different types of lasers from high performance laser. Researchers tested the accuracy of the three lasers comparing their measurements against LVDT. The goal was to select the best laser to mount on the UAV that satisfies railroad accuracy standards.

These lasers work with 8.6V, which assists reducing drone payload. For validation purposes, the research team compared the lasers and LVDT's measurement of sinusoidal and various bridge train crossing events collected in the field. Figure 5 shows the displacements obtained using lasers measuring railroad bridge crossing events simulated on the shake table. Figure 5 (a) shows the layout of the experiment; Figure 5 (b) shows results of laser Keyence IL-300; Figure 5 (c) shows results of laser Keyence IL-600; Figure 5 (d) shows results of laser Keyence IL-100. Considering both accuracy and range, the research team selected the IL-100 whose accuracy was comparable to that of the LVDT.



(a) (b)

(c) (d)

Figure 5: Lasers' and LVDT'S displacement of train-bridge crossing events: (a) experimemt set up; (b) IL-300 laser; (c) IL-600 laser; (d) IL-100 laser.

Laboratory Flight (Laser+ Camera+UAV Testing)

A full laboratory experiment was done to collect more realistic data sets and diagnose the possible challenges for the field experiment. The team used the MAHRES Laboratory of UNM. The laser and a downward iPhone were mounted on the drone and the bridge's displacement was simulated by moving one board. Figure 6 shows the indoor drone.

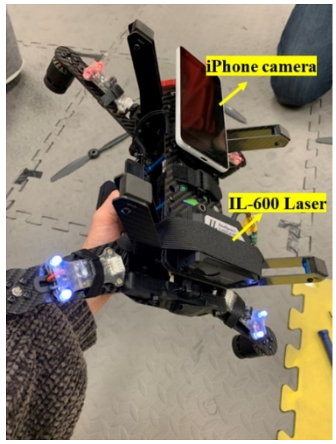
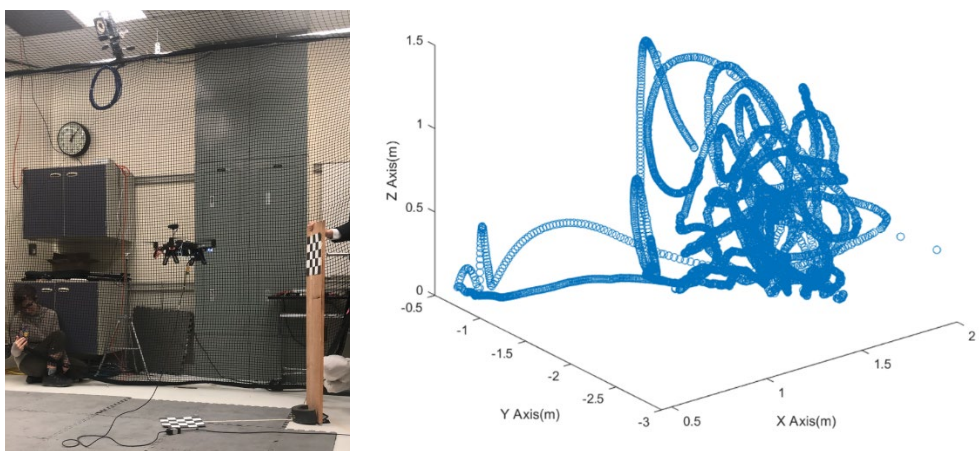


Figure 6: iPhone and laser attached to the drone.

The research team conducted the experiment in with a team of nine students. The drone's motion was recorded by the VICON cameras in the MAHRES lab (Figure 7(a)). Three sets of data were collected for post processing: laser, iPhone, and LVDT data. The outcome of this experiment helped to determine the requirements for algorithm and system design. The drone's 3D motion captured by VICON is shown in Figure 7 (b).



(a) **(b)**

Figure 7: UAV/Laser/Camera experiment; (a) new system in laboratory; (b) movement captured by the VICON camera.

The measured information from the drone's hovering indoors, including translational and rotational motions, were used as a reference to design both the hardware system and the algorithm of this project. This lab experiment indicated that the UAV hovering range is in general higher than laser's measurement range. On the other hand, the existence of a tether disturbed the flight, therefore researchers decided to prioritize developing a system to operate without tether. Also, as seen in the figure 7(b) due to the large range of drone movement during the flight, there was a signifigant amount of missed data. To address the controlled flight issues the team decided to develop a new a system for untethered flights that may hover during flight.

Preparing UAV for flight

The following requirements were considered during the UAV design:

(1) need to develop a new hardware system to fly untethered. The team developed an untethered, remote DAQ system for the laser and acceleration sensor.

(2) the weight of the power supply needs to be reduced: the team attached two carbon bars to place the laser head away from the center of the drone and closer to the bridge surface during flights. Several 3D printed cases were created to hold sensors and balance the weight of the drone.

(3) The two carbon bars had vibrations caused by the drone's engine; these vibrations were measured with an accelerometer installed at the tip. A 3D printed box as shown in Figure 9 (c), was used as a damper. Additionally, some strings were used to minimize the vibration on the bars. The attached accelerometer recorded the vibration during the whole flight. A comprehensive list of hardware components created for the remote flight follows.

a. Laser's remote DAQ system

This system had the capability to both store information on a microSD card, and also allowed data to be monitored remotely via wireless transmission. One of the most important devices in the system was a unit that stores laser measurements. This device has a programmable analog output that varies from 0 V to 5 V for a given distance range. It was programmed to measure between 0mm to 300mm. The preferred resolution could be obtained using a 10-bit analog-to-digital converter (ADC) microcontroller. The flowchart of data logger's design is shown in Figure 8.

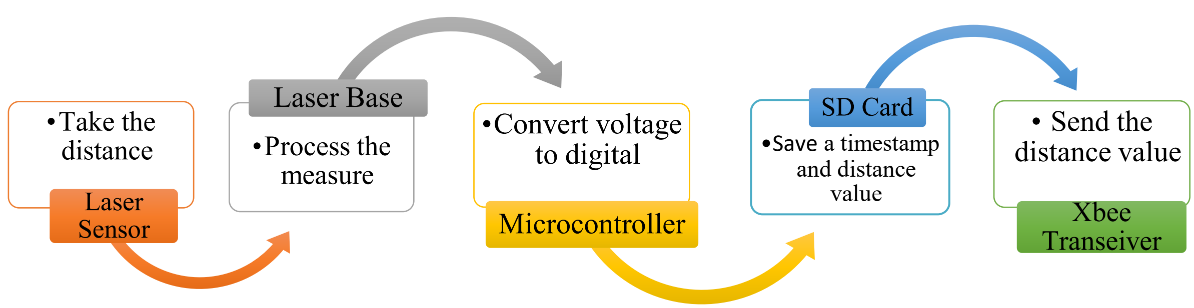


Figure 8: Steps of the methodology to develop a remote laser DAQ system.

b. Acceleration sensor

The team used a Triple-Axis Accelerometer, MMA8451, which has 14-bits resolution. An acceleration data logger was used in conjunction with I2C serial communication to request and receive the sensor acceleration data on the X, Y, and Z axes corresponding to the pitch, roll, and change in altitude of the drone. Another parameter was added in the calculations that allow us to compensate for these movements: the measurements were taken with a maximum range of 2 G (Gravity), which was appropriate for the accelerations collected during flight. In addition, the data was stored with a column corresponding to the timestamp for post synchronization.

