CIAMTIS
U.S. DOT Region 3 University Transportation Center

CIAMTIS Lehigh Research Experience for Undergraduates (REU) Program – Year 5

October 4, 2023

Prepared by:
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16. Abstract

Lehigh University, through its Institute for Cyber Physical Infrastructure and Energy (I-CPIE) and its Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, in conjunction with Lehigh University's STEM Summer Institutes (STEM-SI) program, conducted a 10-week CIAMTIS Lehigh Research Experience for Undergraduates (REU) program. The program ran from May 31, 2023 through August 4, 2023. One Lehigh University undergraduate student participated in the research-centric program, which exposed the students to a well-rounded professional development experience. Students were assigned to an active CIAMTIS research project at ATLSS or a research project that fit within the mission of CIAMTIS under the direction of the project Principal Investigator and faculty mentor to help the student navigate through the research project experience. Additionally, program activities included professional skills development workshops and trainings. The program culminated with a final report, presentation, and poster on the student's research findings.

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TABLE OF CONTENTS

APPENDIX A

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

Introduction

BACKGROUND

Lehigh University, through its Institute for Cyber Physical Infrastructure and Energy (I-CPIE) and its Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, in conjunction with Lehigh University's STEM Summer Institutes (STEM-SI) program, conducted a 10-week CIAMTIS Lehigh Research Experience for Undergraduates (REU) program. The program ran from May 31, 2023 through August 4, 2023. One Lehigh University undergraduate student participated in the research-centric program, which exposed the students to a well-rounded professional development experience. Students were assigned to an active CIAMTIS research project at ATLSS or a research project that fit within the mission of CIAMTIS under the direction of the project Principal Investigator and faculty mentor to help the student navigate through the research project experience. Additionally, program activities included professional skills development workshops and trainings. The program culminated with a final report, presentation, and poster on the student's research findings.

OBJECTIVES

The objective of the REU program is to provide the student with a well-rounded professional development experience, featuring research as part of an active CIAMTIS research project at Lehigh University or a research project that fits withn the mission of CIAMTIS, and also including professional skills development workshops and seminars. This program exposed the student to research areas important to CIAMTIS while providing the student with research and professional development training that will prepare the student for future professional endeavors.

DATA AND DATA STRUCTURES

The participating student developed a final report, presentation, and poster. A copy of the final report are included within Appendix A of this final report. A copy of the poster is shown in Figure 1.

CHAPTER 2

Methodology

INTRODUCTION

The REU program was conducted under the following criteria:

1. CIAMTIS Lehigh project principal investigators identified candidate students to participate in the Summer 2023 CIAMTIS Lehigh REU program. Additionally, an announcement regarding the STEM-SI program opportunities was distributed to Lehigh University undergraduate Civil and Environmental Engineering students for program consideration.

2. Recommendations and resumes were reviewed and interviews conducted, as necessary, in order to identify a candidate student for each active CIAMTIS Lehigh research project.

3. REU program dates were finalized as May 31, 2023 – August 4, 2023.

4. Students identified for the program were notified of their selection.

5. Principal Investigators and graduate student mentors were finalized for each project.

6. Program workshops and seminars were identified and scheduled.

7. Operation of the CIAMTIS Lehigh REU program, including workshops and project research, took place under the direction of the project Principal Investigator and project mentors.

8. Program participants completed final reports, posters, and formal presentations at the conclusion of the program.

CHAPTER 3

Findings

The project matrix, along with the particpating student, for the CIAMTIS Lehigh REU program is presented in Table 1. The results of this research were summarized in a final project report, which accompany this report in Appendix A, along with a final poster, which are shown in Figure 1. The student made a final program presentation to the project PIs prior to the conclusion of the program. Note that a second student withdrew from the CIAMTIS Lehigh REU program, after selection to the program, in late May, just prior to the start of the program.

Table 1. Project, student, university, and faculty mentor matrix for the 2023 CIAMTIS Lehigh REU program.

CIAMTIS Project Title	REU Student	University	Faculty Mentor
Utilizing Crowdsensing for Structural Health Monitoring of Bridges	Jenny Fiore	Lehigh University	Shamim Pakzad

Utilizing Crowdsensing to Monitor Structural Health of Bridges

Jenny Fiore, Liam Cronin, Giulia Marasco, Shamim Pakzad
Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA

Introduction

- Approximately 617,000 bridges in the USA was rated C by the ASCE's 2021 Infrastructure Report Card
- Traditional vibration-based monitoring schemes use fixed sensor networks that are expensive to install and maintain
- Goal of this project is to crowdsense vibration data from passing vehicles, scooters, and bikes to estimate dynamic properties of the bridge

Method

a. Data collection

b. Wavelet Cross-Spectrum Estimation

$W[A_P] = W_P, W[A_Q] = W_Q$

$C_{PQ} = W_P W_Q^*$

c. System Identification

Figure 2: Proposed steps for wavelet cross-spectrum and bridge modal identification framework.

Model Bridge - Results

Figure 3: a) Smartphones on carts crossing the bridge sampling the accelerations synchronously. b) Normalized first singular value at each frequency of aggregate wavelet cross-spectrum. c) Vertical mode shapes.

Case Study - Fahy Bridge

Figure 4: a) Fahy Bridge in Bethlehem, PA. b) Smartphone attached to base of scooter utilizing mounting tape. c) Full scooter and smartphone apparatus.

Orientation No.	ΔD (Meters)
1	1
2	7
3	14
4	26.5
5	37
6	48
7	58.5
8	69.3

Figure 5: Orientations of scooters with smartphones traversing the bridge sampling the accelerations of the Fahy Bridge.

Fahy Bridge - Results

Figure 6: Fixed sensor orientation on Fahy Bridge and first three modes.

Figure 7: Acceleration, GPS and position of scooter and sensor for a single run on the Fahy Bridge.

