Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Development, Training, Education, and Implementation of Low-Cost Sensing Technologies for Bridge Structural Health Monitoring (SHM)

Project No. 17STUNM02

Lead University: University of New Mexico

Preserving Existing Transportation Systems

Final Report

November 2018

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Acknowledgments

The authors want to thank the following collaborators who supported this research: Chinese Earthquake Administration (CEA), Institute of Engineering Mechanics (IEM) (China), Microsoft, Los Alamos National Laboratory (LANL), Canadian National Railway (CN), Los Alamos County (LAC), Association of American Railroads (AAR), Albuquerque Rocket Society (ARS), Albuquerque Tramway, Union Pacific (UP), BNSF railway, and Polytec.

TECHNICAL DOCUMENTATION PAGE

1. Project No.	2. Government Accession No.	3. Recipient's Catalog No.
17STUNM02		

4. Title and Subtitle	5. Report Date
Development, Training, Education, and Implementation of Low-Cost Sensing Technologies for Bridge Structural Health Monitoring (SHM)	Nov. 2018
	6. Performing Organization Code
7. Author(s) PI: Fernando Moreu https://orcid.org/0000-0002-7105-7843 Co-PI: Chris Lippitt https:/orcid.org/0000-0001-7979-7857 GRA: Dilendra Maharjan https:/orcid.org/0000-0001-6365-072X GRA: Marlon Aguero https://orcid.org/0000-0001-7739-1378 GRA: Roya Nasimi https://orcid.org/0000-0001-9057-796X	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Transportation Consortium of South-Central States (Tran-SET) University Transportation Center for Region 6 3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. 69A3551747106
12. Sponsoring Agency Name and Address United States of America Department of Transportation Research and Innovative Technology Administration	**13. Type of Report and Period Covered** Final Research Report May 2017 – May 2018
	14. Sponsoring Agency Code

15. Supplementary Notes
Report uploaded and accessible at: [Tran-SET's website (http://transet.lsu.edu/)](http://transet.lsu.edu/)

16. Abstract
Transportation infrastructure needs continuous monitoring. However, traditional inspections cost money and are conducted visually. New technologies for bridge monitoring are expensive and complex. This project involved developing cost-effective sensor technologies that can be applied towards the maintenance of railroad bridges by recording reference-free transverse displacement. More specifically, this project developed new applications of new technologies (Arduino, wireless smart sensors, drones, Hololens) and promoted workforce development with an emphasis on outreach of high-school students. This project was carried out in three main phases: (1) development and validation of technologies, (2) education and outreach to students, and (3) outreach to industry consisting in one professional workshop. The findings from the first phase showed that the data gathered by these new low-cost sensing systems were comparable to the data collected using traditional sensors. Researchers collected the findings of the second phase of the project through surveys conducted from Middle school, High school and college students during and after outreach activities. these surveys showed that many of the participant students got more interested in the use of new technologies after getting familiar with them. Finally, researchers collected the findings of the third phase of the project through a workshop collecting the interest and challenges of the owners of railroad infrastructure. The top interest of railroad owners is to explore the use of new technologies to increase safety in the field. The conclusions of this research include prioritization on developing low-cost technologies that can measure simple parameters in the field of interest to existing inspectors.

17. Key Words	18. Distribution Statement
Low-cost sensors; Bridge management; Augmented reality; Structural health monitoring; Education and training.	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	66	

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AAR	Association of American Railroads
AI	Artificial Intelligence
AR	Augmented Reality
ARS	Albuquerque Rocket Society
ASCE	American Society of Civil Engineers
BNSF	Burlington Northern Santa Fe Railway
CEA	Chinese Earthquake Administration
CMU	Carnegie Mellon University
CN	Canadian National Railway
EMI	Engineering Mechanics Institute
FRA	Federal Railway Administration
IEM	Institute of Engineering Mechanics
IMAC	International Modal Analysis Conference
ITS	Intelligent Transportation Systems
IWSHM	International Workshop of Structural Health Monitoring
LAC	Los Alamos County
LANL	Los Alamos National Laboratory
LEWIS	Low-cost Efficient Wireless Intelligent Sensor
LEWIS2	Low-cost Efficient Wireless Intelligent Sensor (Version 2)
LDV	Laser Doppler Vibrometer
LVDT	Linear Variable Differential Transducer
MIT	Massachusetts Institute of Technology
MRR	Maintenance, Repair and Replacement
NMDOT	New Mexico Department of Transportation
SHM	Structural Health Monitoring
SMILab	Smart Management of Infrastructure Laboratory
TTCI	Transportation Technology Center, Inc.
UAS	Unmanned Aerial System
UNM	University of New Mexico

UP	Union Pacific
WS	Wireless Sensor
WSS	Wireless Smart Sensors

EXECUTIVE SUMMARY

This project consisted in three phases directed to implementation of low-cost sensing technologies to monitor infrastructure: development, training and education, and outreach to industry. The first phase carried out the development of new low-cost, efficient sensors for bridge monitoring applications that can be used in the field to determine the condition of the bridge. The main result was the new sensor both hardware and software, and its validation. Th new low-cost sensors developed in this project were able to collect displacements with the same accuracy of traditional sensors. However, the low-cost sensors are more affordable by infrastructure owners, which makes them more attractive to be implemented by industry. These sensors were capable of recording reference-free displacement of bridges which will be eventually used in monitoring bridge infrastructure under live loads. This low-cost technology allows owners to make decisions about infrastructure. This project also explored the use of Augmented Reality (AR) and drones to collect information from the field of value to owners and compared them with their current monitoring techniques. The results were comparable in accuracy but less expensive and complex to owners, and the stakeholders recommended their implementation. Additionally, the use of the low-cost sensors for remote sensing was explored engaging students in the monitoring of aerospace vibrations with the same low-cost sensor technology, and the recommendation was to explore using trajectory tracking using low-cost sensors for transportation monitoring in the future for very low cost. The second phase of the project involved the training, education, and implementation of outreach activities for students (including precollege, undergraduate, and graduate students) using these new technologies for inspecting transportation infrastructure. The research in new technologies (Arduino, 3D printing, wireless smart sensors, drones, AR) promoted workforce development from the early stages of education in transportation engineering. The findings identified that students at all levels became more interested in technology to maintain infrastructure after becoming involved in the design and fabrication of the low-cost sensors. Finally, the third phase of the project consisted in one workshop with infrastructure owners and professionals in Fort Worth, Texas, during the American Society of Civil Engineers (ASCE) 2018 Structural Congress. The main objective of the workshop was to inquire about challenges infrastructure owners are facing in the adoption of new technologies in their day to day monitoring and inspection activities. Three railroad owners and two representatives of railroad administrations attended the workshop as keynote panelists, focusing the discussion in the implementation of technologies for railroad infrastructure. The audience included in addition highway engineers, academicians, and students. The result of the workshop concluded that infrastructure owners are interested to implement new technologies for inspections that increase the safety in the field. The recommendation from infrastructure owners is to develop monitoring technologies that can augment the safety of inspectors or inspection activities. The content of the project is brought in Figure 1.

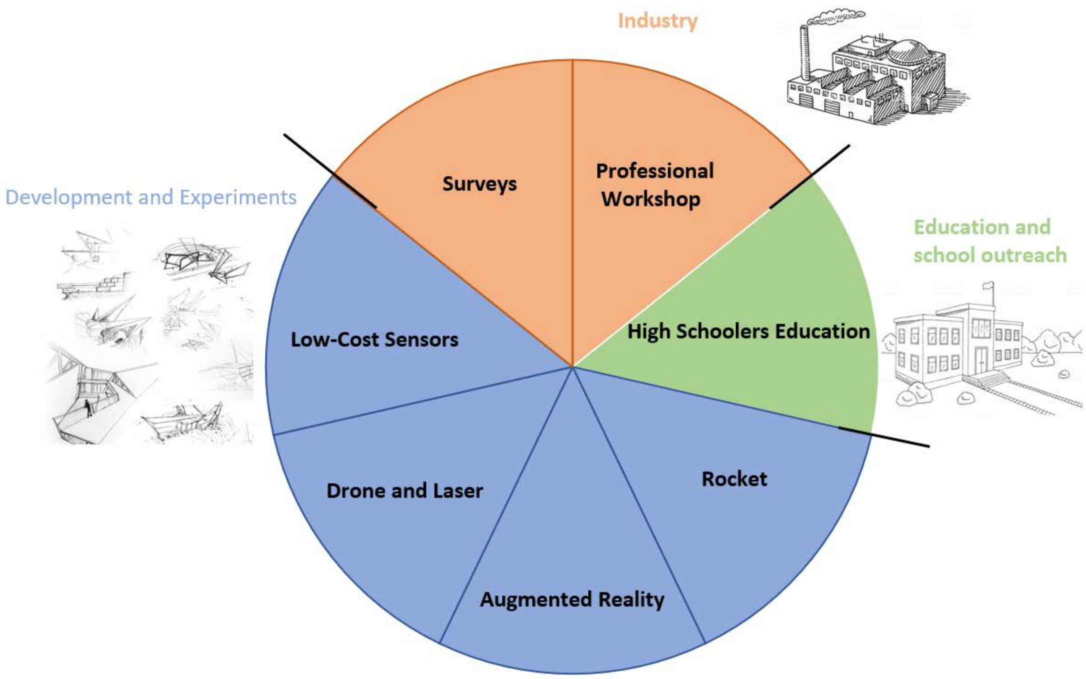


Figure 1. Summary of jobs during project.

IMPLEMENTATION STATEMENT

The research team developed a new inspector-centered system (sensing reference-free displacement under train-crossing events) that cost-effectively collects information of value to railroad bridge inspectors. Also, this project explored novel sensing technologies including AR (2016) and Unmanned Aerial Systems (UAS) to inform stakeholders about their infrastructure, prioritizing collecting information of value to them, such as displacements.

For the implementation of this technology and adoption into practice, the close relationship with the Canadian National Railway (CN) will ensure this project integrates new technology with industry needs in the area of railroad bridge inspection. The multidisciplinary team of researchers will specifically describe how current technologies can empower infrastructure inspectors by discussing challenges and opportunities with the railroad and infrastructure owners. Researchers will show owners the sensors and technologies, and will discuss the needs of doing changes so they can be used in the field for collecting data of value to them. Similarly, the research team will show AR to owners and will collect their feedback on the challenges and opportunities to adopt AR in the field by the railroad bridge inspector community. Finally, the research team will discuss with railroad owners the challenges related to using drones in the field to collect displacements and will list the correction measures to implement drones and lasers to collect data from the field.

The research team will also explore the implementation of new technologies with New Mexico's infrastructure owners, to collect their input and learn challenges and opportunities to adopt these technologies from the public office inspector's perspective. The implementation phase of the project will include showing the low-cost sensing technology and the augmented reality applications to New Mexico's infrastructure owners and collecting their recommendations for implementation for inspections. The PI, Co-PI, and the students will collect feedback from the engineers in terms of the value of the technology can bring to their bridge maintenance operations. In the project duration (first twelve months) the research team conducted a workshop with the railroad owners' community. The questions are added in Appendix 1, 2 and 3 at the end of the report. In the implementation phase, the students and the PI will ask the same questions to New Mexico infrastructure's owners.

The main goal of this research was to develop low-cost sensors capable to collect displacements, in conjunction with the exploration of other new technologies such as drones and augmented reality. The goal of the implementation is to identify and list what are the challenges for transitioning this new sensing technology to the day-to-day operations and decisions of infrastructure owners.

1. INTRODUCTION

North American infrastructure systems, including transportation networks, are increasingly decaying in terms of safety and capacity, and network demands are changing. Consequently, the cost of bridge repair and adaption for higher loads are increasing, surpassing available funds. Inspectors try to collect intelligent information in the field that informs their assessment, as their reports serve as the main source of information used by managers to make critical infrastructure decisions and prioritize which infrastructure to repair. However, infrastructure owners and managers need more quantifiable information to improve their objectivity and the safety of inspectors. Field inspections are expensive, sometimes working conditions are not safe, and lead to subjective and inaccurate information. Using this as a business opportunity, sensing companies recommend replacing inspectors with “smart sensing technologies.” However, current sensing approaches collect a massive amount of data, videos and pictures that owners cannot readily employ to make decisions at the site. Furthermore, smart sensing data needs to be analyzed in the laboratory setting to be of use.

Current sensing approaches are not collecting parameters that inform the decisions that need to be made in the field on real-time (during inspections). Also, the costs associated with instrumenting the infrastructure with sensors are not affordable by transportation infrastructure managers. Secondly, structural models are developed by academics and research companies to better model responses, but since developing computational models are time consuming and very complex for the practical uses, those computational advances are not useful to current inspection needs. To overcome this problem, this research project designed a new approach between an interdisciplinary academic research team (Civil, construction and environmental engineering and Geography), Los Alamos National Laboratory (LANL), the CN, Burlington Northern and Santa Fe Railway Company (BNSF), owners of railway infrastructure, and the New Mexico Department of Transportation (NMDOT). This partnership enabled technology that equip humans (inspectors) with machine capabilities to carry out their inspections more effectively using low-cost sensing approaches that can be used in the field. The results of this partnership empowers bridge inspectors to collect data cost-effectively which can improve the management of railroad bridge networks. One bridge from CN and the facilities from the Association of American Railroads (AAR) in Pueblo, Colorado will serve as validation site equipment in the field test. The strong collaboration between national laboratories, Universities in Region 6 (New Mexico, Texas, Louisiana, Arkansas, and Oklahoma), and transportation stakeholders from both highway and railway organizations will allow for practical development of new low-cost sensing approaches to monitoring infrastructure performance. The participation of experts in infrastructure maintenance and sensing in the workshop (sponsored by this project) allowed students to gain exposure to industry careers related to infrastructure management and maintenance using new technologies.

2. OBJECTIVE

The objective of the project was to develop new low-cost sensors and explore other new technologies to inspect railroad bridges; to conduct training and education for future workforce and students at different levels of training; and to held one workshop to get feedback from industry about the technology proposed.

More specifically, the various objectives of the project to achieve this goal were to:

1. Develop a new, original, low-cost sensing technology (Arduino sensors) for bridge structural health monitoring (SHM) by conducting laboratory and field testing for validation;
2. Validate the accuracy of the new sensor in comparison with other sensors traditionally approved and remote sensing requirements for field implementations; the validation was carried be both in the time domain and frequency domain;
3. Explore other possible technologies such as Augmented Reality (AR), Laser Doppler Vibrometer (LDV), and Unmanned Aerial System (UAS) that can be used in bridge SHM;
4. Develop and implement training and education/outreach programs with students, professionals, and infrastructure owners; and
5. Conduct a workshop to determine the value of the technology for bridge construction and maintenance operations. The workshop was conducted with universities, national laboratories, and infrastructure stakeholders, prioritizing the progress needed to achieve the development and application of new sensing technologies in current inspection and maintenance practices.

3. SCOPE

The scope of this study involved:

(i) Identifying top sensing technologies needs by owners of railroad infrastructure and developed a pilot program to develop it.

(ii) Testing the identified technology both in educational and professional setting.

(iii) Involving both students and industry in (ii).

Following are the limitations of the proposed technologies studied in this project:

a) Low-cost sensors: only tested and validated in laboratory setting. The field validation is still not conducted and will be conducted in a real railroad bridge once there is access permitted to the site.
b) UAS with LDV: needs to be tethered to the ground. This limits the ability of UAS to fly up to the height of the bridge and measure displacements.
c) AR (augmented reality): the inspector cannot use the AR device in very bright sunlight due to dim displays.