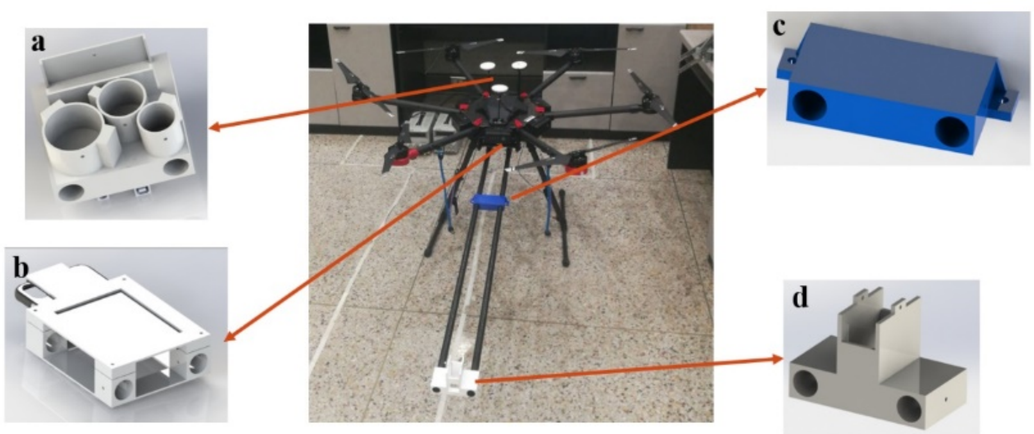
c. RGB light

An RGB LED light (Red, Green, Blue) was added on UAV to inform the pilot on the distance of UAV from the surface during the data collection. This was done in consideration to the comments provided by the railroad survey. The system must be simple to operate by giving more control to the pilot. The RGB light provided a reference point for operation. The LED turned into red when the distance between the laser head and the target were under 125 mm; green when the distance was between 125mm and 175 mm; and blue when the distance exceeded 175 mm. This setup was to assist the pilot to position the UAV within a desired range with the light is green.

d. 3D printed Boxes

A conventional 3D printer was used to produce multiple cases added to the UAV. The 3D printed cases were designed and fabricated with different objectives. Case number one was designed for holding the laser at the tip of the bars. Case two was used to hold the phone under the drone. Case three was added to hold the laser's amplifier, counterweight, and extra wires on the back of the drone. Case four was a solid piece that was added to the midpoint of the carbon bars to act as a damper. An accelerometer's data logger was added to measure the vibration of the carbon bars. Figure 9 shows the 3D printed cases used on the UAV.

Figure 9: Printed cases for (a) Balance weight and amplifier (b) Camera (c) Damper (d)



Laser.

e. System's power supply

The system needed three different sources of power. One of them supplied the power of the laser head directly from the drone batteries. The other two power supplies were Alkaline 9V batteries that were needed for the laser DAQ system and acceleration DAQ system.

f. checkerboard

The size of the checkerboard was selected considering the expected height of the flight. The checkerboard served as a reference for the frames collected by the camera on the UAV and were used for the video processing. The size of the checkerboard was important to ensure the videos provide enough resolution to estimate the displacments of the UAV.

g. summary

Table 1 details all components used on the drone and their corresponding weight.

Table 1. Estimated total load added to the drone.

Component	Payload
Laser	135 grams
Carbon bars	226 grams
Power supplies	113 grams
Camera	290 grams
DAQ system	71 grams
Acceleration system	73 grams
Amplifier and whole wire system	150 grams
Balance weight	1000 grams
3D printed cases	280 grams
Strings	158 grams
Total	2,496 grams

Software

Algorithm Camera/Laser Displacement

An algorithm was developed to find the motion of the camera using the frames of the video captured during the experiment. The preliminary algorithm used a camera model and solved it for displacements assuming the camera has a constant height, so that a fixed scale factor was considered for the entire method to simplify. The frames used in this algorithm are distorted and need to be calibrated.

Figure 10 summarizes the overall procedure of finding dynamic displacement of the bridge using preliminary workflow with both laser and camera. Camera parameters such as intrinsic, extrinsic, rotation, and the re-projected image points were obtained prior to image processing. The re-projected image coordinates were converted to real coordinates using these parameters. The displacement values were calculated by the coordinates of each frame of the video. The resulting displacement measured by the method was validated with an LVDT.

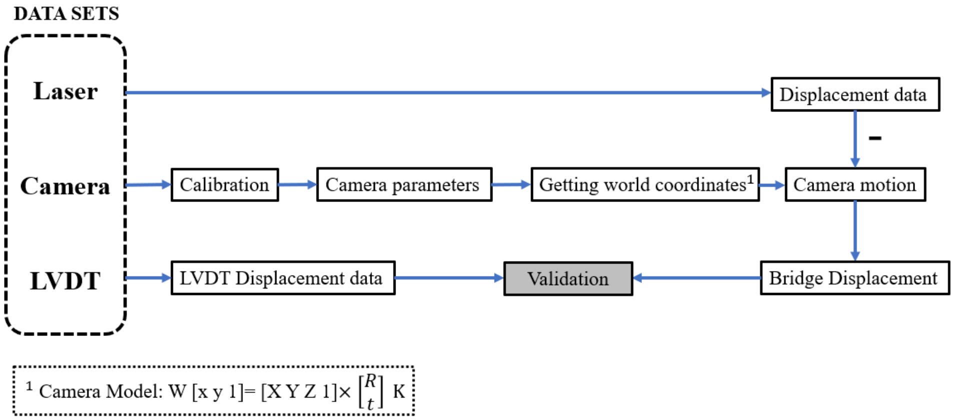


Figure 10: Algorithm's procedure to find dynamic displacement values of the bridge.

Algorithm Experiments

a. 1D displacement test

In this stage, the research team conducted an experiment with a combination of three sensors: laser, camera, and LVDT, as a proof of concept to the proposed methodology. To this end, a simple experimental set up was made in the laboratory and data was collected and processed, see more details in Nasimi and Moreu (2021 a.)