Conclusion

Model Bridge – Utilizing smartphones and a novel data synchronization app, the method was able to identify four vertical mode shapes and two torsional modes with a maximum frequency of 31.75 Hz. The experiment shows a proof of concept for a scalable to widespread bridge system identification.

Future Steps

Fahy Bridge – Analyze collected scooter data on Fahy bridge. Investigate the impact of vehicle dynamics on the proposed method and quantify potential dataset for each mode of transportation.

Acknowledgements

CIAMTIS – Center for Integrated Asset Management for Multimodal Transportation Infrastructure Systems,

PITA – Pennsylvania Infrastructure Technology Alliance.

Figure 1. Project poster for CIAMTIS project titled *Utilizing Crowdsensing for Structural Health Monitoring of Bridges.*

The REU Program

Beyond the research project, the student engaged in various professional development activities throughout the duration of the 10-week program, as outlined below:

- Orientation and Training sessions:
    - Program orientation integrated with Lehigh University's STEM-SI Research Experience for Undergraduates program and focused on :
        - Laboratory Safety, by Randy Shebby, Assistant Director, Department of Environmental Health and Safety, Lehigh University
        - Research Ethics, by Neal Simon, Professor, Biological Sciences, and Vassie Ware, Professor, Biological Sciences, Lehigh University
    - Technical report writing presentation
- Professional development sessions:
    - *Resume and Cover Letter 101* by Jashanae Day Brinker, Associate Director, Center for Career and Professional Development, Lehigh University
    - *Successful Interviewing* by Jenn Abraham, Associate Director, Center for Career and Professional Development, Lehigh University
- Weekly community development research seminars by Lehigh University faculty
- Weekly morning cafe group discussions
- Research activities:
    - Students worked on their respective CIAMTIS-focused projects
- Final Presentations:
    - Students made 15-minute final presentations with accompanying question and answer session
- Final Poster :
    - Students create poster and present to fellow students and alumni judges as part of STEM-SI Research Day expo at Lehigh University.

CHAPTER 4

Recommendations

Future REU Program

Participating REU students were provided with a well-rounded professional development experience that focused on conducting research as part of active CIAMTIS research projects at Lehigh University under the direction of project PIs and mentors. Three participating REU students also engaged in training and orientation sessions, professional development sessions, seminars, and research group activities focused on enhancing the students' overall professional skills and exposure.

Lehigh's CIAMTIS administration plans on continuing the REU program in the Summer of 2023.

Appendix A

CIAMTIS
U.S. DOT Region 3 University Transportation Center

Utilizing Crowdsensing to Monitor the Structural Health of Bridges

August 4, 2023

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16. Abstract

Across the US, aging infrastructure is a significant danger to public safety. Current measures of bridge monitoring include visual inspection and stationary vibration monitoring. Due to limitations in visual inspections and high costs and maintenance of sensor networks these systems are not sufficient. A proposed bridge identification system utilizing crowd sensing offers an innovative way to continuously monitor the dynamic properties of bridges and illicit immediate attention when changes are found. This work tests a cross spectrum-based framework that uses only two-time synchronous mobile sensors for modal frequency and full mode shape identification with a high spatial resolution. The proposed method can estimate both vertical and torsional modes with MAC values of 0.9675 using only two sensors. This experiment shows proof of concept for a scalable to widespread bridge identification system. Using this proposition and to continue studies, data was collected using electric scooters on the Fahy Memorial Bridge in Bethlehem, PA.

17. Key Words

System identification, crowdsensing, mobile sensing, smartphones, frequency domain decomposition, structural health

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TABLE OF CONTENTS

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Introduction

BACKGROUND

According to ASCE's 2021 Infrastructure Report Card, bridges in the USA had an overall rating of C. As influential components of our infrastructure with approximately 617,000 bridges across the country, they are crucial to public safety. Even with low ratings, bridges deemed structurally deficient can still generate a traffic rate of around 170 million trips [1]. The low rating shows the need to continue to monitor bridge health closely as they continue to age. Developing a bridge identification system utilizing crowdsensing offers a new innovative way to measure the dynamic properties of bridges and to monitor their health.

Currently, bridges are monitored through visual inspection or fixed sensors with a traditional vibration-based monitoring scheme. Visual inspections are most common, however, on average they are conducted every two years and inaccessible areas make it impossible to detect damage. Stationary vibration monitoring utilizes strain gauges or accelerometers to determine dynamic properties [2]. These sensors are useful in monitoring changes over time that are not clear to the human eye. However, their high cost, maintenance, and low spatial resolution result in low levels of operation [3].

OBJECTIVES

The main objective of this research is to use crowdsensing vibration data from passing vehicles, scooters, and bikes to estimate the dynamic properties of bridges. *Figure 2* shows a flow chart visually representing the proposed bridge identification system. shows crowdsensing in effect as vehicles cross a structure. Estimating the dynamic properties of a structure over time allows for continuous monitoring of health and changes can indicate immediate assessment.

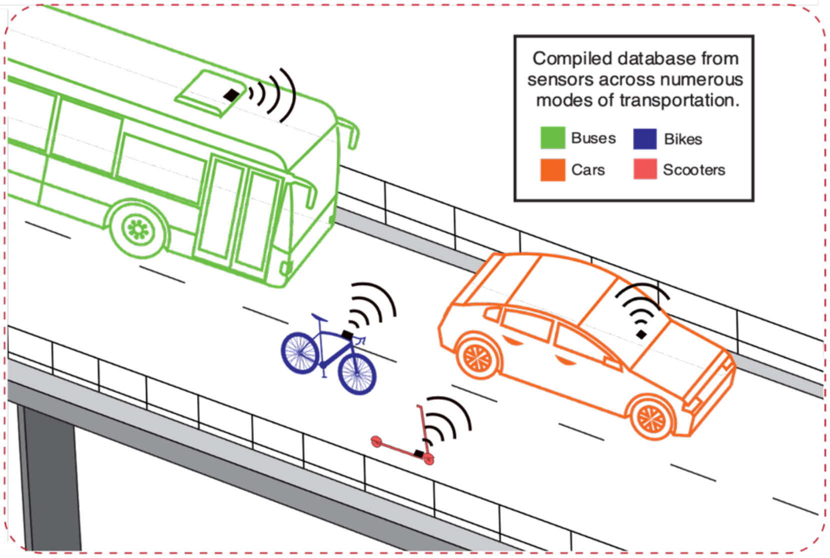


Figure 1: Representation of vast options for crowdsensing across different modes of transportation on bridges.