4. METHODOLOGY

4.1. Development of Low-cost Sensors and Methods for Validation

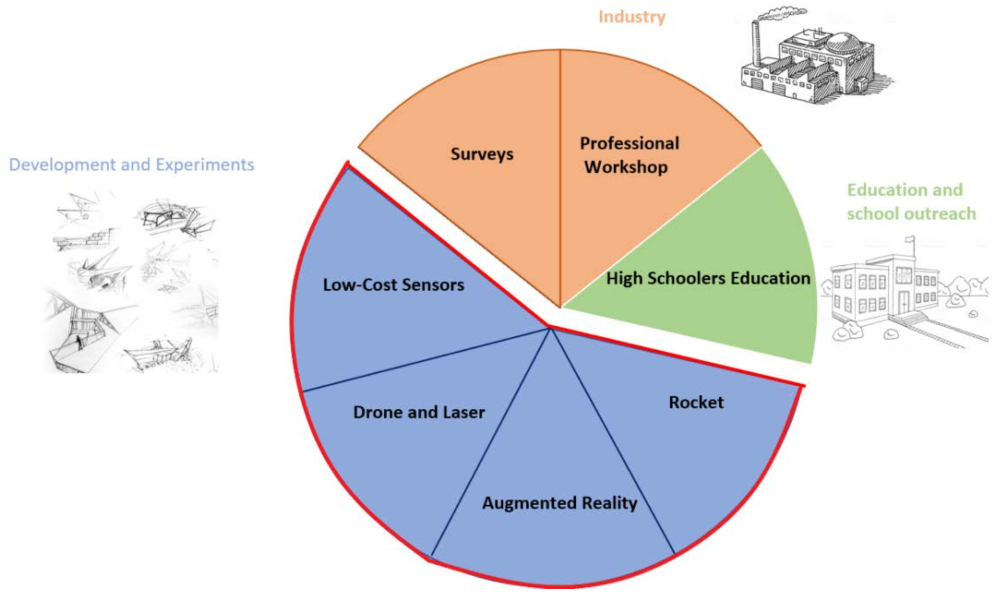


Figure 2. Phase 1 of the project.

The scientific method followed for the development of low-cost sensors consisted of the following steps:

1. Hypothesis: low-cost sensors can collect information of value for decision-makers with significant less cost but similar accuracy, which is not available today.
2. State-of-the-Art: exploring available literature and identify missing elements to reach the hypothesis.
3. Design, prototype, and fabrication of the sensor under economic constrains (low-cost).
4. Validation experiment: comparison of accuracy of the low-cost sensor with traditional sensors for parameters of interest to owner.

The results and conclusions of these steps are discussed under Section 5 of this report.

4.1.1. Hypothesis

According to railroad managers, displacement of railroad bridges under service loads is an important parameter in the condition assessment and performance evaluation. However, measuring bridge responses in the field is often costly and labor-intensive. Many of the Wireless Smart Sensors (WSS) applications available are either developed in-house, and are not accessible by the public, or are commercially available only at high costs. Moreover, the software support for those sensors are limited and the code is often closed-sourced. From a practical standpoint, railroads are interested in easy-to-manage WSS with small complexity that can inform the structural performance of their bridge network in real-time while observing the movements of the bridge under traffic operations. A new open-source hardware and software approach could address the challenges and facilitate a platform for open-source sensing that will enable accurate monitoring of critical infrastructure cost-effectively and wirelessly in the field.

4.1.2. State-of-the-Art

There are several monitoring approaches focusing on measuring bridge responses under traffic. For instance, Uppal et al. discussed the relationship between train speeds crossing a timber bridge and the vertical deflection of the span by measuring the responses with linear variable differential transducers (LVDTs) *(1)*. Likewise, Moreu et al. investigated the service condition of timber bridges by collecting transverse displacements with LVDTs *(2)*. However, while measuring bridge responses with traditional sensors such as LVDTs provide quantitative data about the condition of the bridges, it is relatively difficult to record such responses because a fixed reference frame to attach the sensor is rarely available *(3)*.

Traditional monitoring approaches often employ wires to reliably collect sensor measurement and store data *(4,5)*. However, installation of wired sensors can be labor-intensive. For example, Celebi has estimated a cost of about $5,000 (USD) per sensing channel *(6)*. Farrar pointed out that the cost of instrumenting Tsing Ma suspension bridge in Hong Kong with over 350 sensors may have exceeded $8 million *(7)*. With the rapid advancement in smart sensing and wireless communication technology in the last decade, researchers directed efforts towards the use of WSS to cost-efficiently monitor critical infrastructure *(8, 9, 23, 24, 25)*. One of the first known WSS for the monitoring of railroad bridges, BriMon is formed by Chebrolu et al. *(10)*. This WSS is based on the TmoteSky sensor board *(11, 12)* and can capture bridge vibrations with a sampling rate of up to 20 Hz. Bischoff et al. developed WSS also based on the TmoteSky sensor board to measure strains of railroad bridges at a sampling rate of 100 Hz *(13)*. Cho et al. *(14)* used WSS based on Imote2 *(15)* to obtain dynamic characteristics of a swing truss bridge. Moreu et al. *(16-18)* and Kim et al. *(19)* measured displacements of railroad bridges also with Imote2 based WSS. Wang *(20, 21)* and Hsu et al. *(22)* developed a wireless sensing unit based on Atmega128 microcontroller for structural health monitoring and validated the performance of the unit in several case studies. As mentioned in the hypothesis above, to date there are not many sensors that can measure with high accuracy the dynamic displacements of railroad bridges that are low-cost.

4.1.3. Design, Prototype, and Fabrication

The research team designed, developed, fabricated, and patented a wireless sensor (WS). This combination consisted of a small, low-cost, low-power sensor deployed for sensing and monitoring physical parameters. The sensor is capable to transmit the collected data to a central control system by using a wireless communication. The sensor node is made of basic components *(10)*: sensor, microcontroller, external memory, transceiver, and power source. The sensor acquires data from the environment and converts this analog data to digital data. The microcontroller is used as a processor to acquire and process receiver sensor raw data and stores the results. The external memory saves large amount of data enabling posterior access to the data by the user and provide remote sensing abilities. The transceiver unit enables sharing data with the end-user. Finally, there is a power unit that consists of an energy sink (battery, capacitor or both). Depending on application requirements, additional units can be added. See Figure 3, Figure 4, and Table 1.

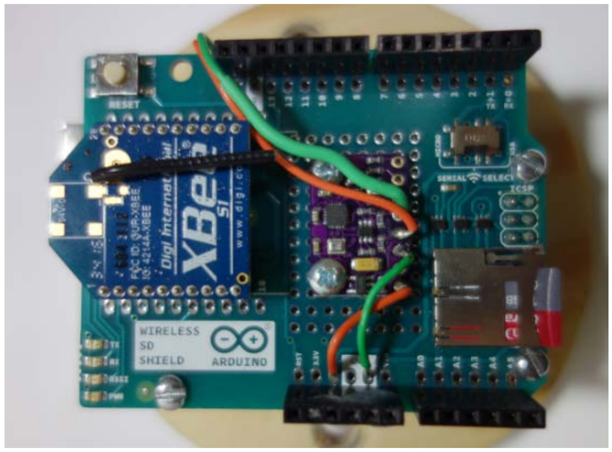


Figure 3. Assembled Low-cost, Efficient Wireless Intelligent Sensor (LEWIS).

Table 1. Essential sensing platform components LEWIS2.

Component	Description	Market Price, $
Arduino Uno R3	Microcontroller board	$4.00
MPU9250 breakout board	Low-cost acceleration sensing unit	$25.00
XBee Series 1 Module	Wireless transmission module	$9.99
Xbee Explorer	SparkFun XBee Explorer USB	$25.00
Arduino Wireless SD Shield	Interface board between XBee	$24.95
Battery	module and Arduino	$15.00
SD Card	Battery Nanotech 1.0	$6.33
	SanDisk Ultra 80MBs MicroSD	$10.00
	Memory Card - 16GB	
	Total	**$95.3 - $116.3**

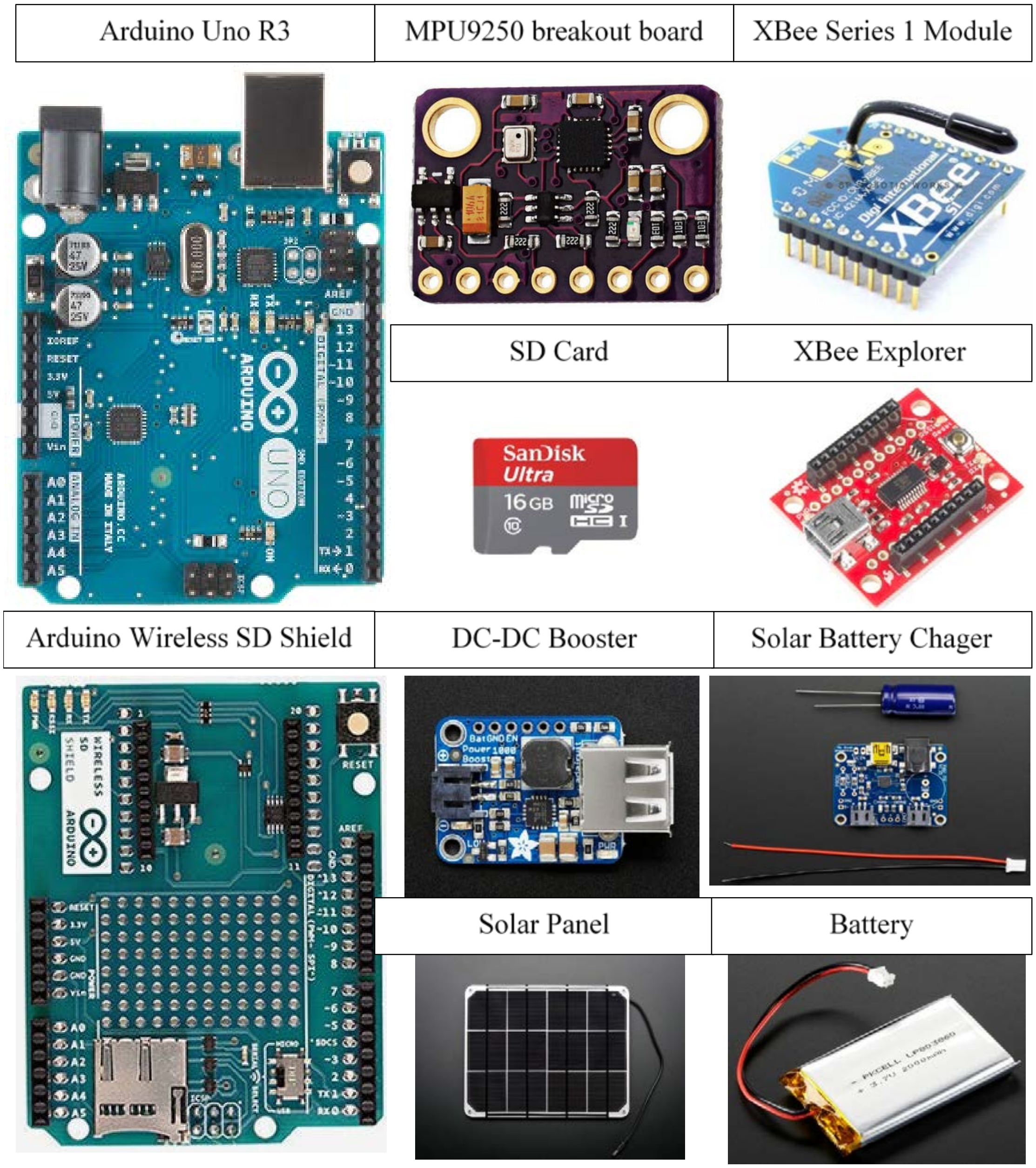


Figure 4. Components of the Arduino-based updated Low-cost, Efficient Wireless Intelligent Sensors (LEWIS).

4.1.4. Validation

Researchers of this project validated the performance of the low-cost wireless sensing platform through a series of laboratory experiments. The sensing platform was excited with a shake table simulating transverse displacements of railroad bridges captured on the field and the resulting responses were transmitted to a base station in real-time wirelessly (see Figure 5). The efficiency of the sensing platform was evaluated by comparing the estimated real-time displacements to the responses obtained from a commercial accelerometer, and an LVDT dedicated to collect the reference displacements. Results demonstrated that, compared to traditional sensing approaches which require fixed reference frame and utilize expensive instrumentation, the proposed sensing platform provides a cost-effective, wireless and real-time dynamic transverse displacement measurement of railroad bridges without further offline data processing.

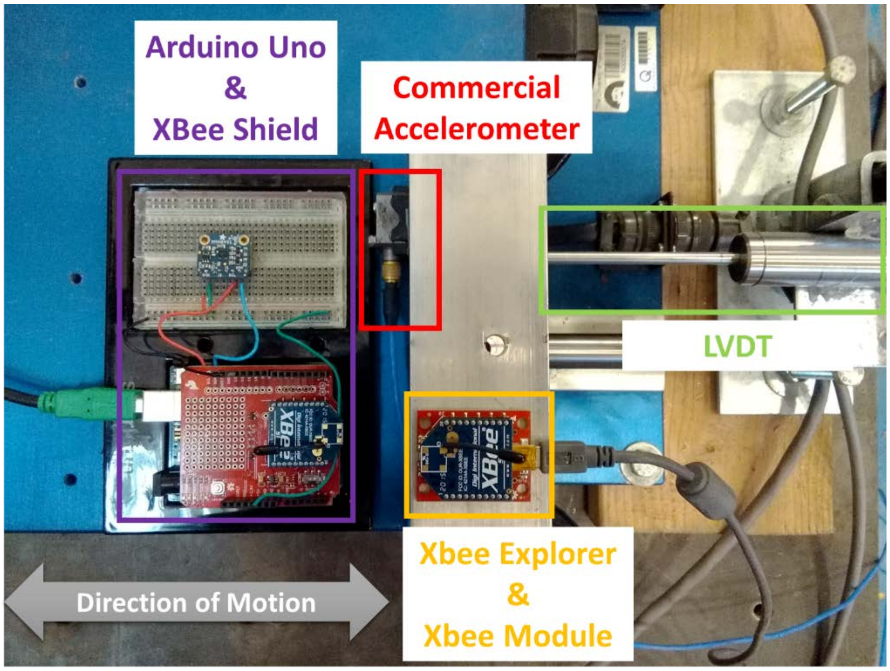


Figure 5. Experimental test setup for displacement estimation.

4.2. Training, Education, and Outreach Programs

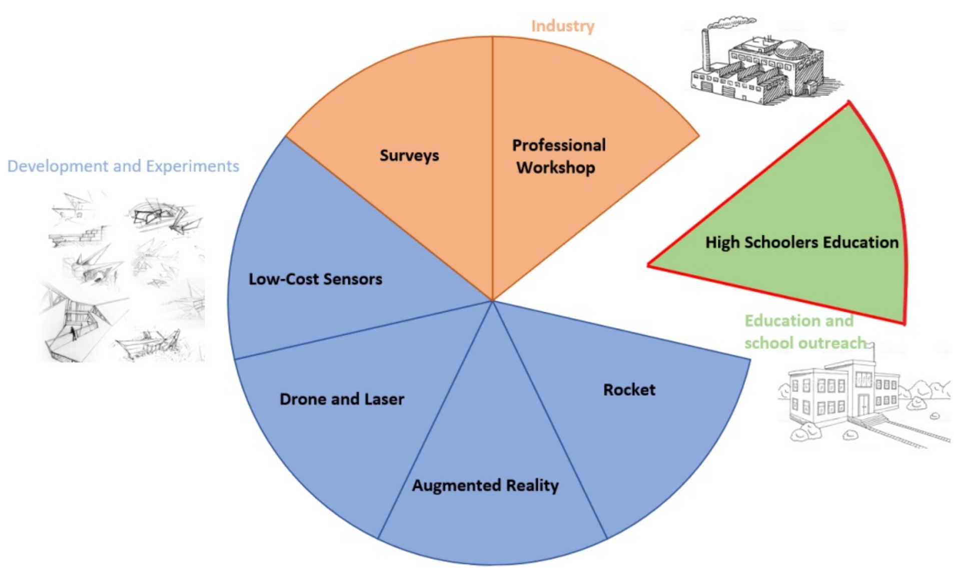


Figure 6. Phase 2 of the project.