TASK #3: Railroad requirements to operate in the field

The research group attended the Association of American Railroads (AAR) Annual Research Review in March 25-27 (Colorado Springs and Pueblo, Colorado). The main purpose of attending this AAR conference was to receive feedback, concerns, and suggestions for the implementation from the railroad industry about this project: (http://aar.com/2019AnnualReview_register.php). The team prepared a survey and selected ten experts in the conference in coordination with the AAR and FRA leadership team (Dr. Duane Otter, and Cam Stuart, respectively, who were attending the meeting.) During these interviews, the research team explained the project, the hardware and software limitations, and requested the experts to fill the surveys to identify what the main challenges for implementation. Figures 11-13 show the results of the survey. Figure 11 shows how approximately 8 out of 10 experts considered the complexity and unreliability of using drones in the field as the main challenge. The price and safety were not considered as their top concerns. Figure 12 lists the percentage of interests in various aspects related to the use of UAV for railroad bridge inspections: cost, simplicity, weight, accuracy, real-time, and accessibility to remote spots. According to this survey, all these items received the same level of attention by the railroad community. This research considered all aspects mentioned in this list. Figure 13 shows the wish list of the railroad to make drone inspections successful in real applications. As seen in the other surveys, the accuracy was the top interest of railroad owners.

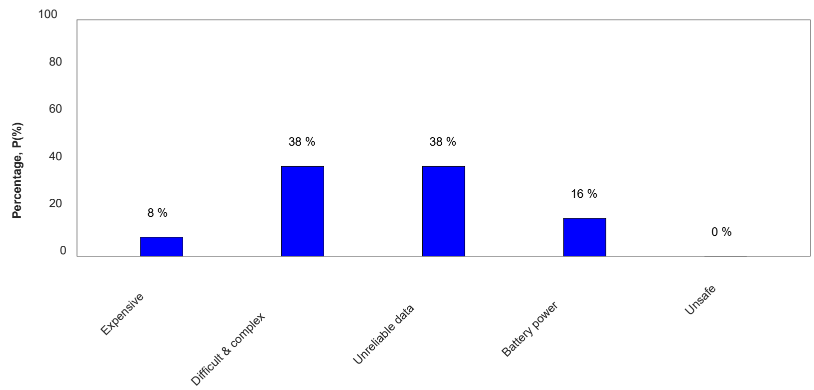


Figure 11: Related challenges with the use of drones for the railroads.

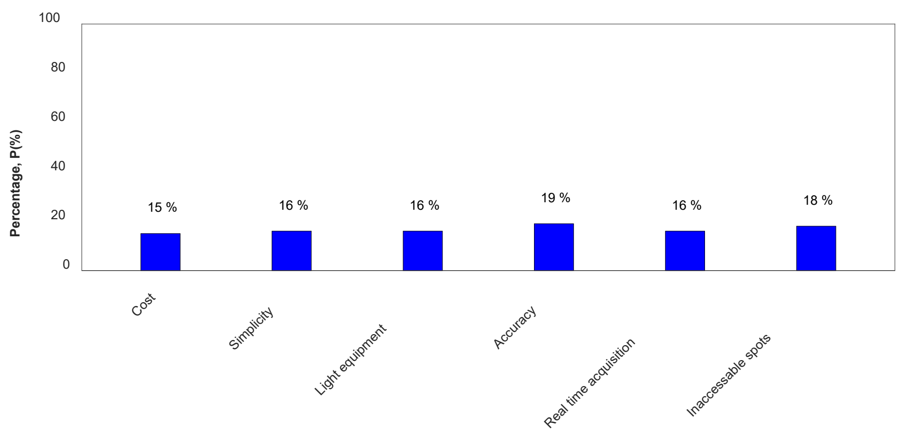


Figure 12: Important items for railroad managers to be considered to do bridge inspections using drone-laser.

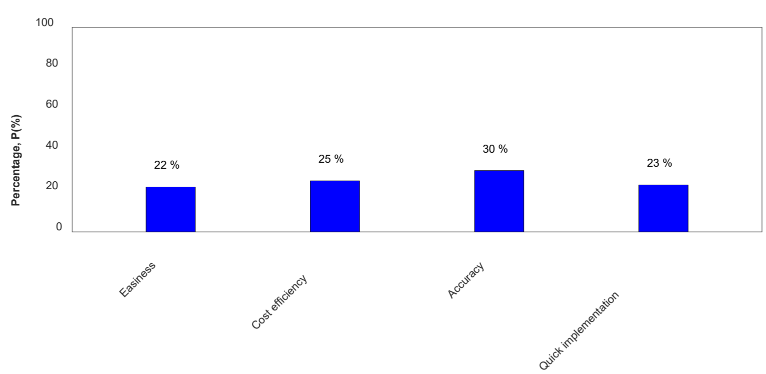


Figure 13: Important things to be considered to make drone inspections successful in railroads.

The main concerns of the railroad community were the accuracy and reliability of the data and the complexity and the difficulty of the operations. The research group decided to address the accuracy concern of the experts and the challenges of untethered flight.

Finally, according to the railroad industry, other signal departments in the different railroads need to be contacted to ensure their feedback is included in the actual implementation in open traffic. More specifically, the results of such a pilot study need to be planned with AREMA Committee 37 (signal systems.)

TASK #4: Develop and test the monitoring approach of this technology in Albuquerque

The team scheduled multiple field experiments to educate the research team of any required adjustments from the laboratory methods and to identify challenges related to large scale and environmental effects. The research team proceeded in Task #4 with a bottom-up strategy, from basic flights without sensors to a final data acquisition with all components, to replicate a similar scenario of railroad bridge monitoring. The results showed that the monitoring strategy validated in the laboratory can be used in outdoors. The detail of each experiment is given below.

Preparation flights, July 24th, 2019

Figure 14 shows the pre-test flight. The FAA regulations for outdoor operations were introduced to the research team members to ensure that the team prepared for the test with lasers and cameras ahead of time. The pre-test flight had two steps: first, the research group conducted a pre-test flight to evaluate the new pilot's control on the drone; second, researchers determined all the necessary steps required for drone operations, safety, and development of hardware system including data loggers, sensors, and batteries. In this flight, no data was collected as the emphasis was the flight control and experiment set up in an outdoor environment.

Figure 14: preparation flight.

Pre-test setup: August 2nd, 2019

The objective of the pre-test experiment was to prepare the sensors and the set up for successful data acquisition in outdoors. A simulated flight was conducted with the research team to inform the real dynamic experiment with real outdoor distances. The research team analyzed the pre-test setup pictures, distances, limitations, and determined how to prepare for data collection (Figure 15). The team scheduled the first outdoor experiment with the new integrated system, merging the results and findings from preparation flights and pre-test set up. A group of seven people attended the Balloon Fiesta Park and collected distances, set up the outdoor test, and prepared for the flight in a real outdoor scenario. This experiment was conducted at 7 P.M. The team: (1) determined layout of distances, mock bridge panel, cameras, LVDT, and DAQ for data collection; (2) coordinated both pilot and data acquisition in order to enable real-time flight control; (3) tested protocols for experiment, distance from checkerboard, and duration of experiment in mock train crossing events.