CHAPTER 2

Methodology

INTRODUCTION

The proposed bridge identification system is comprised of two steps, data acquisition and identification. Data is first sourced from smartphones and stored over time. The collected data includes date, time, GPS location, and acceleration measurements. GPS location is crucial in determining when acceleration measurements should begin and end and matching it to a specific bridge ID.

The stored data is processed to determine the dynamic characteristics of the bridge overtime. Monitoring properties of the bridge also tracks the health of the structure as changes indicate fatigue or failure and prompt immediate inspection. *Figure 2* shows a flow chart visually representing the proposed bridge identification system.

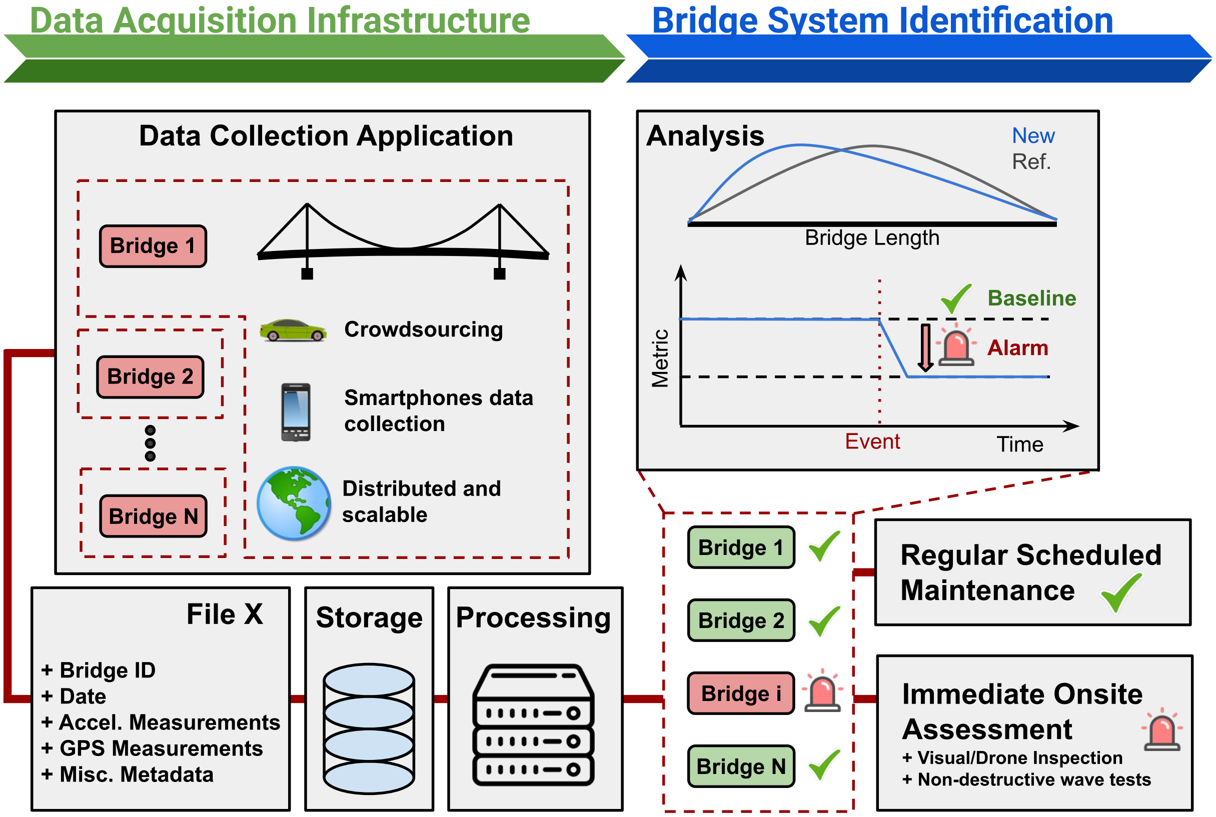


Figure 2: Flow diagram demonstrating the proposed bridge identification system.

Method

When crowdsourcing data, sensors will be random and scattered. Many trips in the data set will most likely involve one vehicle at a time on a bridge; however, there will be instances when multiple vehicles will be crossing the bridge at the same time. With multiple sensors collecting simultaneously the subset can be leveraged for complete bridge modal identification by estimating the response cross-spectrum with a high spatial resolution. *Figure 3* shows the proposed plan.