This project developed training, education, and outreach programs over the low-cost sensing technologies for bridge SHM to students. The modules of training were developed by the researchers which could be effectively employed at classrooms for non-technical background personnel. Undergraduate and graduate level students collaborated with researchers to conduct training and educational seminars for high school students.

4.2.1. Hypothesis

The methodology for education and research was based on the hypothesis that developing sensors in the classroom (see Section 4.1.3.) can increase their adoption for research as well as to increase the exposure of high school students to the transportation industry.

4.2.2. Strategy for Education and Outreach (High School)

The major strategy opted by researchers was to provide hands-on technical skills to build and operate low-cost sensors (like the Arduino-based accelerometers). Trainings were focused on providing practical skills to the students and practitioners to assemble sensors that can be used in real-world applications. High school students were educated about the smart transportation systems and ways of integrating new technologies with existing infrastructures. Sixteen high school students attended the educational seminar outreach (Figure 7). Students built sensors in the classroom and then tested them in the Albuquerque Tramway.

Figure 7. Training of high school students with industry about smart transportation systems.

In order to evaluate the effectiveness of the activity with the high school students, the instructors carried out four surveys following the sensing at the Tramway with low-cost sensors. The first survey (Survey 1) was performed ten days prior to the student class on intelligent transportation systems. Survey two was conducted at the start of the student class on day 1. Survey 3 was conducted immediately after the student class on day 2, while survey four was performed immediately after the experiment on the Tramway. In this part of the project school students were taught about the sensors and they also installed them to Tramway towers and used these sensors to monitor the movements of Tramway cars. The surveys were completed by asking the high school students to answer a series of questions focused on their pre- and post-student class experience. For surveys one and two, the high school students were asked to answer only yes and no questions. For surveys three and four, the high school students answered the questions on a scale from one to five, with one meaning very low while five meaning very high.

For surveys one and two, the high school students were asked four questions, including:

1. Have you heard the term of intelligent transportation systems (ITS) before;
2. Have you used any sensors to collect transportation-related data;
3. Are you interested in building your own sensor for ITS application; and
4. Would you use ITS sensors in research/real life?

For surveys two and three, the high school students were asked five questions, including:

1. After the student workshops, how confident are you be able to explain to someone how to build a sensor;
2. How would you rate the overall usefulness of this student workshop;
3. After the student workshop, how comfortable are you to apply what you learned to the future;
4. Would you recommend this program to others; and
5. After taking the program, would you like to attend similar programs in the future?

4.3. Industry Workshop

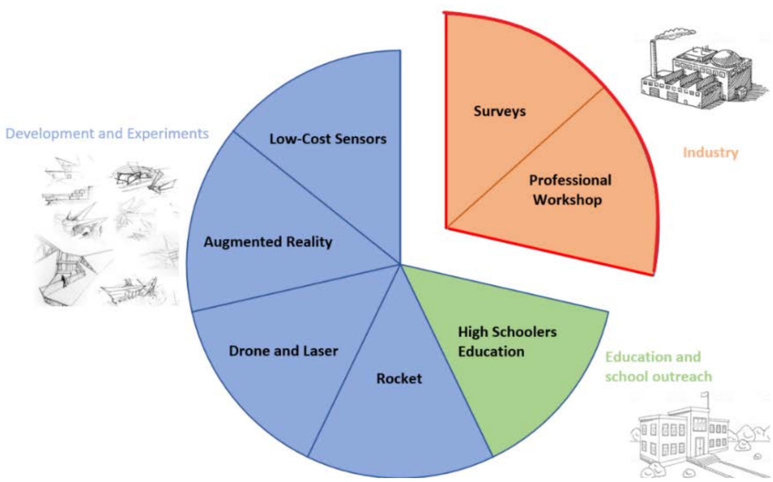


Figure 8. Third phase of the project.

4.3.1. Hypothesis

The workshop was designed to explore solutions for present challenges and future needs for SHM application in the railroad infrastructure industry. To identify these challenges and needs this project gathered together various railroad owners to collect their input about new technologies related to railroad infrastructure monitoring. The organizers managed to be inclusive in terms of representing the interest of different parties in railroad community, though the railroad industry had a dominant presence in the workshop. Hence, most of the discussion was focused on conducting inspections and monitoring of railroad infrastructure, specifically bridges, to try to collect as many different inputs/opinions regarding the technology ability to be used by industry, as opposed to phone calls or surveys not conducted in person. Similarly, by having a panel session at a large conference, the researchers aimed to collect more interaction between the actual owners and the community in this topic, which typically does not get presented in depth in the American Society of Civil Engineers (ASCE).

4.3.2. Strategy

Dr. Fernando Moreu and his graduate students Dilendra Maharjan and Marlon Aguero from the Department of Civil, Construction, and Environmental Engineering hosted the workshop on Thursday April 19^{th} 2018 at the Sheraton Fort Worth Downtown Hotel at Fort Worth, Texas. The invitations were sent to different stakeholders including, but not limited to, infrastructure owners, industry professionals, academicians, researchers and students (Figure 9). The Appendix 5 shows the list of the attendants to the workshop.

Figure 9. Participants shared challenges and opportunities in the domain of SHM in workshop conducted in Fort Worth, Texas (April 2018).

4.3.3. Methodology

The workshop covered challenges of implementing new technologies for SHM, adoption of frontier technologies and challenges for smart management of infrastructure in general. The workshop strived to identify three main interest areas where research effort could be advanced:

a) Challenges for infrastructure maintenance and management.
b) Challenges for implementing new technologies, sensors, applications and algorithms.
c) Frontier between future need and technologies.

Participants were encouraged to actively participate in discussions to be more interactive. Participants from different railroad companies were given opportunities to interact with other participants on the topic of smart management of railroad infrastructures.

Later the same day, Professor Moreu chaired the panel review "Structural Health and Performance Monitoring of Railroad Infrastructure: Owners' Perspective" (*26*). Railroad owners shared with the structural engineering community their priorities, strategies, methodologies, and results to structural health and performance monitoring applied to railroad infrastructure management. This session primarily described industry cases from North American railroads, including railroads from both US and Canada.

5. FINDINGS

5.1 Low-cost Sensors

5.1.1. Results of Low-Cost Sensors Development

Researcher developed both the hardware and software required to collect displacements under trains using a low-cost platform. The new Arduino based platform was the most efficient and cost-effective propositions for SHM purposes and was the chosen one to be tested for this research. Three different versions of sensor were developed using this platform, latest version being Low-Cost Efficient Wireless Sensors (LEWIS) Version 2 (LEWIS2). LEWIS2 was able to integrate numerous sensors besides accelerometers. Laboratory data validations of those sensors measuring bridge displacement were tested using a shake table.

The Arduino Uno based sensing platform designed as a result of this research can extract dynamic displacement from acceleration with a low-cost accelerometer, MMA8451Q using a displacement reconstruction algorithm on-board. This algorithm is a Finite Impulse Response (FIR) filter and it requires current and previous acceleration data to estimate displacement. Given the limited capabilities of Arduino Uno, a simple memory management system is applied to compensate memory requirements of the FIR filter. The computed displacements are transmitted to a base station using a XBee radio module attached to the sensing platform.

The plots in Figure 10 show the experimental results conducted by group of researchers (PI, post doc and graduate students) in the Smart Management of Infrastructure Laboratory (SMILab) at the University of New Mexico. In the series of experiments, the bridge response was simulated in shake table with data collected from real railroad bridge vibrations. Commercial accelerometers and reference displacement sensors (LVDT) were also used in the experiment. The commercial accelerometer and LVDT are instrumented to measure the displacement with the help of Data Acquisition using VibPilot instrument. Later the results obtained from the low-cost sensors were compared to the commercial ones to validate the effectiveness of those low-cost sensors. As shown in Table 2, the developed sensors have remarkable accuracy with low percentage error. These results are the main outcome of the research of this project, which is developing low-cost sensors that can measure reference-free displacements of bridges under trains, which was identified as the major sensing need of railroad owners. The plots in Figure 10 show the success on the validation of the new low-cost sensor in collecting reference-free displacements under trains.

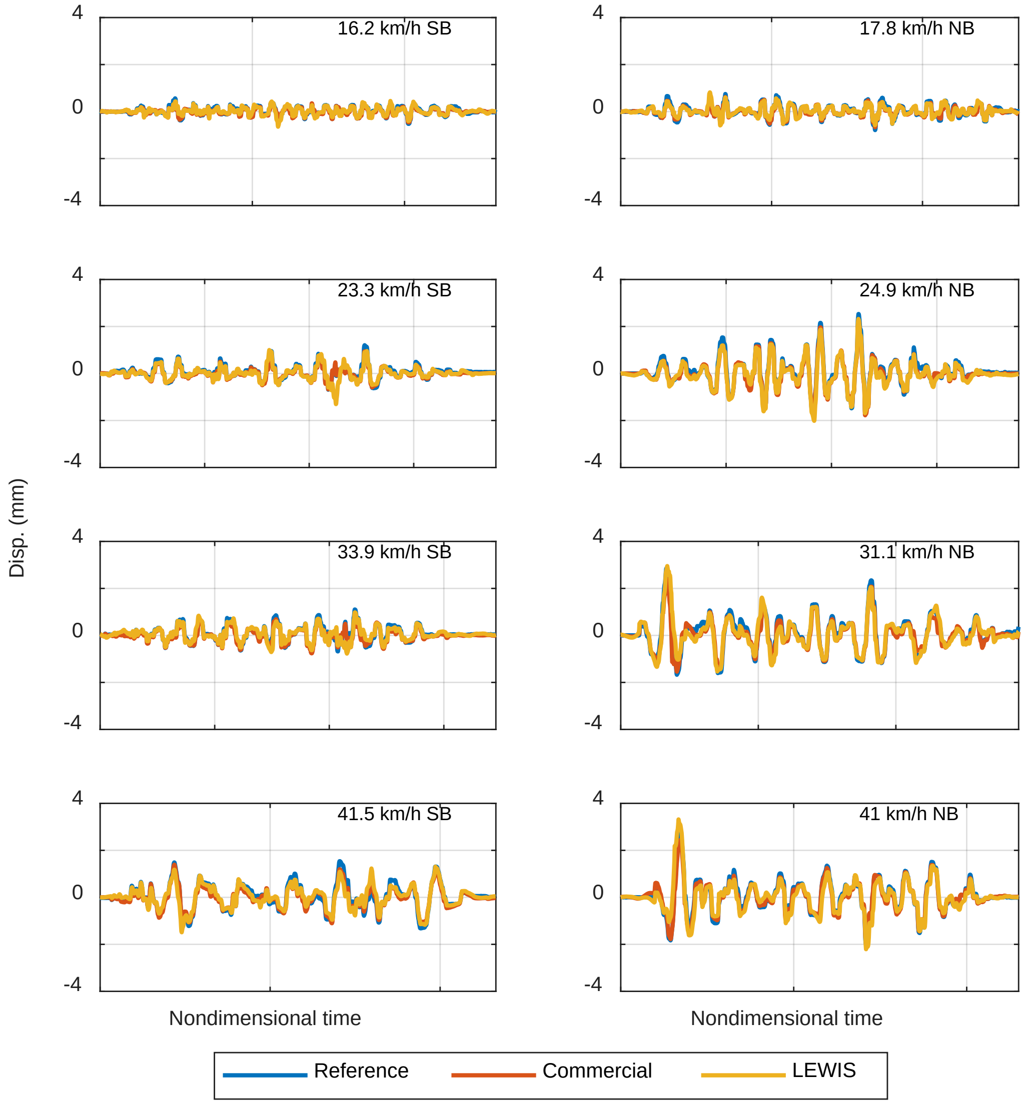


Figure 10. Comparison of LEWIS with commercial accelerometer and reference LVDT measurement.

Table 2. Performance results for displacement comparisons.

Train #	E_1 [%]		E_2 [%]	
	Commercial	LEWIS	Commercial	LEWIS
1	18.51	14.82	10.00	12.88
2	15.44	3.52	8.81	13.01
3	21.31	8.35	7.19	13.09
4	10.71	8.32	4.94	6.03
5	**26.16**	11.09	8.95	13.18
6	16.58	3.26	5.80	9.51
7	9.68	3.28	**10.48**	**13.23**
8	12.77	**19.10**	4.71	10.21

The Power Spectrum Densities (PSD) of the eight train crossing data captured by the low-cost sensors and the commercial accelerometer are show in Figure 11. These plots show comparisons in frequency domain analysis of low-cost wireless sensors and commercial sensors. The experimental results demonstrate that the wireless sensors are capable of accurately measure dynamic transverse displacement of railroad bridges cost-effectively in real time without the need to a fixed reference frame.

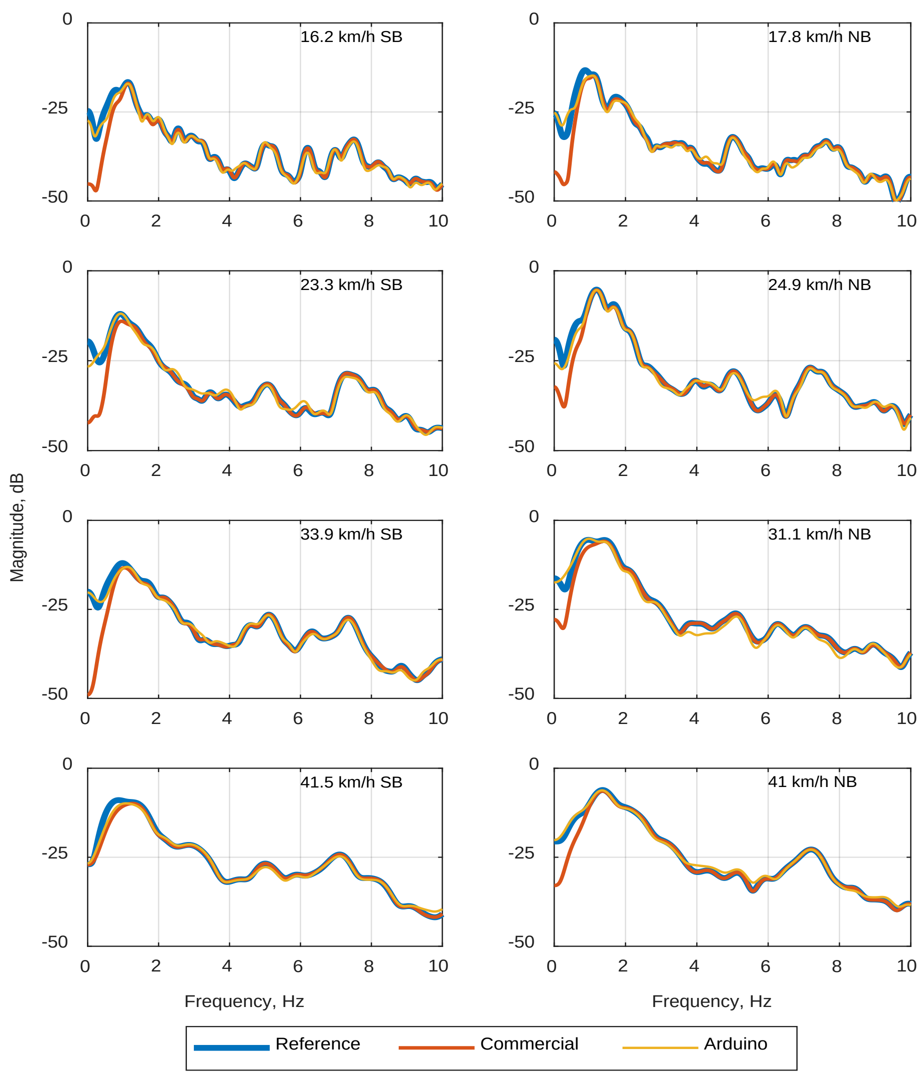


Figure 11. Power spectrum densities for displacement responses.