Figure 15: Pre-test experiment in real outdoor scenario.

Experiment 1: August 12th, 2019

The first outdoor experiment was conducted to collect real data in order to achieve the following objectives: (1) stability of the new system for safety of the pilot, operations, simulated bridge, wind effect; (2) camera data during flight, appropriate distance for video capture, computer-vision limitations, clarity of the video during drone operations; (3) laser data quality, laser range for successful displacement measurement, laser vibration (a wireless accelerometer was added for outdoor experiment); (4) LVDT location in coordination with laser measurements, for research validation (installment height, rod opening, LVDT stability with sand bags, LVDT vibrations during experiment); (5) synchronization of (2), (3) and (4): design a field data synchronization strategy so data can be later correlated between the four different DAQs: laser, camera, LVDT and accelerometer.

On the test date the group could fly system and collect data without any technical issues even with a 11 MPH wind. Six group members attended this experiment (Figure 16.)

Data/ outcome of experiment 1:

The group identified point to be considered in the actual experiment to achieve research objectives. For example, to achieve synchronization of the data, the group used an orange tape that could be seen in video frames. A sudden impact was imposed to the board and the tape to know the exact moment of such event for the LVDT, camera, and laser. Five different tests were analyzed. Figure 17 shows the result of one of the experiments.

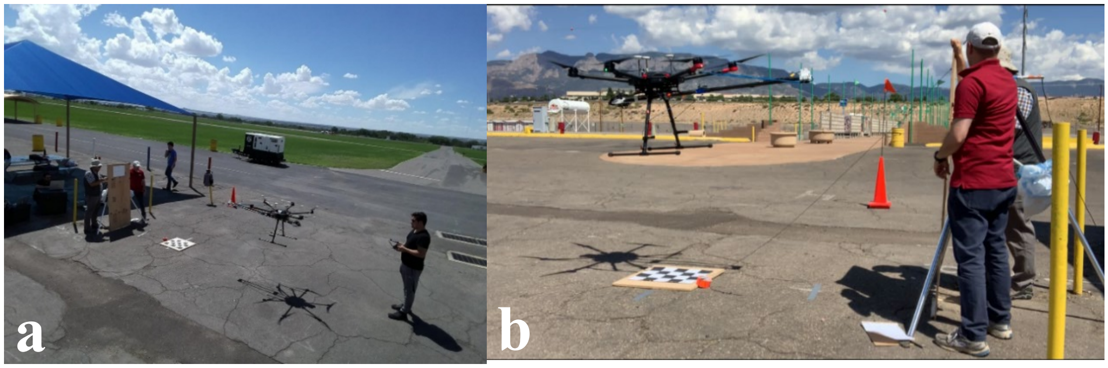


Figure 16: Experiment in Balloon fiesta park: (a) filming of the drone experiment from a different drone; (b) filming of the drone experiment also available in Youtube.

Figure 17 shows some missing data from the laser signal, plotted as fixed values. To reach higher resolution in laser data, the research team decreased the default range of the laser from 0-80cm to 0-30cm. However, the drone experience higher range than the designed 30 cm during the hovering. To collect a better laser signal, the range was increased, and another field experiment was scheduled to be conducted in ideal conditions.

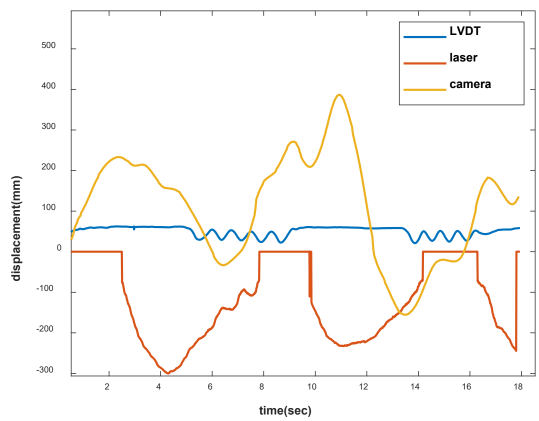


Figure 17: LVDT, Laser, Camera data of the Experiment 1, test number 4.

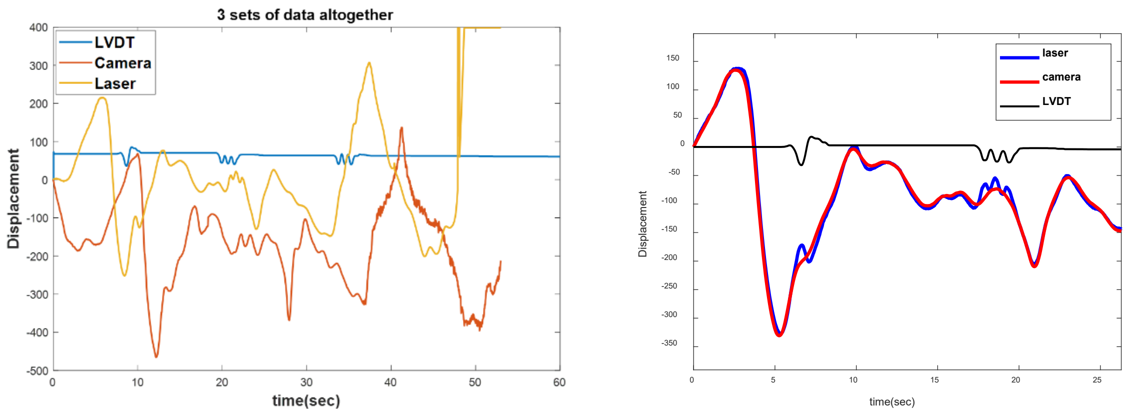
Experiment 2: August 23rd, 2019

This experiment was conducted with assistance of five researchers (Figure 18). The setup of the experiment was the same as before, except for the modified laser range and data logger. Six different experiments were conducted and the details are shown in Table 2. Among these experiments, test number five was selected for detailed analysis. The original data and the synchronized data in a selected frame of time (until 25 seconds) are shown in Figure 19 (a) and Figure 19 (b), respectively. As seen in Figure 19, the synchronized data from the drone and the laser captures the behavior of the drone with the laser.

Figure 18: Field experiment on August 23rd: field images with UAV flight.