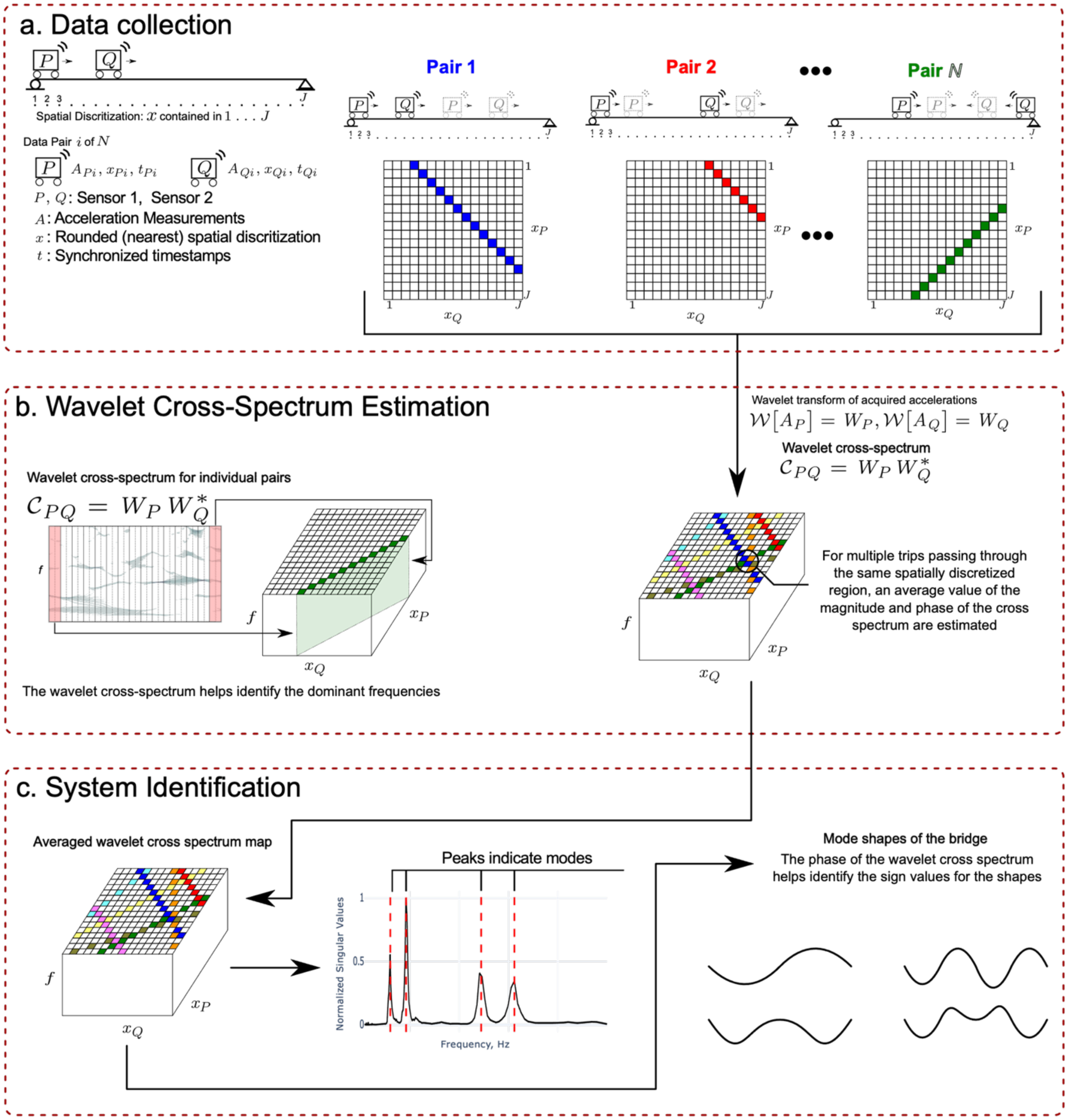
Part a of *Figure 3* shows a spatio-temporal map in a two-dimensional field defined by the sensor positions. Coordinates x_p and x_Q are used to define the N vehicle pair data. With more sets of N, the matrix abundance increases. Analyzing multiple sensors enhances the resolution of dynamic characterization.

Part b of *Figure 3* shows wavelet cross-spectrum estimation. This method takes the acceleration measurements from the sensor pair and performs a wavelet transform on each time series. The wavelet cross-spectrum for the pair is calculated following Equation 2. This calculation is repeated for all pairs in the dataset and then averaged with respect to the positions of the sensors.

$$(1) \quad \mathcal{W}[A_P] \ = W_p$$

$$(2) \ C_{PQ=} W_P W_Q^*$$

Part c of *Figure 3* shows how the averaged wavelet cross-spectrum map is used for system identification. The cross-spectrum can be decomposed with the singular value decomposition at each frequency. Frequencies with large singular values indicate natural frequencies and the corresponding singular vectors are the mode shapes.



For multiple trips passing through the same spatially discretized region, an average value of the magnitude and phase of the cross spectrum are estimated

The wavelet cross-spectrum helps identify the dominant frequencies

The phase of the wavelet cross spectrum helps identify the sign values for the shapes

Figure 3: Proposed steps for wavelet cross-spectrum and bridge modal identification framework.

CHAPTER 3

Model Bridge

INTRODUCTION

The method was tested on a model bridge in a lab-controlled experiment in the ATLSS Center at Lehigh University. The goal of the experiment was to recreate a heavily trafficked bridge with a set of mobile sensors attached to ridged carts repeatedly pulled back and forth along the bridge. *Figure 4*a shows the model bridge, a thin steel plate supported on pins at 30 cm from both ends and a hydraulic jack below the bridge that applied a horizontal post-tensioning force. Pullies and an AppliedMotion STAC6-Si motor were used to move the ridged carts that carried the mobile smartphones across the bridge. The carts are shown in *Figure 4*b. The motor was controlled by the Si Programmer software and moved at a speed of 0.13 m/s. Each phone ran a novel app sampling acceleration synchronously collecting GPS location and acceleration at a sampling frequency of approximately 400Hz.

*Figure 4*c shows a diagram of the paths the carts took and how during filtering, routes were linearized along a path. *Table 1* shows the mobile sensor and cart configuration used for each case and their start and end locations. Each vehicle crossed the bridge in 40 trips total for each orientation. Using two tracks, one on either side, is crucial for finding the torsional modes in addition to the vertical modes. *Figure 4*c also features the evenly spaced fixed sensors placed along the edge of the model. The network was used as a baseline to measure the accuracy of the mobile sensor data.

*Figure 4*d, is a graph comparing the position of each sensor with one line signifying a singular sensor path and trip. Carts from both paths are shown, differentiated by color.