5.1.2. Low-Cost Sensors Reference-Free Trajectory and Remote Sensing

Background: In addition to the ability of low-costs sensors to collect reference-free displacements, the researchers developed the functionality of the LEWIS2 to also collect trajectory. In order to explore this application, the civil engineering students teamed up with mechanical engineering students and tested the LEWIS2 sensor launched in a rocket. The engineering students wanted to test the ability of the low-cost sensor to measure remotely data of vibration as well as the trajectory of the rocket. Through analysis of the acceleration and angular velocity data collected from the sensor, researchers effectively monitored other parameters of interest remotely using LEWIS2. Additionally, with this feature, the researchers wanted to study the low-cost sensor ability for remote sensing. Collecting trajectory using low-cost sensors can be a useful parameter for transportation monitoring.

Results of LEWSI2 for Remote Sensing and Trajectory Monitoring: After the sensor was integrated into the rocket (see Figure 12), the rocket was placed on the launch rail. At this point, data acquisition was activated wirelessly, and the rocket was then raised in the vertical position awaiting launch.

Figure 12. Activation and recovery of the wireless sensor remotely to record the acceleration and angular velocity.

Figure 13 shows the ability of the LEWIS2 sensor to collect remote data. The value of this feature is that the sensor does not need to be used in the laboratory, but it can be placed outdoors with battery and collect data autonomously, which is of interest of owners of transportation infrastructure. Students become more engaged in sensor development and transportation sensing through the multi-disciplinary collaboration with mechanical engineering students.

Figure 14 shows the results of trajectory monitoring of LEWIS2, also collected in the sensor without the need of power supply. The value of this technical feature is that the trajectory of transportation fleet can be also tracked with low-cost sensors, which can be a useful low-cost approach for transportation infrastructure owners.

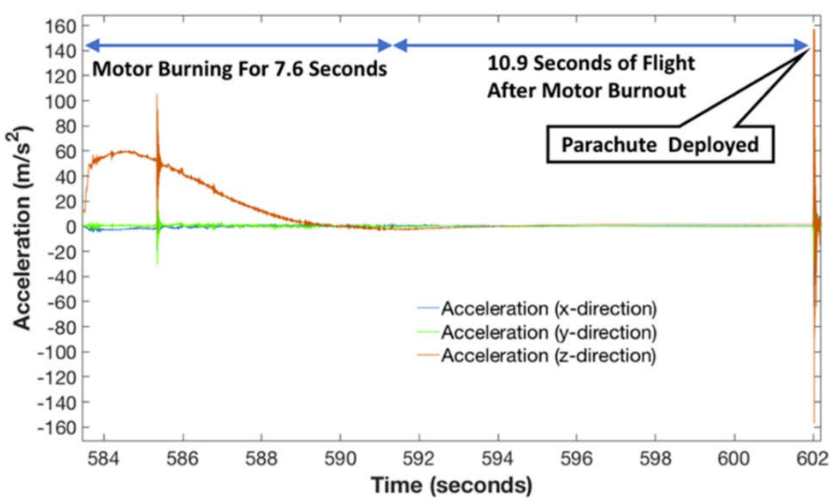


Figure 13. Events captured in the launch of the rocket.

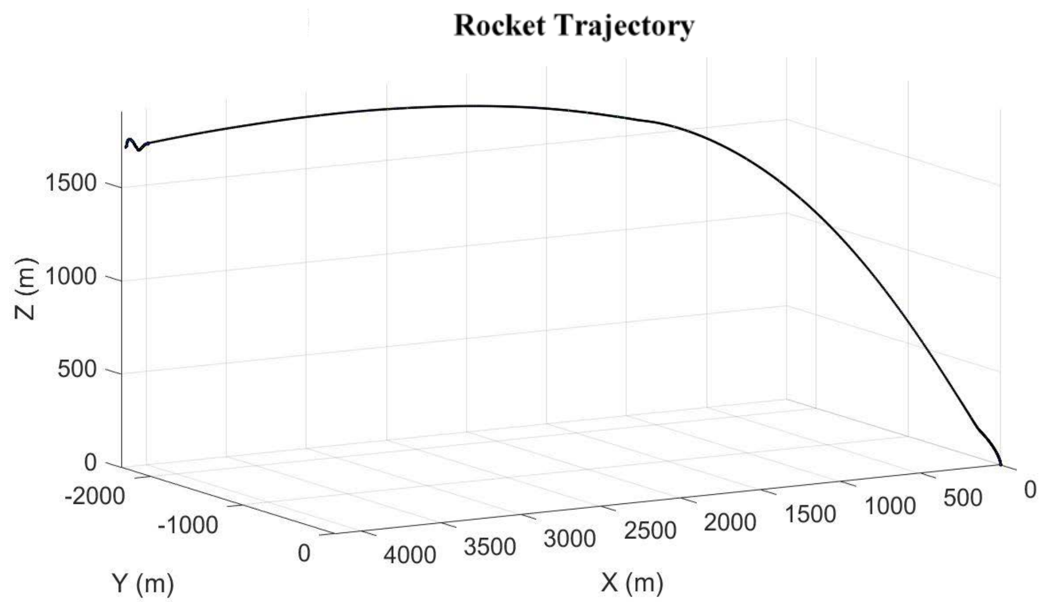


Figure 14. Rocket trajectory captured by LEWIS 2.

5.1.3. Drone and Laser for Reference-Free Displacements

This project also explored using drones for remote assessment of transportation infrastructure by measuring contact-free, reference-free displacements integrating UAS and lasers. Figure 15 shows the validation of the reference-free displacement using conventional sensors and the drone + laser simultaneously. This experiment is the first effort to combine dynamic displacement sensors with drones to collect reference-free displacements, which has value when the railroad infrastructure does not have access to inspector to place the sensors in the bridge. The research team combined this effort with the low-cost sensor effort to illustrate that both approaches are a contribution to the interest of the railroad infrastructure owner to collect reference-free displacements more safely.

Figure 15. Drone and laser field testing.

Figure 16 shows the research steps to integrate drones and lasers to collect dynamic displacements under trains. As shown in the research steps, the reference-free displacement with drones entails both hardware and software integration and can be needed when low-cost sensors cannot be added to the bridge.

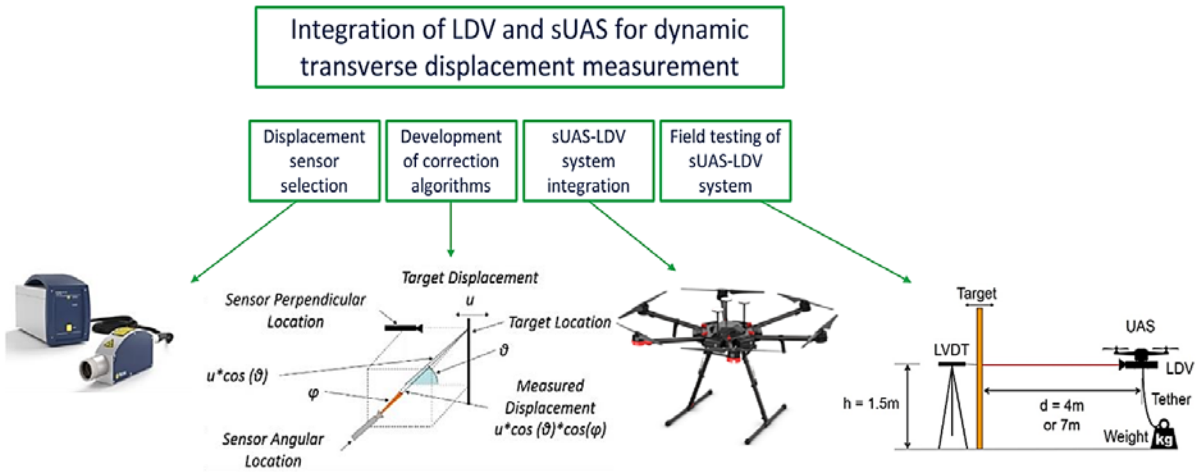


Figure 16. Implementation of laser and UAS for displacement sensing.

Figure 17 shows the results for railroad displacement monitoring using conventional sensors and the drone with laser. The conventional data was collected using LVDT, which is considered the reference displacement. The laser data is collected with the LDV connected to the UAS during flight. The data collected with the LDV attached to the UAS is comparable to the data collected with the LVDT. As shown in these three experiments, the accuracy of this method indicates that under controlled conditions such as no high winds and at a given distance, drones and lasers could be an alternative to collect bridge vibration under trains if the inspector cannot climb to the bridge to install the low-cost sensor.

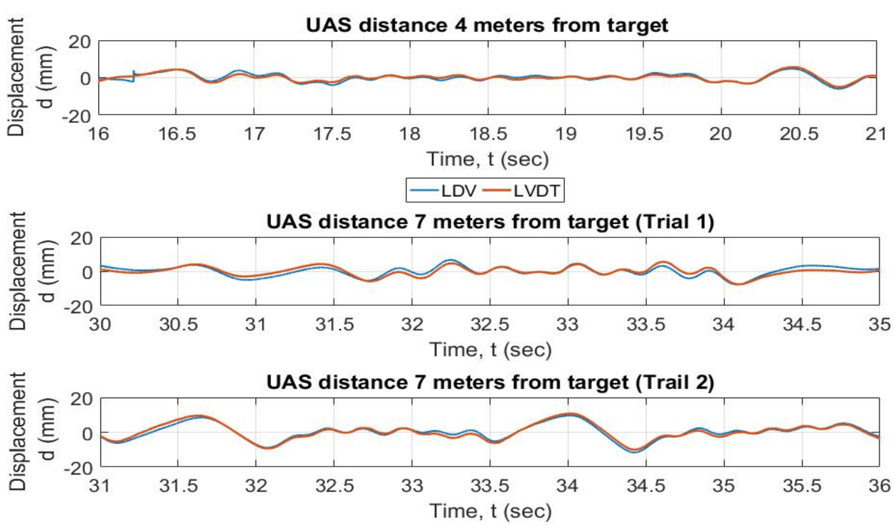
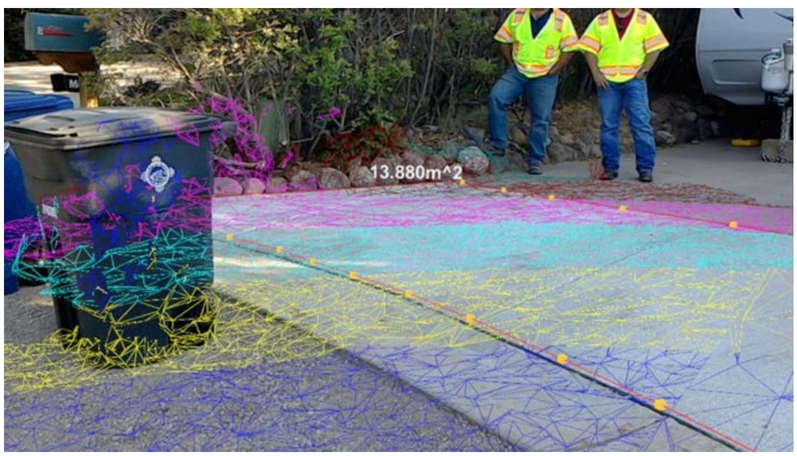


Figure 17. Dynamic transverse data obtained using UAS and laser (LDV) in comparison with traditional sensor (LVDT).

5.1.4. Augmented Reality

This research also explored the ability of AR to collect information of interest to transportation infrastructure owners, for example areas. This was identified of valuable application because collecting areas in the field would not need to be done with survey crews using total stations, but rather with a headset that can collect the 3D environment and calculate the areas automatically. To demonstrate this, the research team collaborated with the Los Alamos County (LAC) engineering division. Researchers of this project were exploring the use of AR to assess infrastructure in collaboration with Los Alamos National Laboratories (LANL). The results of the is effort was a successful in comparison of area collection using traditional measuring techniques and Hololens. The results of this effort in collaboration with LANL is currently being reviewed by a high impact journal paper. Figure 18 shows the comparison of the area collected with county measurements and Hololens in LAC. For the three examples shown in Figure 18, the error was under 2%, which according to the stakeholder owner (LAC) is an acceptable result. These efforts could also be used by NMDOT in the area of billing on irregular shapes of transportation infrastructure, because AR can be useful for small areas where inspectors can walk around and calculate the surfaces without the need of total stations installation (which is not time-efficient).



Augmented Reality Surface Area Response Compared with County Results

	County Measurement (ft²)	HoloLens Average Measurement (ft²)	Difference (ft²)	% Difference
Area 1	187.98	191.5	3.52	1.9%
Area 2	147.67	149	1.33	0.9%
Area 3	129	127.4	1.6	1.2%

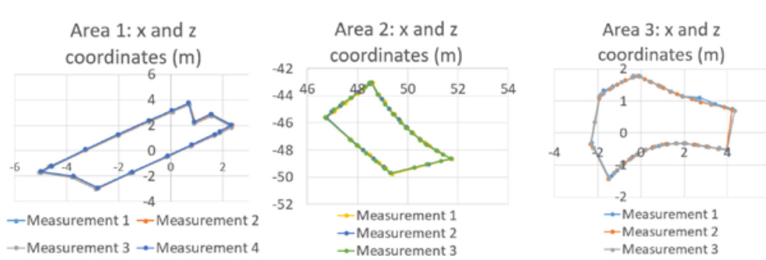


Figure 18. Field measurement using AR with LANL at LAC.

5.2. Educational and Outreach Findings

The second group of findings is separated in two parts. The first part focuses on education to high schoolers on low-cost sensors and quantifying the effect of this activity in their interest in smart transportation infrastructure careers. The second part of results are directed to outreach activities to other groups of interest: middle-schools, college students, and professionals, to explore their feedback and interest in low-cost technologies.

5.2.1. High School Students, Low-Cost Sensors, and Engineering Motivation

The main target of the educational research of this project was the high school students. The main goal of the educational research was to explore whether high school students become motivated to learn more about smart transportation systems by building and testing low-cost sensors themselves or not. Therefore, the researchers designed and conducted a series of activities and surveys to explore, quantify, and obtain conclusions about these activities.

The following figures show the results from survey one (S1) and survey two (S2). As mentioned earlier in Section 4.2.2, survey one was conducted ten days before the workshop to examine if the high school students knew anything about smart transportation systems. Survey two was conducted at the beginning of the workshop.

Figure 19 shows that the high school students became more familiar with the term of intelligent transportation systems during the educational outreach. Figure 20 shows that the high school students at first thought they had used sensors to collect transportation-related data, but after the seminar they had understood the difference between what they thought the data collection was and what it is.

Figure 21 shows that the majority of the high school students (more than 70%) wanted to use Intelligent Transportation Systems (ITS) sensors in research and real life, and that percentage increased after the outreach program. Figure 18 also reveals that more students wanted to use ITS sensors in research and real life after preparing themselves for the upcoming workshops.

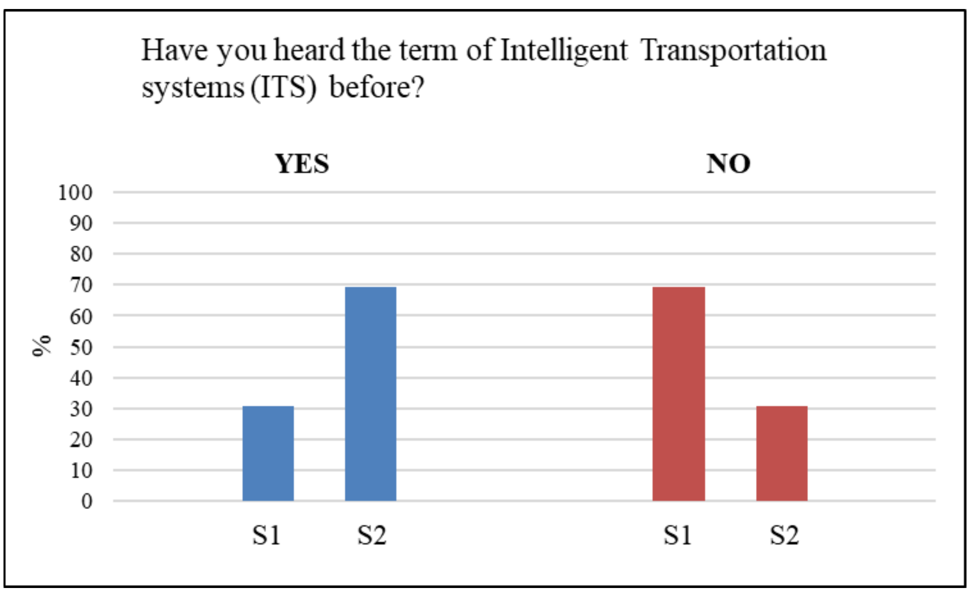


Figure 19. Results for the first question in survey one (S1) and survey two (S2).