Table 2: Tests details of the experiment 2

# of experiment	Start time/original video duration	Data Acquisition duration (laser)	Input signal(watching original video)	Explanations
1	07:15 PM/ 01':59"	70.583 seconds	00:46": Recording 00:55": calibration 01':20": 3 hots/motions 01':41": Done back 01':56":Stopped data	
2	07:25 PM/ 02':01"	68.27 seconds	00:47": Recording 00:55": Calibration 01':19": 3 Bridges 01:23"-24":3-4 Bridges 01"40": Drone back 01':54":Stopped data	LVDT stopped 3-4 seconds late
3	07:30 PM/ 01':53"	68.767 seconds	00:40": Recording 00:50": Calibration 01':00: 3 Bridges 01':15": 3Bridges 01':34": Drone back 01':50": Stopped data	After end of this experiment data were checked
4	07:38 PM/ 01':37"	58.753 seconds		No Calibration and some other information missed. This experiment wont be considered for now.
5	07:40 PM/ 01':38"	60.132 seconds	00:31" Recording 00:41" Calibration 00:53": 3 Bridges 01':07": 3 Bridges 01':21": Drone back 01':35": Stopped data	Good!
6	07:47 PM/ 01':47"	62.765 seconds	00:37": Recording 00:43": 3 Bridges 00:48": 3 Bridges 00:54": 3 Bridges 00:59": 3 Bridges 01':04": 3 Bridges 01':16": 1 Hit 01:19": 1 Hit 01':21": 1 Hit 01':28": Drone back 01':41": Stopped data	



(a) (b)

Figure 19: Original data collected from field with the processes video data:(a) pre-processed data: (b) processed data.

Figure 20 shows the noncontact displacement estimation of the board over a selected range of time. The large errors happen where there were no displacement, and the displacement estimation is accurate where a displacement occurs in the structure. The railroad managers are interested in the performance on peak-to-peak displacements.

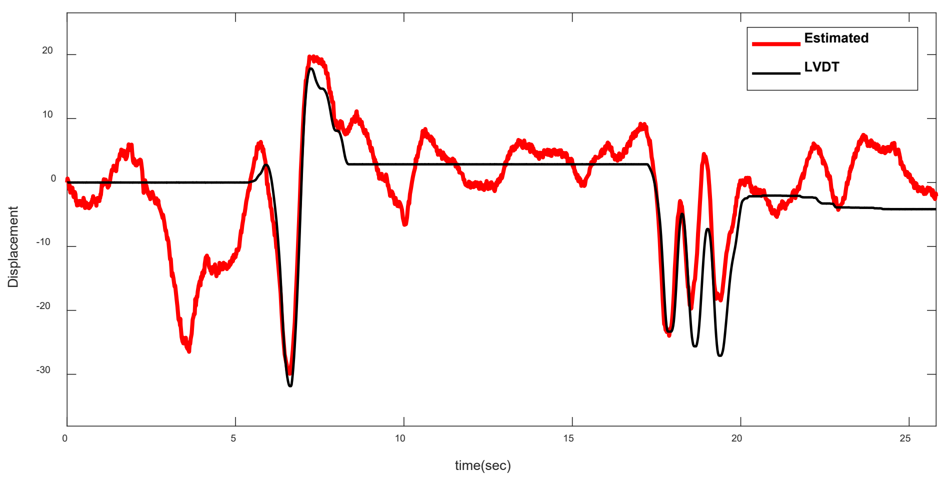


Figure 20: Non-contact displacement estimation.

Field Testing Conclusions informing Stage II

The results of Stage I assisted to identify two new opportunities for implementation in Stage II,:

- The distance between the laser and the bridge should be increased. According to the railroad, this removed the pressure on unexperienced inspectors who may be intimidated to fly the drone too close to the bridge. Based on the options explored earlier in the project, enabled the implementation of a 12 feet range laser which was better suited for bridge measurement. A new laser was ordered for field implementation.

- The results about the Albuquerque flight were reanalyzed to ensure the displacement estimation accuracy was like the accuracy conducted indoors.

TASK #5: Stage I Report

The draft for stage I was submitted to the ERP for review and a zoom meeting was scheduled on October 31st to receive feedback and comments from the project manager and the ERP followed by minutes of the meeting for stage I. The ERP recommended to improve the results accuracy and a larger range laser. ERP member Dr. Duane Otter mentioned that TTCI will be closed during the dates that the project experiments was planned to be conducted and the field experiments needs to be postponed. After receiving comments and suggestions from the ERP, the stage I report was submitted on November 15th.

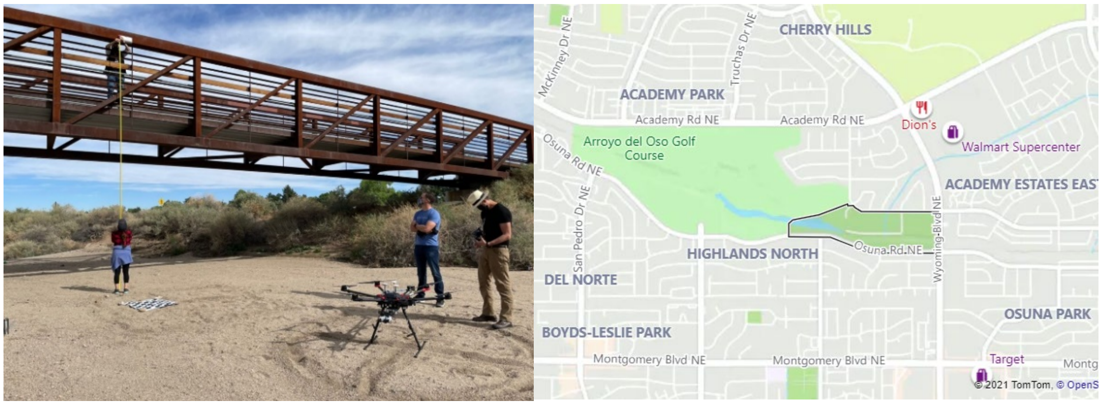
TASK #6: Bridge Test

Following the suggestions from the ERP, the research team aimed to update the system to meet the requirements and get better results flying near bridges by selecting and programming a new high-range laser.

Due to the COVID-19 pandemic, safety concerns, and university regulations, the research team had to postpone the test to a later date and look for other options to conduct the test near a railroad bridge without the need to travel outside of the state. The team investigated options. This was discussed extensively with the ERP on April 24th, 2020. It was agreed that any possibility of collecting real data from any bridge should be included to the project given the current COVID-19 pandemic. Given travel restrictions, the ERP indicated that collecting data from nearby bridges in Albuquerque would benefit the learning of implementation of the technology, even if they were not railroad bridges. Then a pedestrian bridge with access to the research team was selected.

Following the ERP recommendation, the research team managed to obtain the required permissions from the city, park, and police for the bridge that was in Arroyo Del Oso Park, Albuquerque. The selected bridge was a 147 ft span and 19 ft tall steel pedestrian bridge, Figure 21.

For this test, preparations included the creation of a new drone system following the suggestion of ERP to keep the drone at least 6 ft away from the bridge. Additionally, new challenges regarding piloting, safety, laser, and computer vision were explored on a real bridge environment on a full-scale experiment. In real world scenario, it is expected to have a wind gust effect on UAV due to train pass. Even though the effect of train wind gust cannot be tested on the selected pedestrian bridge, multiple experiments in stage I of the project at Balloon Fiesta Park showed that the accuracy of the algorithm is not affected adversely by wind if the checkerboard remains in the video frame during the experiment.