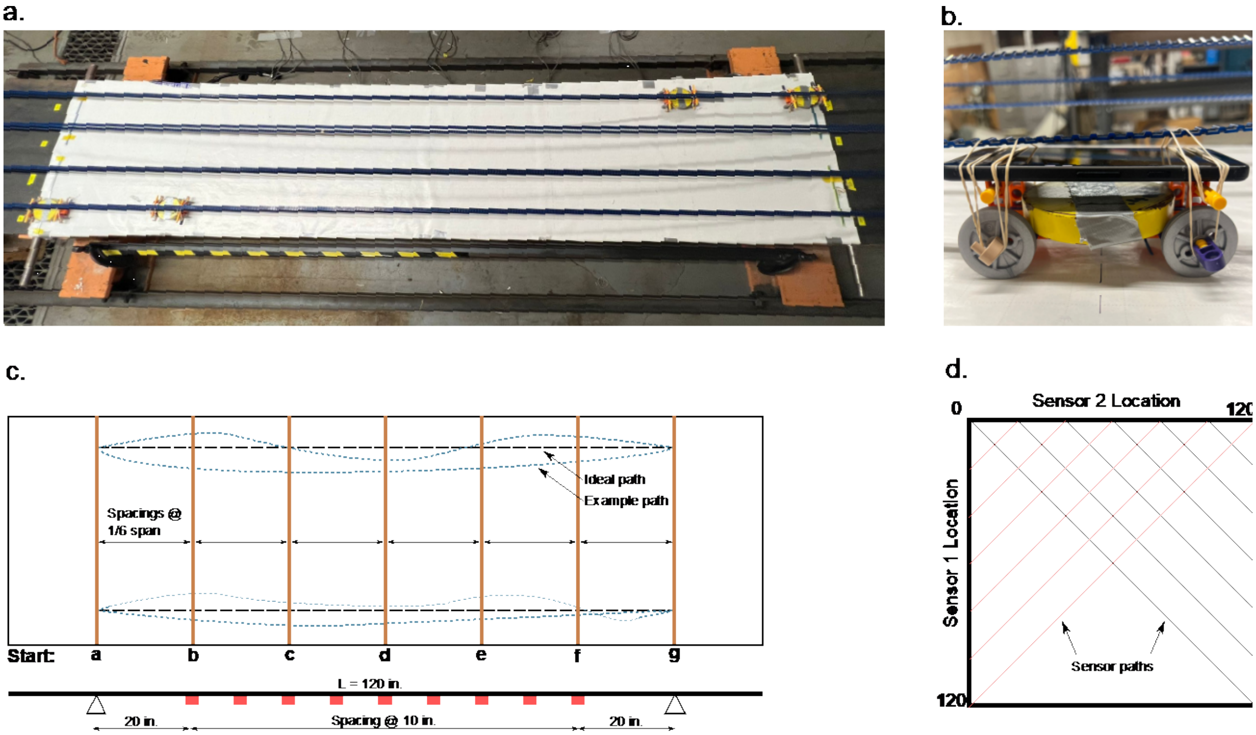


Figure 4: Thin plate excited by random impulses across the span mimics the dynamics of a heavily trafficked bridge. a) Smartphones on carts traverse the bridge sampling the accelerations of the bridge synchronously. b) Image of rigid cart carrying a smartphone. c) Diagram of model bridge showing the idealized linear path the carts were pulled along the structure. More than one pulley was used to find the torsional modes as well as the vertical. Also contains the dimensions and starting positions of the carts for each trial. d) Pictorially demonstrates the coverage of the position-position map thought out the testing.

Table 1: Sensor configurations.

		Track 1		Track 2	
Case	Position	Cart 1	Cart 2	Cart 3	Cart 4
I	Start	0 m	0.5 m	3.0 m	2.5 m
	End	2.5 m	3.0 m	0.5 m	0 m
II	Start	0 m	1.0 m	3.0 m	2.0 m
	End	2.0 m	3.0 m	1.0 m	0 m
III	Start	0 m	1.50 m	3.0 m	1.5 m
	End	1.5 m	3.0 m	1.5 m	0 m
IV	Start	0 m	2.0 m	3.0 m	1.0 m
	End	1.0 m	3.0 m	2.0 m	0 m
V	Start	0 m	2.5 m	3.0 m	0.5 m
	End	0.5 m	3.0 m	2.5 m	0 m

RESULTS

After data analysis, the first results generated a frequency spectrum comparing the reference fixed sensor to the mobile sensor modes. *Figure 5* shows said frequency spectrum. The red dashed lines signify the reference frequencies found through the fixed sensors. The black, blue, and gray plots signify the results from across both tracks of mobile sensors. The correlation between peaks and reference lines shows the mobile sensors accurately determined the model's modes. The first 4 peaks correlate to 4 vertical modes and the following 2 are torsional modes.

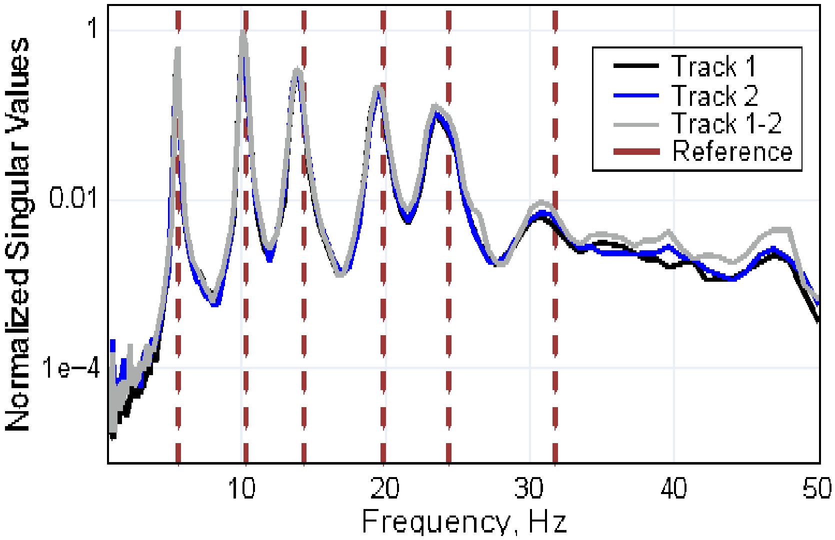


Figure 5 : Normalized first singular value at each frequency of aggregate wavelet-cross-spectrum.