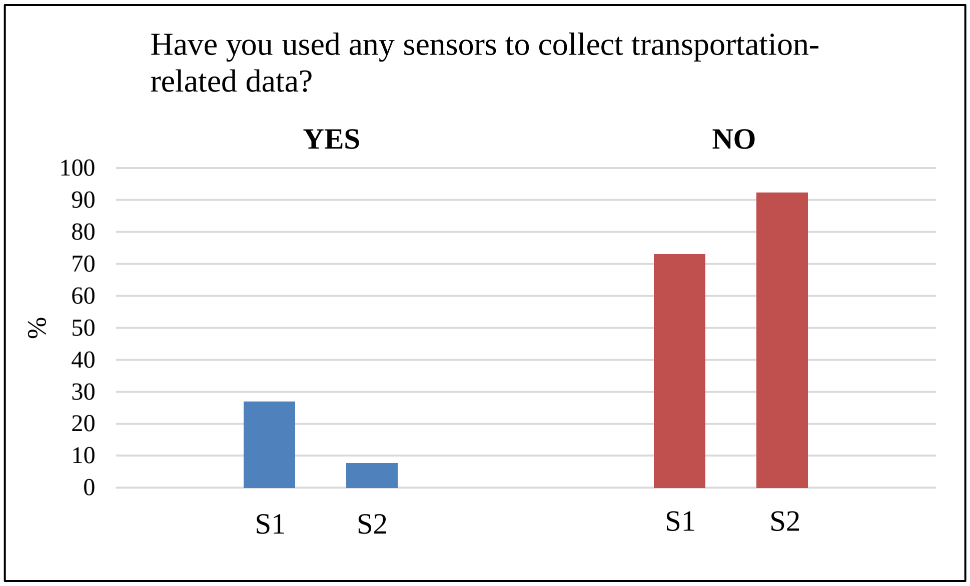


Figure 20. Results for the second question in survey one (S1) and survey two (S2).

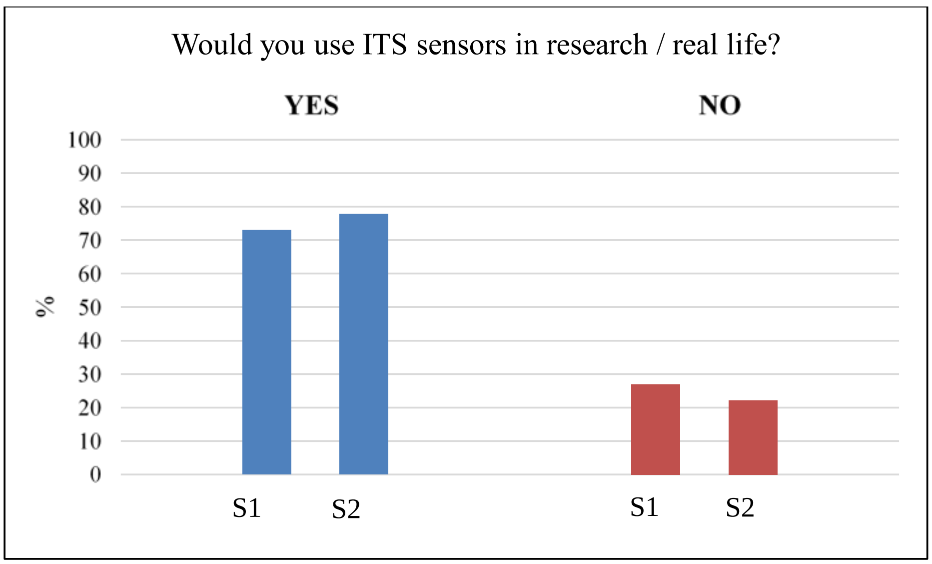


Figure 21. Results for the fourth question in survey one (S1) and survey two (S2).

The following figures show the results from survey three and survey four. As mentioned earlier in section 4.2.2, survey three was conducted immediately after the outreach on day two to examine the impact of the sensor building on students' perspective on ITS sensors. Survey four was performed immediately after the experiment on the Tramway, and the purpose is to investigate the impact of the sensor application on students' perspective on ITS sensors.

In Figure 22, it can be observed that while ratings of 3 and 4 decreased slightly between the two surveys, ratings of 5 increased well over 15 percent. This shows that in general the number of students more comfortable using low-cost sensors increased. Figure 23 shows that regarding recommending this workshop to friends or others, the ratings of 3 and 4 decreased slightly between the two surveys, ratings of 5 increased by approximately 40 percent. So, in general the number of students believing that the workshop would be of interest to others also increased notably with the workshop. Figure 24 shows ratings of 5 increased approximately 15 percent, reinforcing the trend that with the workshop the high school students increased the level of comfort to apply what they learned in the future. Figure 25 and Figure 26 show the same trend indicating that after the workshops the high school students were very satisfied and learned more knowledge than they expected, and they were willing to recommend the same program to their peers.

In conclusion, as it was noted during the outreach, the high school students were enthusiastic about the Arduino sensors project they were going to attend, with a little or no knowledge about it. Moreover, after they built the Arduino sensors by themselves and performed the experiment, they were highly motivated to explore more about ITS sensors and recommend others for gaining knowledge with hands-on experience from such workshops.

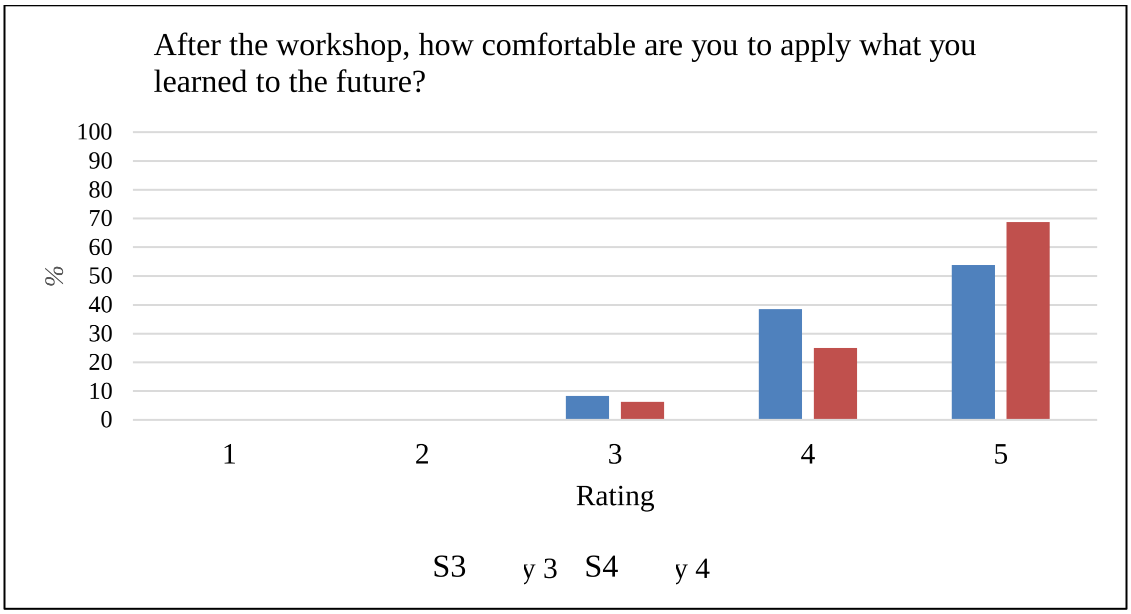


Figure 22. Results for the first question in survey three (S3) and survey four (S4).

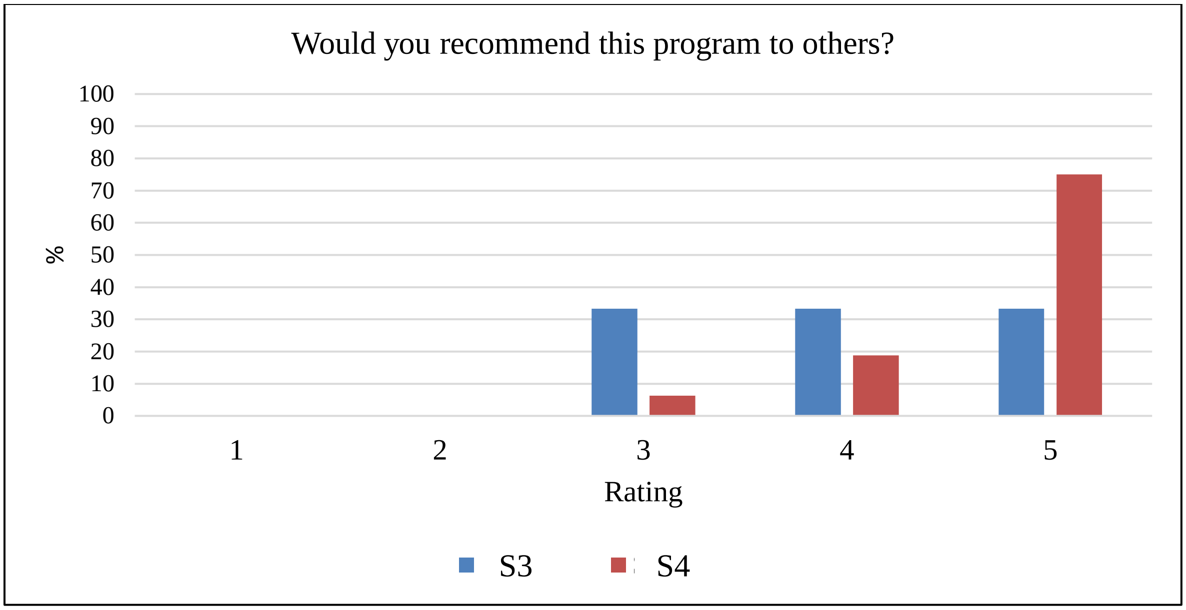


Figure 23. Results for the second question in survey three (S3) and survey four (S4).

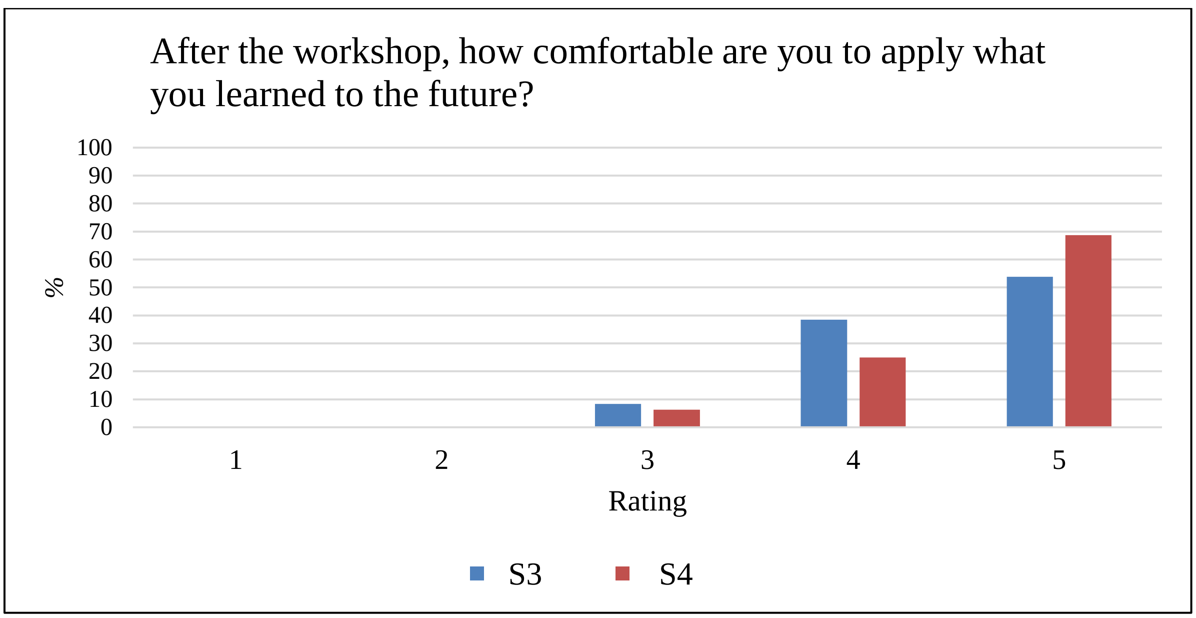


Figure 24. Results for the third question in survey three (S3) and survey four (S4).

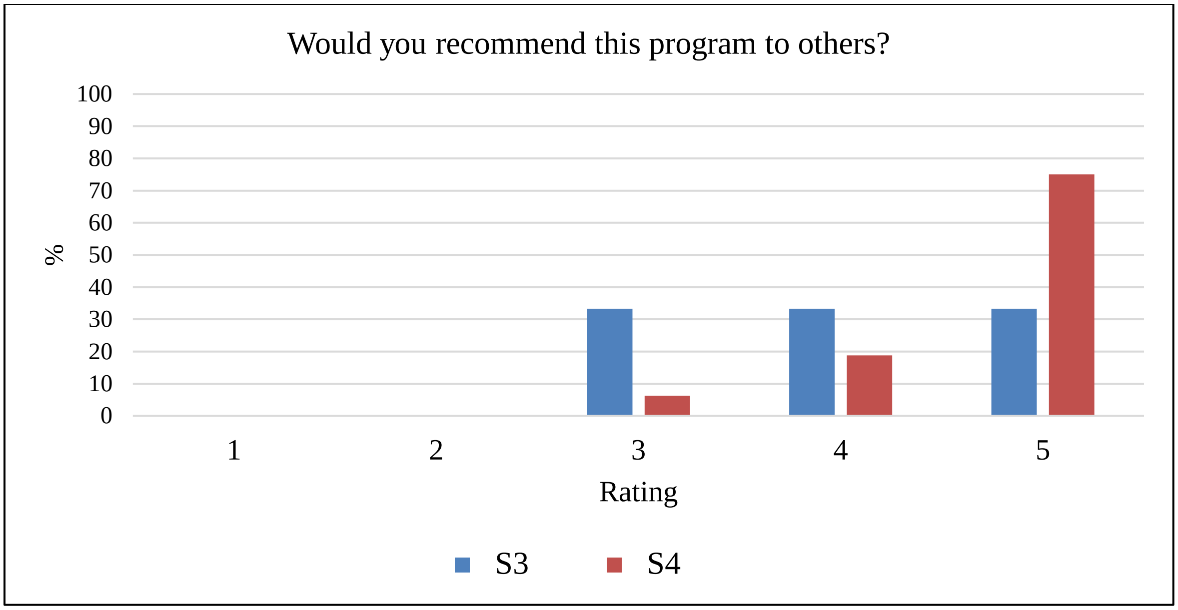


Figure 25. Results for the fourth question in survey three (S3) and survey four (S4).