(a) **(b)**

Figure 21: Arroyo del Oso park: (a) test team at the bridge site; (b) Map location of the bridge.

According to the ERP members, the data collected in the field did not have realistic distances between the UAV and the bridge and that was a priority for the testing implementation. In their opinion, an implementation method should include advancement in validation options of non-contact methods that measure bridges from far distances like those in the field. Due to the higher elevation of the bridge, the team prepared a larger checkerboard target. The ground truth values in previous small scale outdoor experiments were collected using a LVDT. However, bridge experiments in Arroyo Del Oso Park were large scale. Therefore, LVDT was not a preferred validation method for bridge experiment due to installation and access challenges associated with LVDT. Following ERP's feedback, the team selected a larger range and high-resolution commercial laser for field implementations and validation. The Polytec laser doppler vibrometer was chosen to collect accurate measurements over 150 ft away. Figure 22 shows the new validation large range laser for the experiments conducted on the bridge.

Figure 22: Setting up the high range accurate polytec laser in field for validation.

The research team conducted multiple tests near the bridge to collect preliminary results for field implementation and to identify barriers of implementation in real bridge scenarios. First, a field test was conducted to validate the laser and understand the displacement range of the bridge. Several tests were conducted for pilot preparations. In the first full bridge experiment, during data collection, we identified that the light of the laser on the drone was not visible to the pilot in daylight environment. The team added a portable greenlight laser on the UAV next to the laser. The greenlight laser was easily detectable and allowed the pilot to understand the surface they're flying nearby. Figure 23 shows the green laser next to the measurement laser on the UAV, and the two signals on a surface. In real flight conditions, the pilot is not able to see the red light but can follow the green light for positioning the UAV.

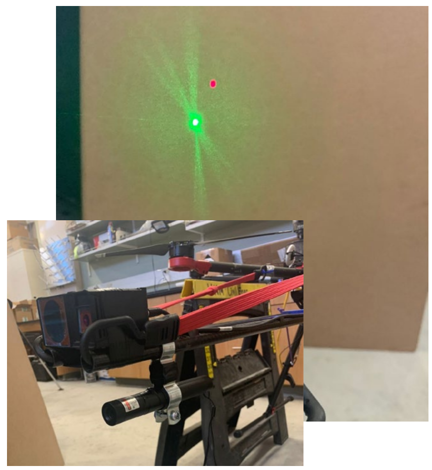


Figure 23: Greenlight laser added on the UAV, next to the displacement measuring laser.

Figure 24 shows one the test conducted in the field with the new set up. The sensing system on the UAV was improved with the new high range IL2000 laser. Additionally, the data logger was improved (see Task #7). The UAV managed to fly at a safe distance from the bridge surface while collecting data (between 6 and 11 ft). The video of the experiment can be found in this link: https://www.youtube.com/watch?v=ZasDaoBCnnc.

Figure 24: Field test with updated UAV system at Arroyo Del Oso Park, Albuquerque.

The team conducted five tests on this experiment. Each experiment was intentionally conducted with different displacement ranges. A simulated bridge movement was imposed on a target which was moved manually simulating a train crossing event . Each test lasted about 100 seconds. Figure 25 shows the analysis of a frame of experiment that was recorded by the camera on the UAV while hovering near the bridge over 20 feet from the ground, similar in height to many of the railroad timber trestles in North America. Figure 26 shows the displacement values collected by the laser doppler vibrometer in test 1 and test 3. The final estimations of the displacement by the UAV are expected to be published in a journal paper to be submitted by June 2022.

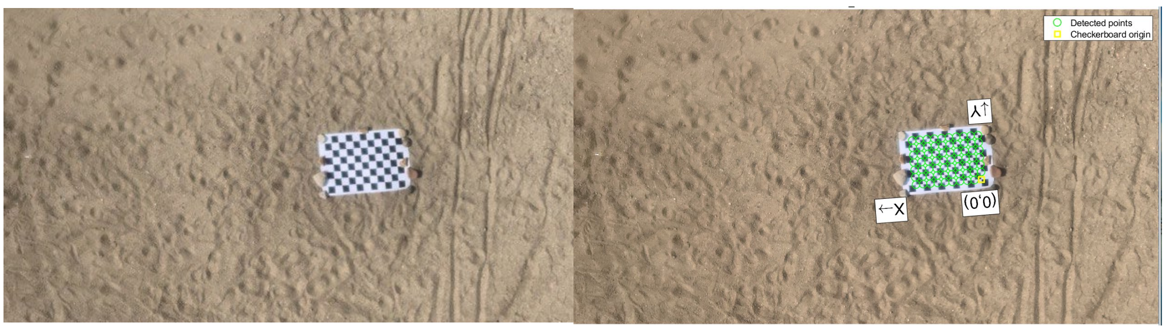
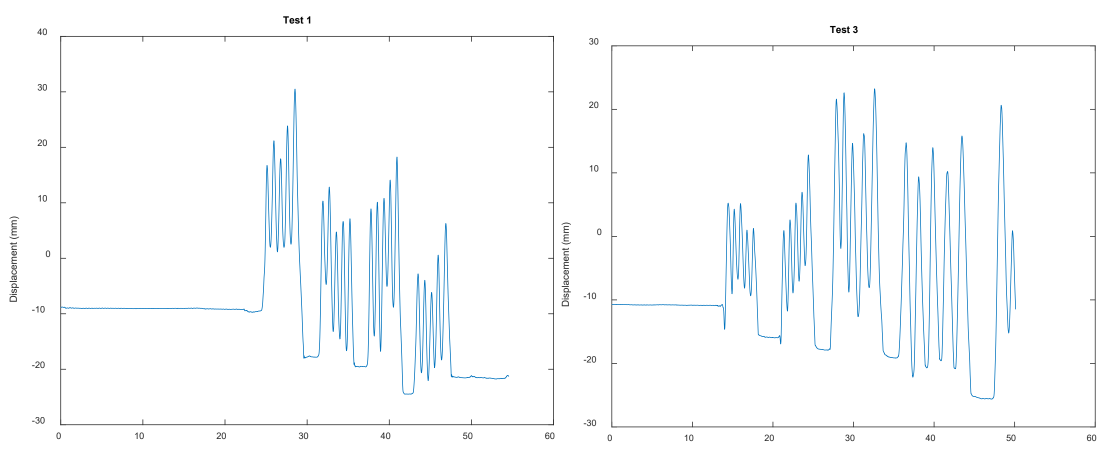


Figure 25: Camera data analysis of test at Arroyo del Oso Park, Albuquerque.