The vertical mode shapes were also generated and are shown in *Figure 6*. The black x plot is the baseline generated from the fixed sensor network, while the red circle plot is from the mobile sensor data. Each mode is labeled with the frequency in Hz and the MAC value. The MAC value measures accuracy of the mobile sensor data compared to the fixed sensor data and the results suggest high accuracy.

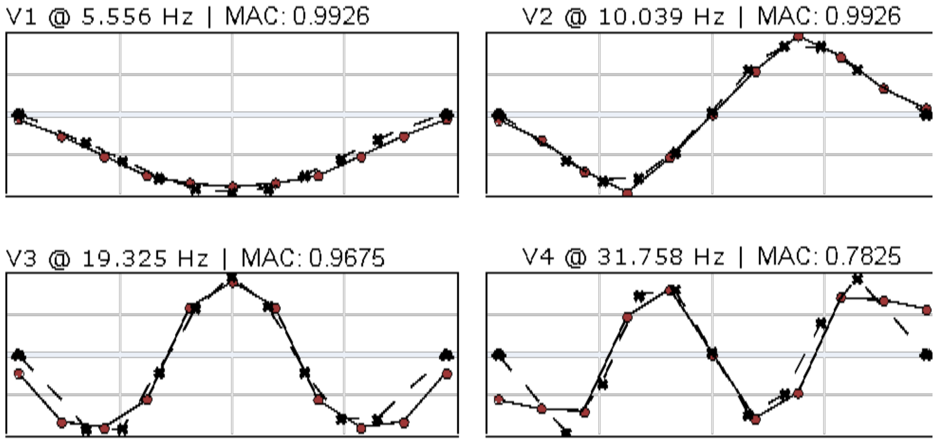


Figure 6: Vertical mode shapes.

CONCLUSIONS

Utilizing smartphones and a novel data synchronization app, the method accurately identified four vertical and two torsional modes and their shapes with a maximum frequency of 31.75 Hz. High accuracy factors between mobile sensor and fixed sensor data shows a proof of concept for a scalable to widespread bridge system identification.

CHAPTER 4

Case Study – Fahy Memorial Bridge

INTRODUCTION

Due to the success of the model bridge and the scaled bridge identification system, the next step is to test the method's results on a larger scale. When choosing a case study bridge for these tests high traffic rates, a protected sidewalk, and proximity to Lehigh University were all requirements. The Fahy Memorial Bridge in Bethlehem, PA was the best option to continue the study.

The Fahy Bridge spans over the Lehigh River and was constructed in 1972. The bridge has a steel and rigid frame type and features four car travel lanes as well as a pedestrian sidewalk. The bridge has a total of 10 spans; however, this study's focus would be on the center span with an approximate length of 175 ft. The center span is shown in *Figure 7*. The bridge has an annual daily traffic of 10,679, and high daily traffic is crucial as the bridge must have enough traffic to move during testing [2].

Figure 7: Fahy Bridge center span over the Lehigh River.

INITIAL TESTING

Initial testing on the bridge was conducted to create a baseline to compare mobile sensor scooter data to. The test was conducted using two smartphones stationary placed on the sidewalk in three different orientations, both running the data synchronization app. Each test was conducted over 8 minutes. *Figure 8* shows the placement of a smartphone on the sidewalk for testing and *Figure 9* shows the orientations as well as the layout of the phones over the center span.

Figure 8 : Placement of smartphone on sidewalk for initial testing of Fahy Bridge.

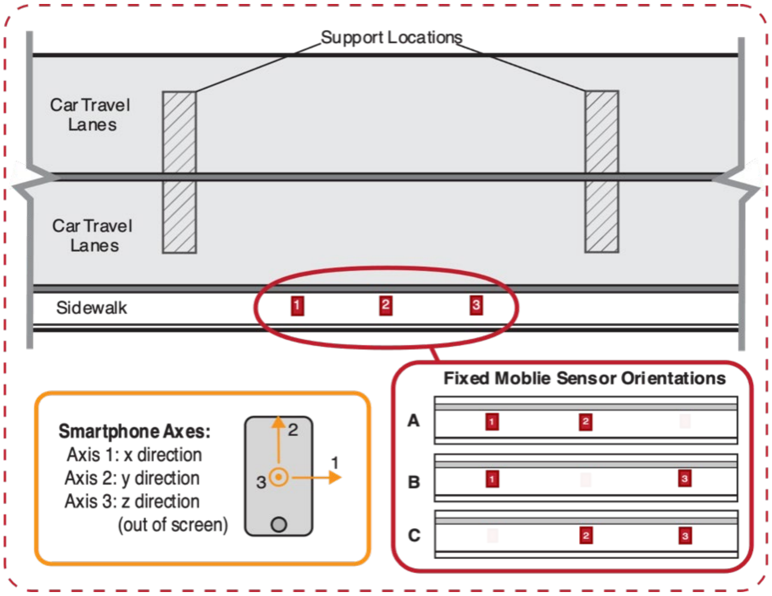


Figure 9: Fixed sensor orientation on Fahy Bridge.

The data collected was analyzed and a frequency spectrum was generated. The spectrum shows three modes ranging from 2.578 Hz to 9.531 Hz. The spectrum is presented in *Figure 10*. Note that axis 3 is in the z direction and is coming out of the screen of the phone.