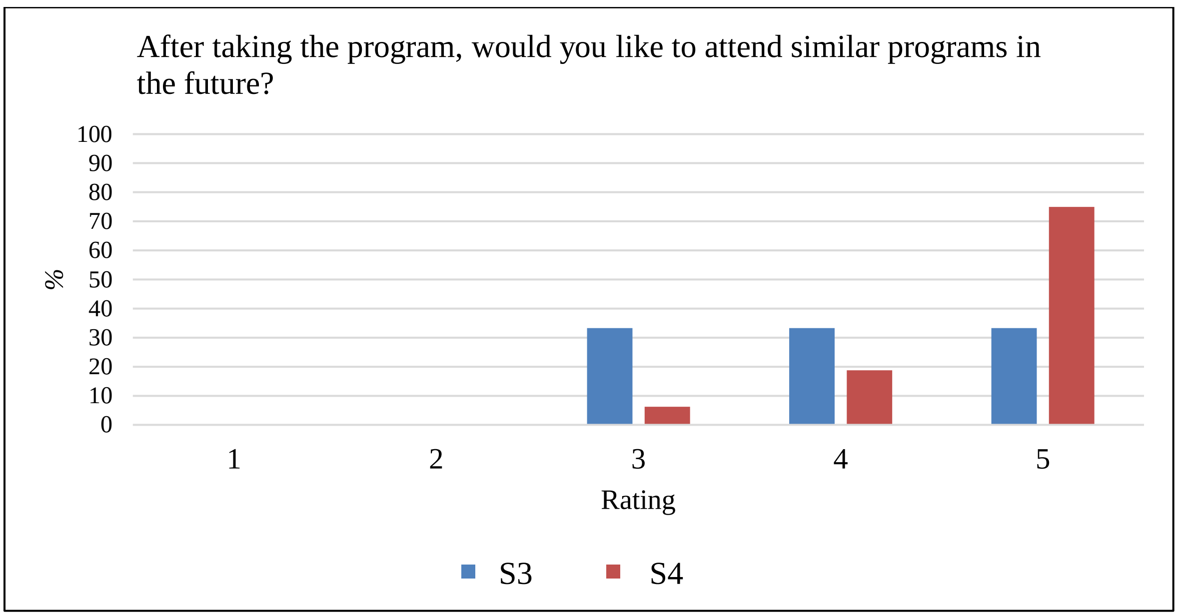


Figure 26. Results for the fifth question in survey three (S3) and survey four (S4).

5.2.2. Results from Other Outreach Activities

Middle Schools: These technologies were shared during outreach activities with middle schoolers, attendants of science and history museum in Albuquerque and the Menaul Academy (Figure 28 and Figure 29). The results were that middle schools were interested in new technologies and are engaged to the concept of AR, which effectively attracts their attention over other displays or presentations not as interactive. As part as training of minorities in STEM, one female high school student conducted her capstone senior design project with graduate students funded by this research project on dance engineering. She presented her results at Massachusetts Institute of Technology (MIT) during ASCE Engineering Mechanics

Institute (EMI) Annual meeting on Cambridge, MA, on May 2018. She was the first high school student to present at ASCE EMI.

Figure 27. AR for structural assessment outreach at the Albuquerque Museum of Science and History (October 2017).

Figure 28. AR for middle school and high school students (Menaul School, Albuquerque, New Mexico).

Undergraduate Students: During the outreach to undergraduate students, it was found that civil engineering students are more interested to sensing technology if they can use it and share it with other related activities beyond transportation infrastructure and in multi-disciplinary settings. During this project, the development of low-cost sensors by civil engineering students included collaborations with undergraduate mechanical engineering students, electrical and computer engineering students, and computer science students. By collaborating with other majors, civil engineering students became motivated to explore new low-cost sensing applications. As shown in Figure 29, wireless sensors were developed in structural laboratory at Centennial, UNM (University of New Mexico) and then tested with a rocket. We collaborated with the Albuquerque Rocket Society (ARS) for the launching of the rocket as shown in Figure 30. The results were also presented at ASCE EMI on May 2018.

Figure 29. Low-cost sensors for aerospace SHM (November 2017).


c

Figure 30. Use of wireless sensors for SHM of Commercial Space Vehicles (November 2017).

Civil engineering students were introduced to LAC engineering department in relation to new technologies (December 2017). Students worked in assessing current state of infrastructure. As shown in Figure 31, the students were relating the research on AR with the conventional survey equipment used by the county, so they could understand the relationship between research and industry.

Figure 31. Visit with LAC bridges at Los Alamos, New Mexico.

Graduate Students: Students were acquainted with low-cost sensing technologies by videos, PowerPoints, Word documents to teach in structural dynamics (CE 521) in UNM for civil engineers (15). The building and testing of the sensor were part of the assignment given to the graduate students (Figure 32). The testing was carried out in Sandia Tramway. Civil Engineering communities are not usually aware of deploying sensors for SHM. This class was turning point in providing current graduate students a powerful tool to use low -cost sensors in their future projects.

Figure 32. Civil engineering students build their own sensors (first time in a civil engineering program).

The experiment was carried out to collect acceleration and angular velocity of the Tramway's sway placing the sensor LEWIS2 over the floor of the Tramway's car. The sensor was installed in the car and in the tower. The ranges for acceleration and angular velocity measurements were +/- 16 g’s and +/- 2000 degree per second, respectively. This experiment exposed graduate students in civil engineering to sensing technology which they can benefit from it in their specific research areas (Figure 33 and Figure 34).

Figure 33. Placement and activation of the wireless sensor on the Tramway.

Figure 34. LEWIS 2 was placed in Tramway Tower to capture acceleration and angular velocity.

A graduate student from SMILab was selected to present ongoing research in ‘Laser Doppler Vibrometer mounted on Unmanned Aerial System for Dynamic Displacement Measurements’ at ASCE EMI conference. In accordance to the objectives of project, this presentation helped collaborating with top researcher in the academia and establish connection with industry professionals (Figure 35).

Figure 35. A graduate student presenting at EMI conference, 2018.

Practitioners: Prof. Fernando Moreu travelled to Orlando, Florida to teach professionals about SHM and using sensors for infrastructure management and maintenance. This coordinated effort with Prof. Hae Young Noh from Carnegie Mellon University (CMU) was a new learning experience for professionals. Those industry professionals were familiarized with low cost sensing technology used for SHM. Students were also guided to build their own low-cost sensors and combined with other embedded sensors (Figure 36 and Figure 37).

IMAC XXXVI, February 11, Orlando, Florida: Moreu Teaching Professionals SHM and How to Use Sensors

February 1, 2018

Dr. Fernando Moreu will be teaching professionals how to build and use accelerometers and sensors for SHM in Orlando, Florida, as part of the International Modal Analysis Conference (IMAC), with colleague Hae Young Noh from Carnegie Mellon University (CMU). The registration for this course is still open at this website: http://sem.org/imac

Dr. Moreu will be teaching how to build low-cost data acquisition platforms to measure simple responses of structures and algorithms which will identify changes on damage and performance using quantitative data analysis. The students will design, build, and test a low-cost sensor that combines low-cost microcontrollers, tilt-meters, and accelerometers. The data collected can be analyzed, clustered, and intelligently classified using fundamental exposure to machine learning protocols and definitions.

More information about the course can be found here http://sem.org/files/events/IMAC36_103.pdf

This activity is supported by the New Mexico Consortium under grant number 249-01; the Transportation Consortium on South-central States (TRANSET), US Department of Transportation (USDOT) Project No. 17STUNM02; and the New Mexico Space Grant Consortium, NASA Award Number NNX15AL51H.

Figure 36. Short-course on sensors and SHM to increase the reaching to communities not usually familiar with using sensors to monitoring transportation infrastructure.

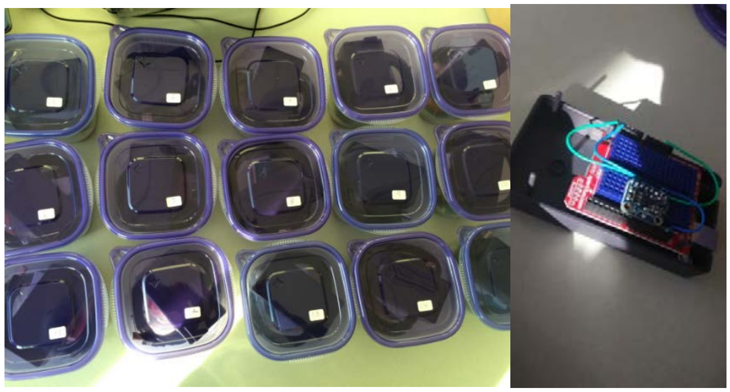


Figure 37. Low-cost sensors for SHM: short-course in Orlando, Florida, February 2018 (developed by high schoolers).

Similarly, Fernando Moreu presented at Palo Alto, California, the effect of AR in industrial settings to professionals (Figure 38), at the International Workshop of Structural Health Monitoring (IWSHM). Fernando Moreu will teach AR to professionals on February 2019 in the International Modal Analysis Conference (IMAC).

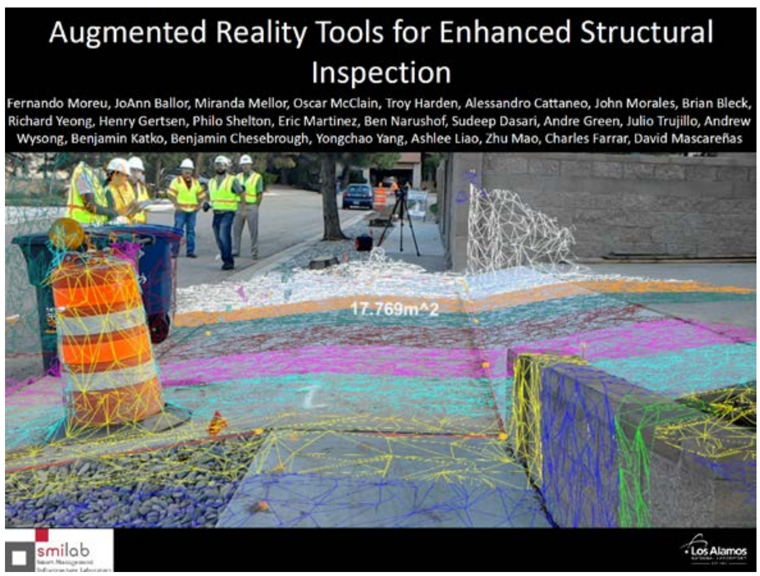


Figure 38. AR presentation at IWSHM September 2017 Stanford, Palo Alto, California.

5.3. Workshop

5.3.1. Workshop Purpose

The purpose of the workshop was to discuss with stakeholders how to prioritize the development needs towards application and implementation of new sensing technologies in current inspection and maintenance practices. More specifically, by interacting with the owners of the infrastructure, the workshop identified top sensing technologies needs and priorities from the owners' perspectives, and elaborate pilot program to develop them. The topics presented in this session described the railroad owner's perspective about infrastructure monitoring which informed new applications and opportunities of interest to researchers in SHM and system identification.

5.3.2. Workshop Audience

Structural engineering designers, project managers, and railroad infrastructure owners were provided with lessons to identify new opportunities to increase the safety and cost-effectiveness related to designing, repairing, or replacing North American infrastructure using the examples from SHM of railroads, generally not covered in detail in past structural engineering congresses. Designers, builders, and stakeholders of any infrastructure system interested in applications of SHM and monitoring with specific actionable applications learnt from the specific presenters covering their perspective as owners interested in health and performance monitoring from an owner's perspective.

Figure 39. Workshop conducted at Fort Worth, Texas (April 2018).

The workshop contributed to the general audience in structural engineering due to the following:

1) The workshop was open to any infrastructure engineer interested in the topic of new technologies from the owners' perspective angle. The results of this workshop are connected to the areas of implementation needs.
2) The participants to the workshop include top leaders from the infrastructure stakeholder and administration domains: bridge engineers, managers, inspectors, and

administrators, both from private and public perspectives. Local universities, administrations, and societies were also invited to participate. Students (both undergraduate and graduate) attended and participated from several universities from the area, on addition to the students from UNM.

Figure 40. Participants at the workshop, May 2018.

Figure 41. Panel members at the ASCE Structure Congress, May 2018.

The workshop was diverse in terms of professional affiliations and work experiences. The participants in the workshop were divided in 5 main categories. As seen in Figure 42, most of the participants are in academia, infrastructures owners and industry professionals. 39% of the attendants were students, which contributes to the training of new generation of professionals in this area.

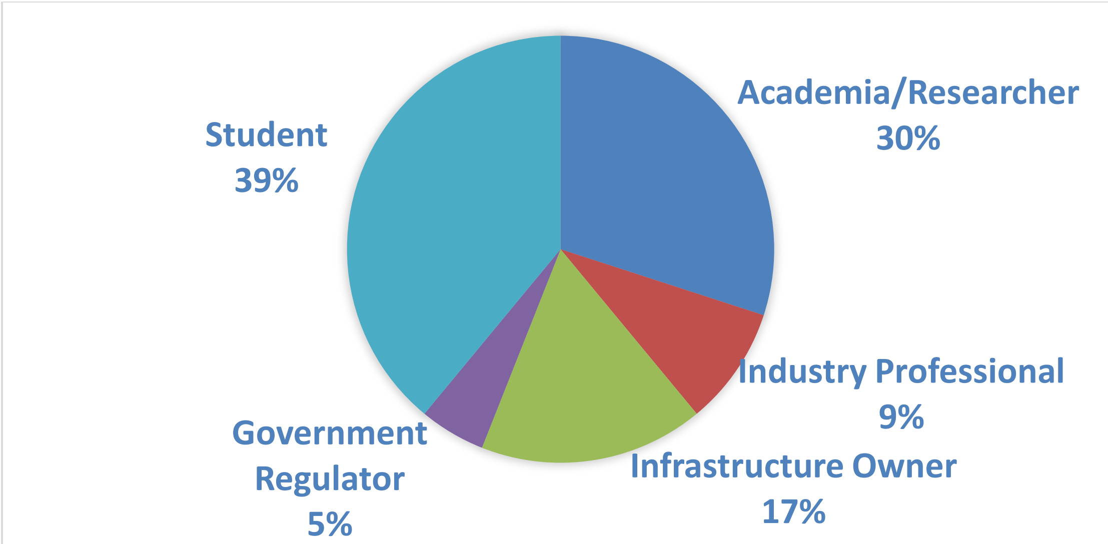


Figure 42. Percentage of workshop participants by occupation.

At the workshop, it was important to identify if the attendants were users of technology in maintenance and management. Figure 43 summarizes the percentage of exposure to new technologies of the different participants in the workshop. As Figure 43 shows, only 15% have a poor level of exposure to new technologies. This indicates that the majority of the attendants to the workshop have some level of exposure to new technologies in their occupations or studies.

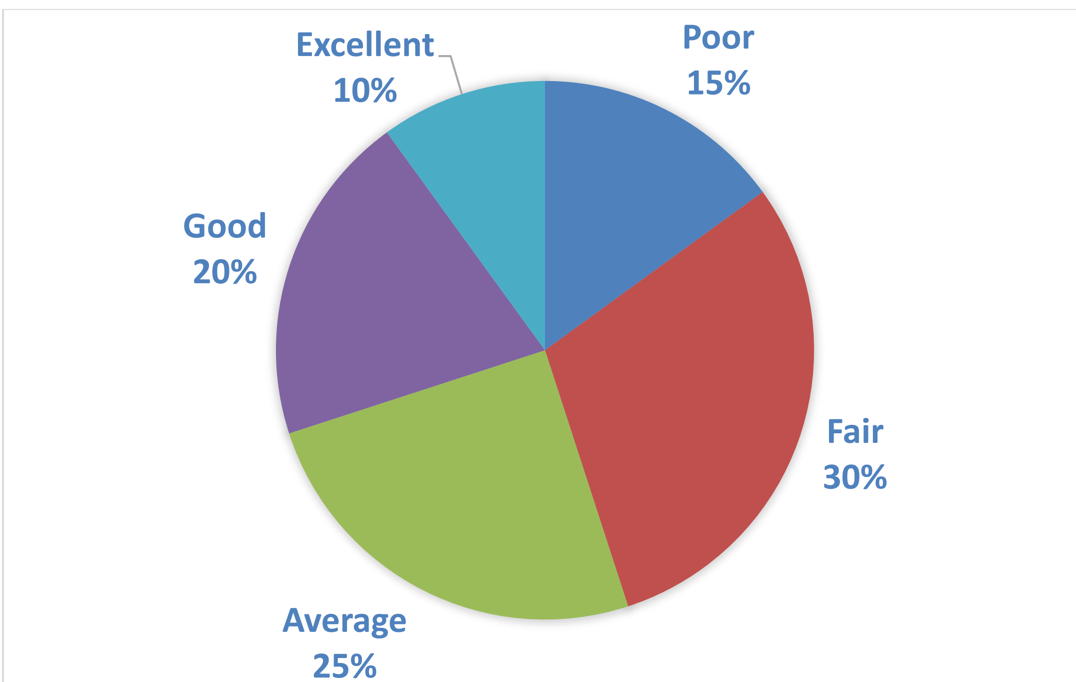


Figure 43. Level of exposure to new technologies in maintenance and management of infrastructure.