The team processed the data from each sensor separately and selected few time frames to analyze the data. Preliminary analysis of the data collected on the UAV estimated the not-contact displacement within milimiters. The average RMS errors were calculated as 8.71 mm and 11.5 mm. The preliminary data analysis showed that the system can collect transverse displacement data from a real bridge with similar height than railroad timber bridges. Future development of the method includes sensor fusion of MIU and camera for increased accuracy in the determination of the UAV location.



(a) **(b)**

Figure 26: Displacement measurements by laser doppler vibrometer; (a) test 1; (b) test 3.

TASK #7: Optimize performance and robustness of the system

Hardware:

Nasimi and Moreu (2021 b) published the list of sensors on UAV and their sampling rates during the experiments in the first stage of the project at the Balloon Fiesta Park. Per suggestions of the ERP members during Stage I Report, new hardware with more advanced properties was added prior to the Stage II field test. A new camera with higher resolution was also added, and tested, in laboratory environments. The railroad wanted to prove higher displacement estimation accuracy prior to the field test, which was achieved. The new laser was Keyence-IL2000. As mentioned in Task #6, the new laser allowed the drone to collect displacements as far as 11.5 feet from the bridge, which was farther than the former layout (2.5 feet.) This laser has a range of 2,500 mm and the reference point for this laser was 1,000 mm which enabled a wider distance between the drone and the bridge (3500 mm=11.5 feet approximately).

Researchers developed a new DAQ system for the new laser to enable wireless data collection. In first stage of the project researchers used an Arduino Uno microcontroller to develop their DAQ system. Arduino Uno has a 10-bit ADC values within the range of 0-5V which means it provided 2^{10}=1024 digital values. This was a good match for the IL-600 laser with the range of 800 mm. This configuration was used in stage 1 of the project. However, the new laser IL-2000 has a range of 2,500 mm. Therefore, researchers used an additional component called Adafruit ADS1115 16bit ADC Board. This component enabled the designed DAQ system to collect data with higher resolution by increasing the ADC value of the Arduino.

Software:

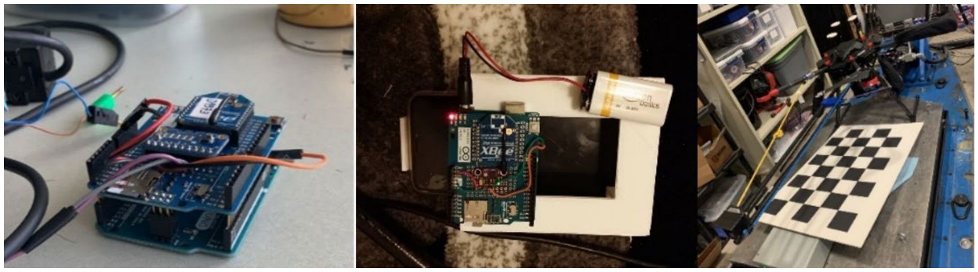
Following the feedback from the Stage I meeting with ERP, the research team prioritized the software to improve the accuracy of the algorithm. ERP member Dr. Rafael Fierro invited the research team to conduct tests at UNM-AFRL laboratory, to confirm the accuracy of the algorithm. The UNM-AFRL laboratory was equipped with VICON cameras. VICON motion capture system can measure dynamic displacement in 50 Hertz with an accuracy level of 0.01 mm. The VICON camera collected the movement of the camera . The cameras pose and orientations acquired by the developed computer-vision algorithm was compared with the measurements from VICON cameras.

The program was modified to demonstrate the ability of the algorithm to estimate the dynamic displacement of a randomy moving camera in 3 directions and 3 angles. Stage I assumed that the camera moved only in one direction sliding a camera on one rail, with zero rotation. The results of experiments at the AFRL laboratory are presented in the paper by the authors (Nasimi and Moreu, 2021 a).

The algorithm was optimized to detect unrecognized frames and interpolating data using the previous and next available frame. This automatic interpolation alleviated the issues with undetected video frames. There was a noise in camera estimations due to the checkerboards error detection from the frames. Researchers applied a moving average filter to remove the noise of the signal.

Additionally, the team developed a method to use the camera data to find the laser angle and correct the angular motions of the laser (Nasimi and Moreu 2021 a).

Finally, the team added an IMU sensor along with the camera in a new configuration of the UAV for future sensor fusion techniques implementation. Figure 27 shows the new DAQ system for higher range laser with the Adafruit ADS1115 ADC board, new camera and IMU system, and the final version of the enhanced UAV system.



(a) ***(b)*** ***(c)***

Figure 27: Updated UAV system: (a) DAQ for large range laser; (b) Camera with IMU; (c) Final configuration of enhanced UAV system.

TASK #8: Adaptation and user interface with railroad

The work to date has been presented and shared with different communities. The feedback from experts were gathered to inform the future steps of the project. The following section outlines the various conversations with railroad owners, engineering events, university centers, including the AREMA Committee 10 (Railroad bridges maintenance) who was hosted in UNM on January 27, 28 and 29, 2020. This Committee meeting hosted the presentation of RS37 to 20+ bridge engineers.

Additionally, the research was introduced to the research community and faculty from computer science department in UNM, who piloted the enhanced UAV system for field tests. Their feedback was collected to identify the limitations and fields for improvement in future.

The research team showed the results from the final field experiments to the ERP to gather their feedback on the potential of the work. In technical discussions with ERP regarding this research, the panel raised their concerns about the security and federal law issues related with the portable green light laser on the UAV. They suggested using high frequency lasers such as invisible IR lasers that are available in the market (Beamshot IR laser sight, 2021). They also, suggested that creating an interface using AR to control the UAV can be an alternative to be considered in future.

Moreover, researchers submitted a paper to EMI 2020 conference in SHMC subcommittee titled "Unmanned Aerial Vehicles (UAVs) Equipped with Lasers, Cameras, and Algorithms Measuring Bridges Condition under Trains". The researchers were selected as one of the finalists to present their works in the event. Researchers presented their work to leaders of SHM from all over US and Europe and got the second place in the competition. The winners were announced on ASCE website:

https://www.asce.org/engineering-mechanics/news/20200604-emi-shmc-student-paper-competition/

TASK # 9: Final report

The final report was completed under COVID environments. The following sections summarize the discussions and completion details of the final report.

Meeting with ERP and PM

Various meetings were conducted between the research team, the PM, and the ERP members to complete the research tasks during COVID and ensured the implementation aspect of the project was covered in the new circumstances. On October 13th, 2020, it was discussed that the project addressed possible improvements in the context of outdoor bridges. On April 24th the recommendation from the ERP was to conduct a field testing in any possible bridge to increase the impact of this research, and the research team identified a tall pedestrian bridge in a park in Albuquerque that was agreed to mimic similar outdoor limitations that would be encountered in railroad timber bridges. The team conducted multiple experiments to identify limitations of implementation and inform suggestions to industry. On September 7th, 2021, the research team presented the outdoor testing results to get feedback from ERP. The ERP and PM reviewed this final report, and it was approved for publication on March 2022.