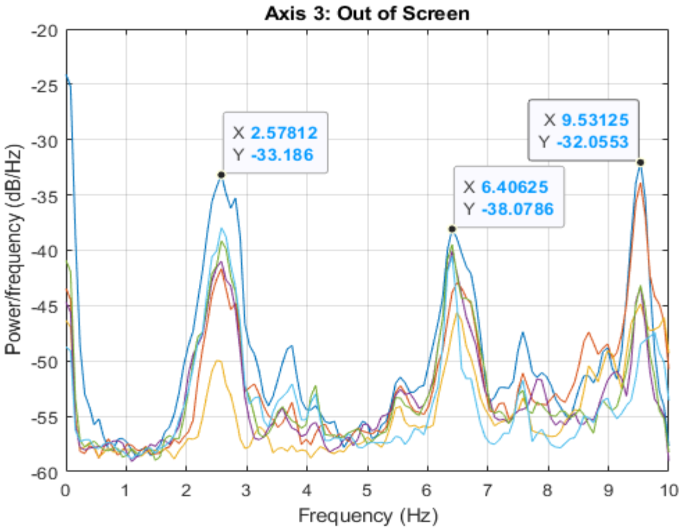


Figure 10: Frequency spectrum of fixed sensors. Results show first three modes.

MOBILE SENSOR TESTING – ELECTRIC SCOOTERS

The next step in data collection was to use mobile sensors and electric scooters. Similar to the rigid carts used on the model bridge, this experiment utilized electric scooters. Mobile phones were mounted to the base of Unagi Electric Scooters and ran the data synchronization app. *Figure 11* shows the scooter apparatus used. A similar procedure to the model bridge was followed with this experiment only using one path and running approximately 500 trips across 8 orientations. *Figure 12* shows a diagram explaining a single trip for both scooters across the bridge. The start and end location of data collection was ensured to be before and after the supports of the center span. Each orientation altered the traveling distance between the two scooters and the speed of the scooters remained 8-10 km/hr for every test.

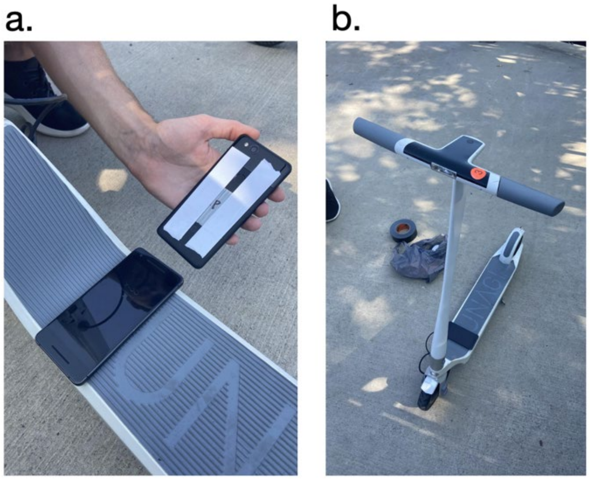
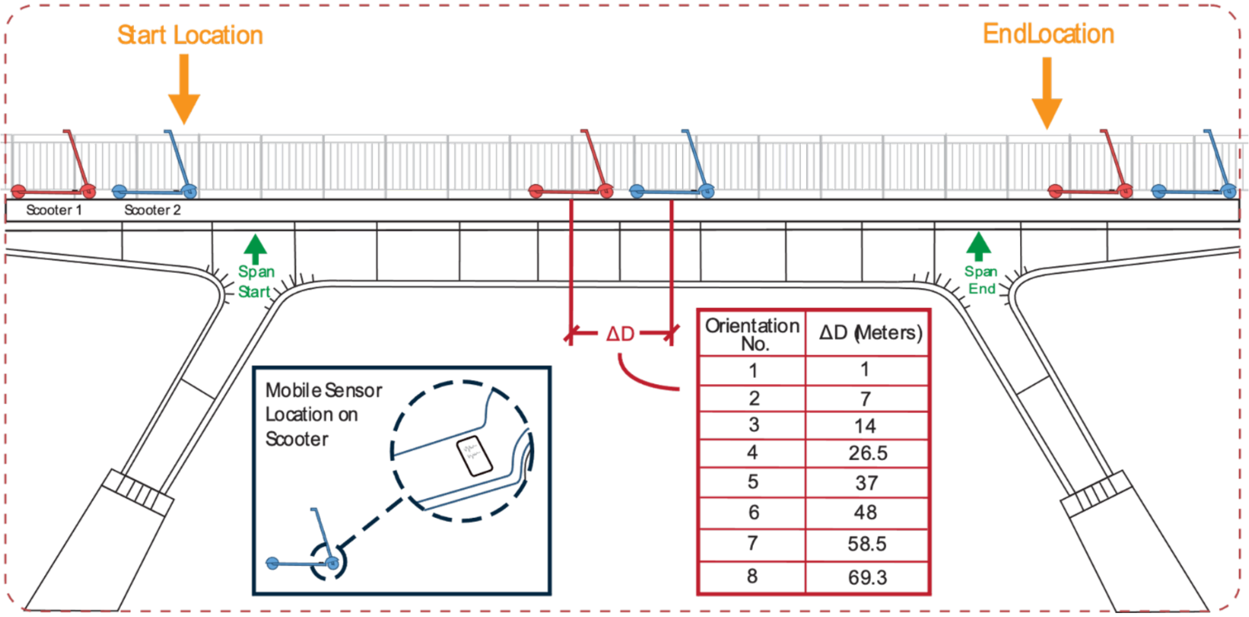


Figure 11 : a) Smartphone attached to base of scooter utilizing mounting tape. b) Full scooter and smartphone apparatus.



Orientation No.	ΔD (Meters)
1	1
2	7
3	14
4	26.5
5	37
6	48
7	58.5
8	69.3

Figure 12 : Orientations of scooters with smartphones traversing the bridge sampling the accelerations of the Fahy Bridge.

RESULTS

After filtering, splicing, and saving data into individual trips, data is still waiting to be analyzed due to limited time. An example output after splicing is shown in *Figure 13*. Each trip was spliced, interpolated, resampled, linearized along an ideal path, and subtracted the mean. The data was spliced using the GPS coordinates signaling the start and end of the center span.