5.3.3. Workshop Survey

The main purpose of the workshop is to identify the challenges of railroad industry in terms of developing, training and implementing new technologies for SHM applications. A workshop survey-based study is an effective tool for understanding perspectives from multitude of participants. To contrast and compare the present and future needs for developing technologies for SHM works, workshops can play an important role in putting attention in most pressing issues regarding implementation of technologies for real world applications.

Participants were asked to fill up three surveys in total before and after the workshop. The surveys were handed out in a questionnaire format which asked participants to provide their viewpoints regarding the challenges and opportunities within the railway infrastructure industry.

At the beginning and at the end of the workshop, workshop participants were asked about their level of confidence in introducing new technologies in future infrastructure maintenance and management work. Before the workshop, most participants were somewhat confident to use the new technologies, as shown in Figure 44. More specifically, as much as 18% of the workshop participants were highly confident to introducing new technologies in their daily activities. After the workshop, the participants who were highly confident to use new technologies in maintenance and management of infrastructure doubled, reaching 36% of the responses.

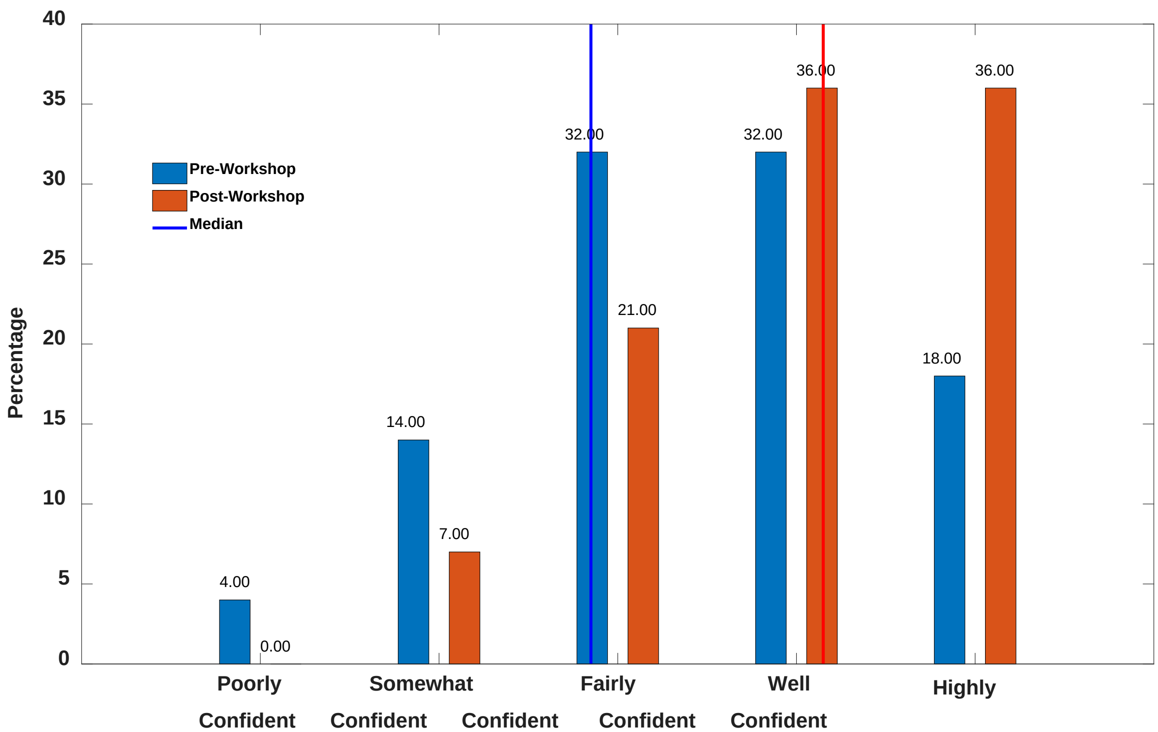


Figure 44. Levels of confidence in using new technologies in future infrastructure maintenance and management work before and after the workshop.

In the workshop, most participants who were familiar with using SHM technologies were well satisfied with what they had. However, there were significant number of participants who believed things could be done better and infrastructure community should invest in research. Figure 45 shows that in general the attendants to the workshop are well satisfied with new technologies.

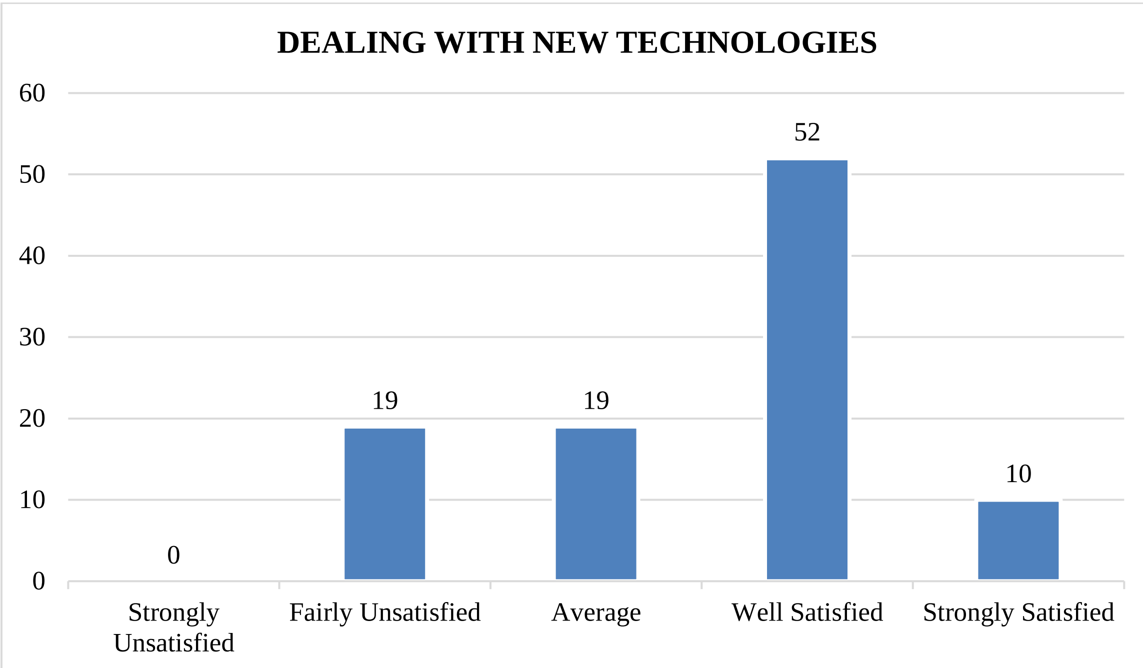


Figure 45. Dealing with new technologies for infrastructure monitoring.

The workshop was conducted with three discussion sessions: (1) Challenges for Infrastructure Management and Maintenance; (2) Challenges for implementing new technologies, sensors, application and algorithms; and (3) Frontiers between future need and technologies. The infrastructure owner and industry professionals had interactive session with academicians and researcher to pin point the need of present and future SHM technologies and tools. The outcome of the sessions was further discussed in a panel review in ASCE Structure Congress at Fort Worth, Texas.

The topics of discussions of the session can be summarized in three figures. These figures were generated based intersection of present challenges categorized on the most frequent keyword iterated by participant in the discussion sessions

The first figure discussed the challenges related to infrastructure management and maintenance (Figure 46). The second figure listed the challenges for implementing new technologies in their normal operations (Figure 47). The last figure listed the frontiers between needs of today and technologies that may be implemented in the future (Figure 48).

In Figure 46, based on the response of participant, it was observed that Technical Challenges and Safety Related Challenges were the most pressing issue for the owners of the infrastructures. They were interlinked with Education/Training and Technological

Advancement, in order to deduce the hierarchy of priority in terms of solving challenges for infrastructure management and maintenance.

Based in Figure 3, railroad operators face safety related challenges as the major problem faced by the industry. The participant believed that, the safety related challenges should be solved by the technological advancement that could be introduced at the site for maintenance and inspection. Education and Training also plays and important part in addressing Technical and Safety related challenges. Researchers and railroad professionals in the workshop stated the current scenario for advancing technology for infrastructure management and maintenance in the railway industry.

For technological advancement, infrastructure owners mentioned remote bridge sensing inspection along with real-time information transferred from the job site to the decision makers were two possible areas where professionals saw significant value for the industry. The ability to inspect inaccessible components of the bridge was also a top research priority of the industry.

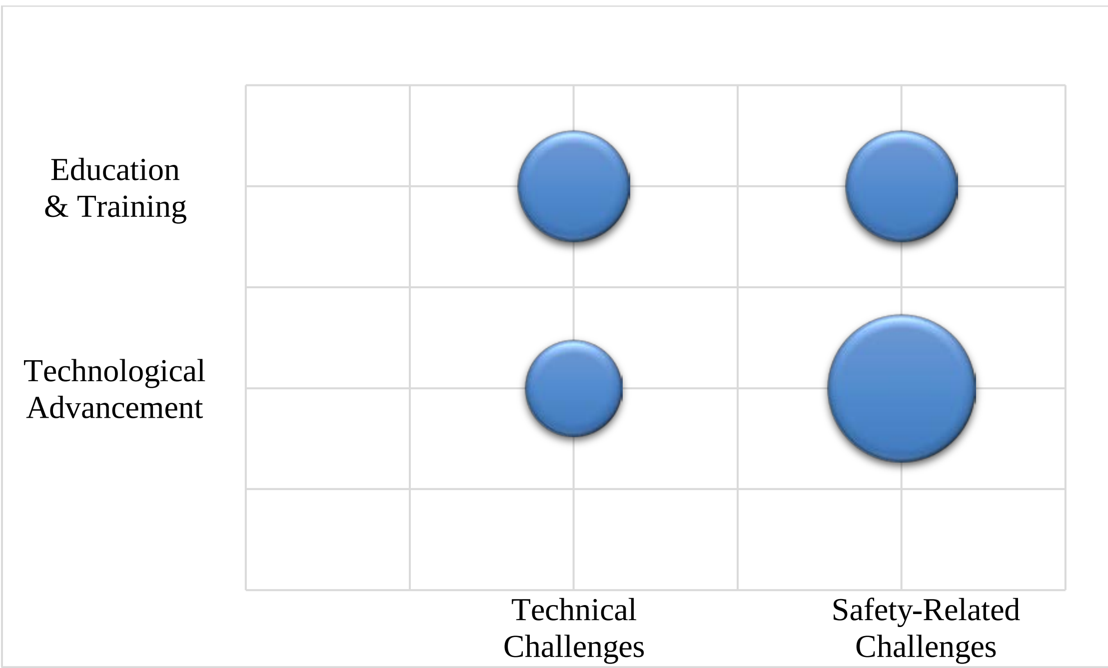


Figure 46. Challenges for infrastructure management and maintenance.

Regarding Figure 47, the participants discussed challenges for implementing new technologies, sensors, algorithms and applications in industry. The participants identified both Data Acquisition and Data Integration as the main challenge faced by industry in terms of implementing new technologies in the areas of sensor, applications and algorithms. Infrastructure Maintenance, Repair and Replacement (MRR) contributed a significant operating expense to the railroad industry. The desirable objective is to reduce the cost of MRR by introducing new innovative technology that is efficient as well as effective in terms of recording data. The technology to be used by the railroad inspectors should be user friendly. For a long-term SHM, self-powered computationally efficient wireless technology is desired by the industry professionals. Automatic field quantification was also pointed out as a challenge to be solved by the researcher. This would minimize the downtime to obtain results from the collected data, giving more power to the owners to take prompt action.

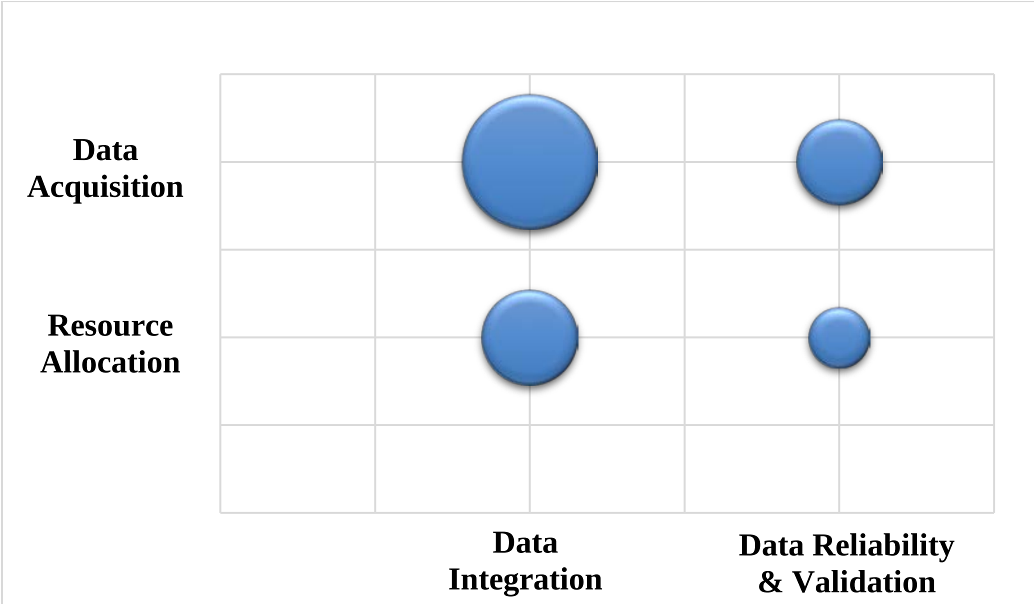


Figure 47. Challenges for implementing new technologies, sensor, applications and algorithms.

Regarding Figure 48, the results identify in which areas Problem Identification, Problem Solving and Implementation would be most useful: human level, system level, or automatization. Based on the response of workshop participants, inspector was best suited to solve the existing implementation issues regarding the future technologies. The implementation part is where sensors are attached to the structures and secured for data collections. On the contrary, participants believed that Automation and Artificial Intelligence (AI) was suitable to solve identification problems. Image processing, computer vision, pattern recognition and machine learning were some of the topics that were discussed under AI that could bring value to MRR related challenges.

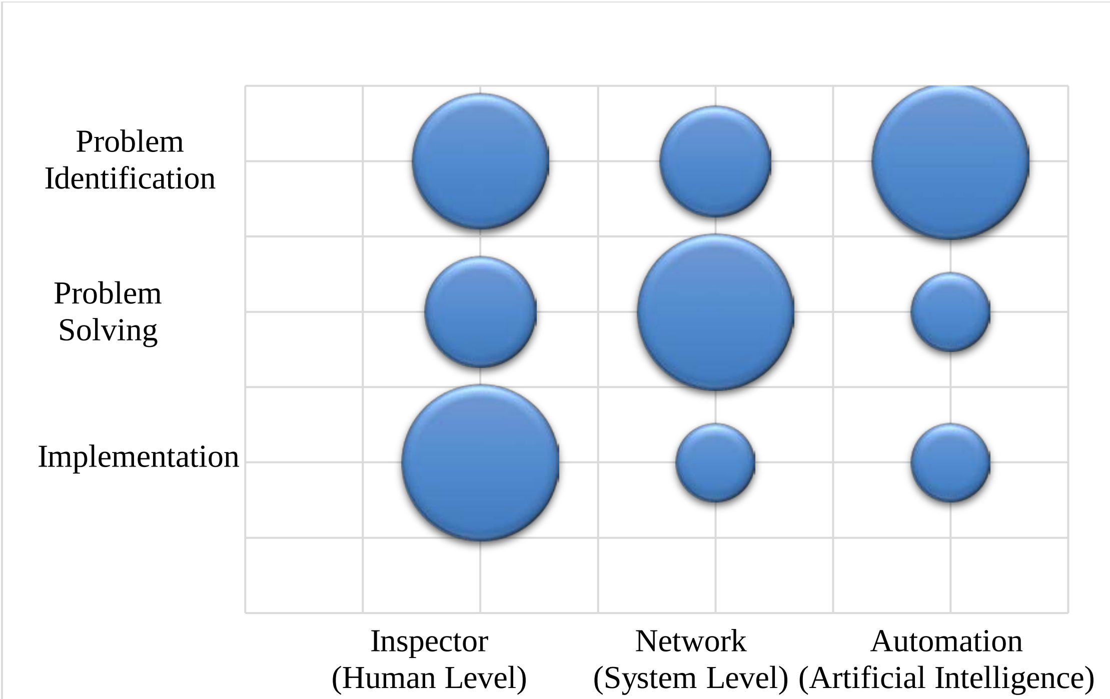


Figure 48. Frontiers between future needs and technologies.