Plans for Implementation

The lessons learned from field tests and the feedback from the experts in different communities can be summarized as follows:

Barriers to Implementation

a. Line of sight for a single pilot makes alignment challenging.
b. Some instability due to laser and counterbalance moment (i. e. tends to pitch forwards and back which increases forward velocity unexpectedly)

Areas of future development

a. Long range lasers would improve the margin of safety.
b. Forward facing FPV remote camera for alignment with ground receiver.
c. Replacing the portable green light laser with an invisible high frequency laser.
d. Creating an interface using AR to conduct automated intelligent UAV control.

Potential collaborations and implementation of the work

The team has submitted a patent for review in June 2020. Additionally, the team has secured funding from other agencies to create a facility at UNM called Lobodrome. This facility is an outdoor laboratory that enables conducting outdoor UAV tests with outdoor VICON cameras. There were conversations held with the PI and CN and BNSF railroad to conduct tests on their railroad bridges. It would be required to include the signal departments of each respective railroad to ensure the collection of data in the field matches specific requirements from the railroad industry. Discussions with the AREMA Committee 37 on the field data collection will ensure the safety of the integration of the displacement collection under traffic from the operations perspective.

Conclusions

The objective of this idea project was to develop a brand-new enhanced UAV system coupled with an algorithm to obtain bridge displacement under train loading without direct access to the bridge itself. This research aimed to obtain transverse displacement that is useful but normally challenging for railroad managers to obtain. The system proposed by the team integrated measurements from a laser and camera mounted on a UAV. The research team corrected the signal of a laser on a hovering UAV using the post-processed data from the camera on the UAV. The camera can provide information about the translational and rotational motion of a UAV during hovering. The angles and displacements of the laser on the UAV could be corrected to find absolute transverse displacement between the moving surface and the UAV.

The algorithm was developed in two steps: 1) The first step used a video of a monocular camera to find the information about the UAV hovering during the flight; 2) The second step used the camera data and integrated it with laser signal to obtain absolute dynamic transverse displacement of the bridge under loading through a signal processing.

The first step of the algorithm required computer vision algorithms development. Multiples experiments were conducted in the laboratory to enable a displacement estimation using a single low-cost, costumer-based camera. The initial algorithm was generated with simplifying assumptions such as 1D movement of the camera and ignoring the rotational motions and scale factor changes during the tests. The research team then improved the algorithm to consider a 6 DOF arbitrary motion of a camera. The final algorithm was tested using the capture motion facilities in the Air Force Research Laboratory (AFRL) at UNM. The algorithm managed to collect motion with an RMS error of 5 mm. Subsequently, the camera data was used to correct the laser displacement to find the non-contact displacement within milimeters.

Hardware and software development are interrelated, therefore the research team developed a cost-efficient system assembly on a UAV that could fly untethered and collect data of a bridge simultaneously with the algorithm development. The research team selected a very low-cost laser and developed a datalogger for the sensors on the UAV using Arduino UNO. The developed data loggers cost less than a $100. The team conducted a field test using the designed system in the Balloon Fiesta Park in Albuquerque. The data of the field test was evaluated by the ERP and informed the research team to enhance the performance of both hardware and software.

Before conducting a real-scale bridge experiment, the team developed a new UAV system with enhaced capabilities. Subsequently, the team conducted the field test in a local bridge in coordination with the city of Albuquerque, Albuquerque police, and park services. The field test showed that the new UAV system can fly and collect data from a real bridge while maintaning a safe distance from the surface of interest. The RMS errors of the real-scale bridge experiments were larger than the small-scale balloon fiesta experiments, but all were less than

10 mm for different car crossing events. Field tests assisted to identify the areas of improvements for future research steps.

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Articles:

1. Nasimi, R., & Moreu, F. (2021). A methodology for measuring the total displacements of structures using a laser–camera system. Computer‐Aided Civil and Infrastructure Engineering, 36(4), 421-437.
2. Nasimi, R., & Moreu, F. (2021). Development and implementation of a laser–camera–UAV System to measure total dynamic transverse displacement. Journal of Engineering Mechanics, 147(8), 04021045.
3. Beamshor IR laser sight, NightStalker Invisible Laser Sight (beamshot.com), Accessed: October 2021.

Links:

1. Field test with updated UAV system. Link
2. Second outdoor experiment filmed using another UAV. Link
3. Third outdoor experiment. Link
4. Second outdoor experiment. Link

Project outcomes:

Journal papers:

1. Nasimi, R., & Moreu, F. (2021). A methodology for measuring the total displacements of structures using a laser–camera system. Computer‐Aided Civil and Infrastructure Engineering, 36(4), 421-437.
2. Nasimi, R., Moreu, F., Development, and Implementation of a Laser-Camera-UAV System to Measure Total Dynamic Transverse Displacement, Journal of Engineering Mechanics, (Accepted on Feb 2021)

In preparation:

1. Nasimi, R., Moreu, F., Fusing vision, laser, IMU to measure accurate transverse displacement of railroad bridges,

Conference papers:

Nasimi, R., Moreu, F., Nasimi, M., Wood, R., New Aerial System with Intelligent Measurement Integration (NASIMI II) for Bridge Monitoring, TRB 2022.

Restrepo, J., Nasimi, R., Moreu, F., Accessing Pedestrian Bridge Serviceability and Displacements Using Low-cost Sensors, TRB 2022.

Nasimi, R., Moreu, F., Stormont, J., Bagherieh, A., Machine learning methodology to classify surface properties to assess rock stability in the field, Transet 2021.

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Patent:

STC Technology Ref. No. 2020-122: "Monitoring reference-free contact-free total displacements and movements with a UAS equipped with lasers and computer-vision" developed by Fernando Moreu, and Roya Nasimi, disclosure date June 2nd 2020.

Presentations and Visibility of TRB Rail SAFETY IDEA 37:

Nasimi, R., Moreu, F., Cobo N., Diaz J. (2020). Unmanned Aerial Vehicles (UAVs) Equipped with Lasers, Cameras, and Algorithms Measuring Bridges Condition under Trains, EMI SHM&C, 2020. (link1, Link 2 , Link 3, Link 4 , MirageNews , EMI eNewsletter,TRB)

National Committee Meeting, Committee 10 Structures, Maintenance & Construction American Railway Engineering and Maintenance-of-Way Association (AREMA); Albuquerque, NM, January 28, 29 2020.

RS37 Measuring Behavior of Railroad Bridges under Revenue Traffic using Lasers and Unmanned Aerial Vehicles (UAVs) for Safer Operations: Implementation, Poster presentation at TRB Annual meeting 2020.

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