The top three graphs in *Figure 13* show the acceleration results across all three axes. Axis 3 is used for data analysis as it is in the z direction. The GPS position of the scooter during the test is also plotted over a map. The black star plot signifies the start and end of the center span and is the linear path used in filtering. The green rectangle surrounding the plot is a manually inputted area used for splicing the data to ensure information collected outside of the center span does not impact results. Lastly, the final graph is the position of the scooter over time. Since the graph is linear it shows the attempts to remain at a constant speed were successful.

Similar to the position map for the model bridge, *Figure 14* plots the coverage graph of each scooter's relative position to each other across all trips. Note that the entire graph is filled suggesting the entirety of the bridge span was mapped.

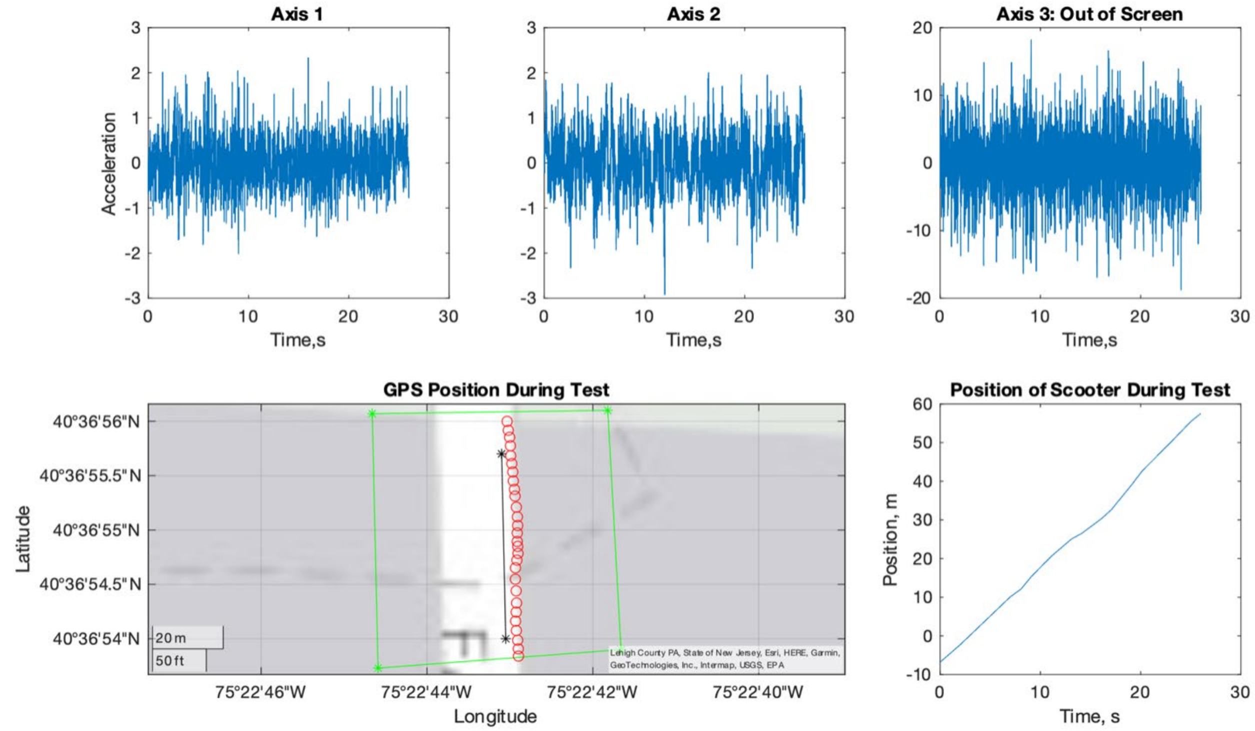
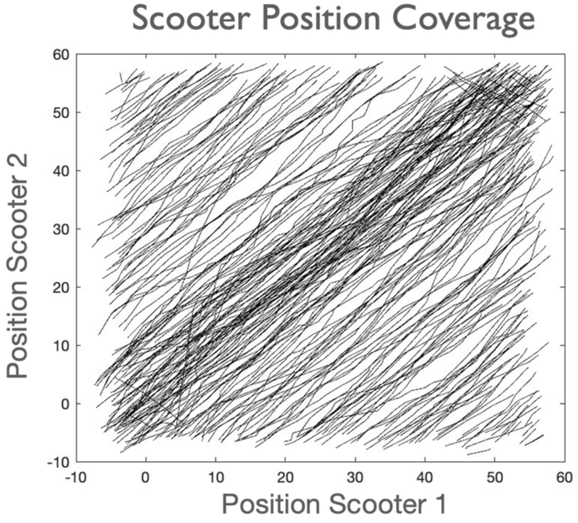


Figure 13 : Acceleration, GPS and position of scooter and sensor for a single trip on the Fahy Bridge.

Figure 14 : Scooter 1 and 2 relative position coverage across all trips.



CHAPTER 5

Future Steps

Scooter Data

Due to the limited time over this research window, the first step for the future is to analyze the scooter data on the Fahy Bridge and compare the results to the fixed sensor initial data collected. A frequency spectrum from the data would be used to compare the two results.

Vehicle Dynamics

Another potential future step is to investigate the impact of vehicle dynamics on the proposed method. Understanding the inner dynamics of the vehicle used is crucial for the analysis portion of this method to ensure vibrations specific to the vehicle are signaled out. This change is critical for determining accurate results.

Learning about vehicle dynamics across all modes of transportation is required. This step is important for scooters, buses, cars, bikes etc.

Quantifying Datasets

This step includes determining how often each mode of transportation crosses such structures and determining if said numbers are enough to run the proposed bridge identification system properly.

References

[1] ASCE. 2021 Infrastructure Report Card, 2021.

[2] U.S. Federal Highway Administration. National bridge inventory.

[3] Daniel N Farhey. Bridge instrumentation and monitoring for structural diagnostics. Structural Health Monitoring, 4(4):301–318, 2005.