5.3.4. Conclusion and Application to Transportation Infrastructure

General feedback form was also provided to the participants to review the conclusions and responses from the participants at the end of the workshop. In conclusion, the topics presented described the railroad owner's perspective about infrastructure monitoring. Additionally, the method chosen to explore the railroad owner's perspective on new technologies were also beneficial in informing new applications and opportunities of interest to researchers in SHM and new technologies. The results of this workshop are applicable to other transportation methods such as highways. For the implementation phase researchers will conduct a similar interview/discussion with the NMDOT bridge group. The participation from bridge inspectors and other DOT staff in this 2nd workshop will be more specific to DOT needs.

5.4. Other Findings/Outcomes

5.4.1. International Collaborations

The following sections describe some additional results that align with the objectives of this project. The support from other agencies enabled to expand the results from the former three sections to other laboratories and forums, supporting a higher visibility of the accomplishments of this research. The support from external agencies to share the development of new technologies overseas proves the value and interest of these technologies for infrastructure maintenance.

Chinese Earthquake Administration: Testing AR in the context of inspections of transportation infrastructure disasters and developing a proof of concept that can be understood by infrastructure owners. In collaboration with the Chinese Earthquake Administration (CEA) and the director of their laboratory in Beijing Professor Tao Wang, Professor Moreu conducted multiple experiments with new technologies to test the ability of low-cost sensors to inform in the post-disaster scenario. Multiple damages were conducted in the laboratory and different sensing strategies were carried out to measure the damages: AR, silicon retina, and displacements collected during the damage. The testing and development of AR (Figure 49-51) was in the context of critical transportation disruption in collaboration with railroads and engineering mechanics institute in the CEA, (Beijing, China, November and December 2017)

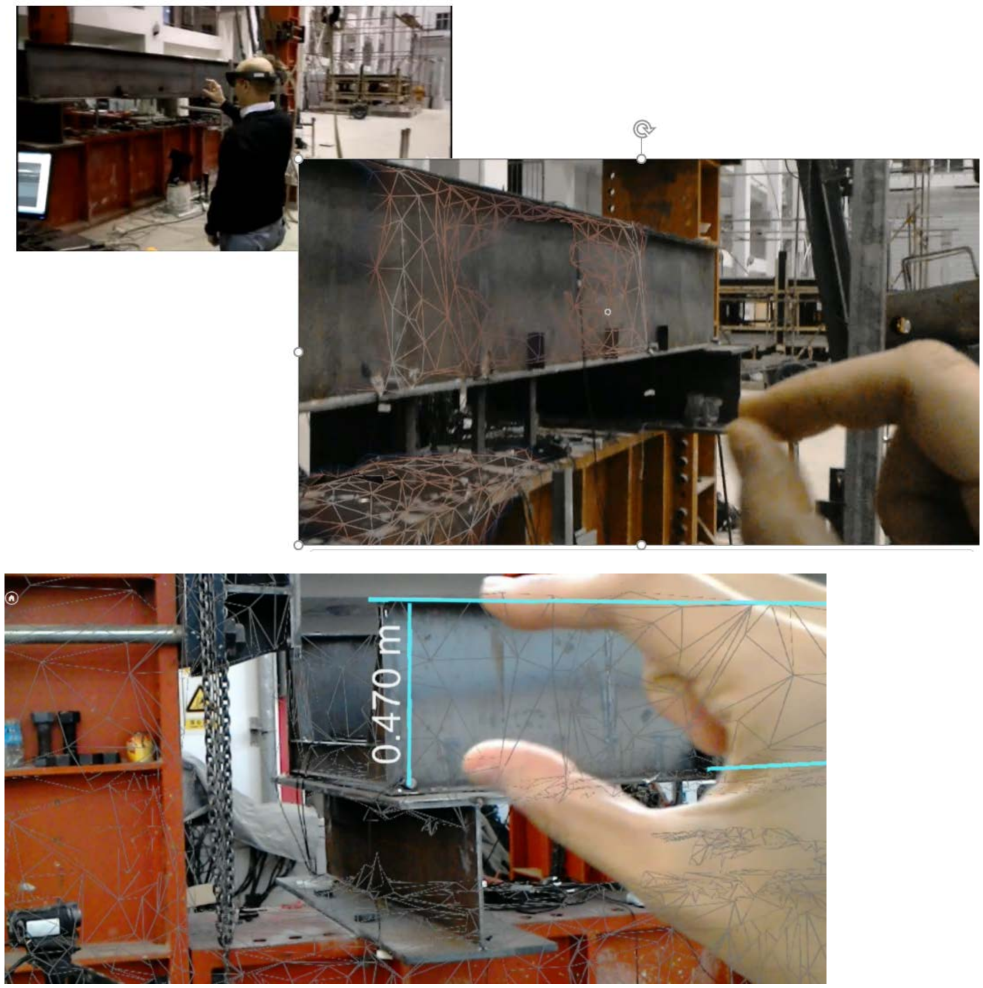


Figure 49. AR for critical transportation infrastructure inspection.

Figure 50. Testing of bridge damage in Chinese Earthquake Administration.

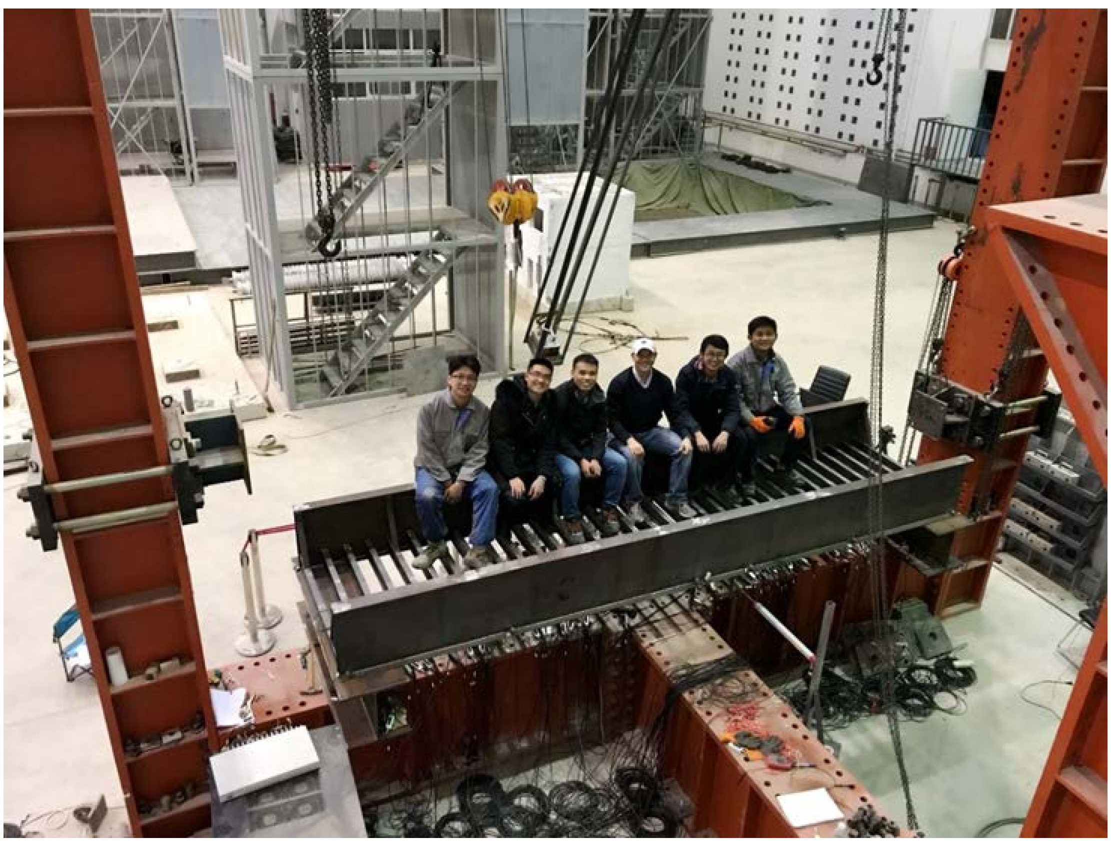


Figure 51. Bridge damage testing with AR at the Chinese Earthquake Administration (November 2017).

Dr. Sungmoon Jung visits UNM: In collaboration with the outreach and exposure of graduate students to different programs and activities, different guests were invited to provide seminars during the school year. Dr. Jung visited UNM on January 26, 2018. Dr. Jung talked about emerging technologies in wind impact mitigations. He introduced to the piezoelectric sensors attached to structures which can adapt to the intensity of wind. He also described new materials used in developing impact mitigation for vehicle collision (Figure 52).

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Visiting Professor from Joint College of Engineering Visits UNM

February 1, 2018

Professor Sungmoon Jung from the Joint College of Engineering of Florida A&M University and Florida State University is visiting UNM this month to discuss research, collaborations, and ideas for a safer infrastructure. Professor Sungmoon Jung is an associate professor at a joint college of engineering of Florida A&M University and Florida State University, department of civil and environmental engineering. Before joining the college, he worked for Caterpillar (2006-08) after receiving his Ph.D. from the University of Illinois at Urbana-Champaign (2004). His research interests include wind engineering, wind energy, and vehicle safety. He is visiting SMILab in a sabbatical leave at the department of civil engineering. He gave a seminar at the EERI student chapter on Friday January entitled "Mitigation of Wind and Impact Effects on Structures."

Figure 52. Sabbatical visit from Dr. Jung at UNM.

Visiting Scholar from Ecuador: During 2017, external international students participated in the research tasks, including undergraduate student from ESPE, Quito, Ecuador, Ronny Moreno, who stayed for 9 weeks studying low-cost sensors for earthquake monitoring.

International Presentations: Dr. Ali Ozdagli presented using low-cost sensors to measure vibrations under earthquakes and heavy train crossings at the international conference for young researchers in earthquake engineering at the University of Illinois at Urbana-Champaign (third Huixian conference) (Figure 53) (August 2017).

Other International Venues: Other international visitors were invited during the year to collaborate with the introduction of students at all levels to other research and educational programs, as well as to enrich their exposure to new technologies. Numerous links have been provided to Tran-SET summarizing those exchanges prior to the implementation phase.

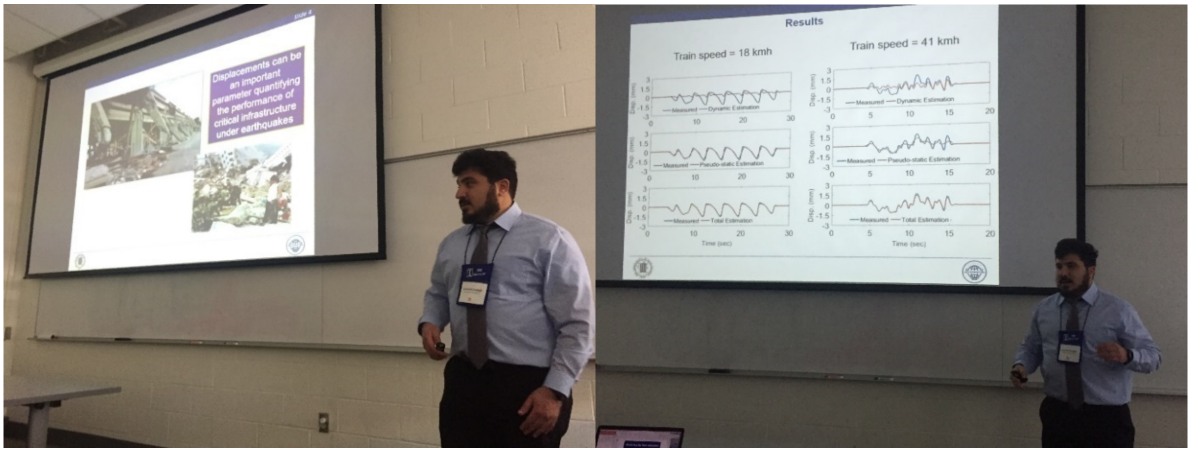

Figure 53. Presentation of low-cost sensors to collect train crossing and earthquakes responses (Illinois, August 2017).

6. CONCLUSIONS

The completion of one year on the project "Development, Training, Education, and Implementation of Low-Cost Sensing Technologies for Bridge Structural Health Monitoring (SHM)" has exceeded the objectives of testing, developing, and implementing low-cost sensors that can be used by different sectors of the transportation industry for collecting data of interest (i.e. displacements under vibrations) to prioritize their decisions in the field. Multiple journal papers have been produced, as well as presentations in national and international conferences, including the first Tran-SET conference in New Orleans in April 3-4 2018. The summary of the results from this work can be listed in the following points:

- High school students demonstrated that their interest in low-cost sensors and technology increased after building sensors and using them in structures. The hands-on experience increased their interest in transportation careers;
- Undergraduate students were exposed to the design and construction of low-cost sensors and were able to use them in multiple settings: shake table, rockets, and Tramway;
- For the first time, a graduate course in structural dynamics included a homework consisting on building a low-cost sensor in 30 minutes, and using it outdoors to collect vibrations and obtain the natural frequency;
- A post-doctoral student was able to develop a near-industry applicable wireless sensor for under $100 that can collect reference-free displacements.
- Different faculty collaborated in mentoring students from high schoolers to graduate students in the fabrication of sensors;
- UAS and lasers were integrated to obtain reference-free displacements and high school students were engaged in such activities, exposing them to new technologies that can be used for management and maintenance prioritization in transportation infrastructure;
- AR has been very effective in attracting students and industry to new technologies that can transform the methods we inspect and maintain transportation infrastructure. From middle school to graduate education, faculty, and industry, AR has attracted the interest towards inspection of structures before and after damages;
- International collaborations have demonstrated the interest of this research by external institutions, faculty, and educational programs;
- Industry has demonstrated their interest in low-cost sensors due to the fact that they can obtain similar information than conventional sensors for less cost;
- A special short course on low-cost sensors to industry demonstrated the high interest by professionals to learn how to build and use low-cost sensors that they can choose to apply later on their specific areas of interest; and
- In the future, low-cost sensors will become a normal tool for civil engineering professionals. Including this component as part of the curriculum benefitted the class on structural dynamics on Spring 2018. Students are now familiar with sensing technology.

This project aligns with the ASCE 2025 Vision for the civil engineer of the future, who will be relying on the use of sensors and data to inform their decisions.

7. RECOMMENDATIONS

Based on the results and the conclusions of this project, field implementation on different infrastructure projects of low-cost sensors could enhance the value of low-cost sensors for infrastructure management and maintenance prioritization. The very low cost can be an attractive feature for their implementation in the field and the use of the data for collecting data of interest of railroad bridges, specifically, displacements under railroad crossings over the bridge.

The authors of this project recommend the training of large amounts of professionals and industry decision-makers in low-cost technologies as well as identifying areas of interest where to use and implement remote sensing, AR, and drone technology to inform their decisions. The authors recommend conducting a larger workshop that engages all DOTs to list the parameters that they would like to sense or measure so new technologies can be developed to measure those for them. Finally, the authors of this study encourage civil engineering programs to include sensing and data processing training to students in their graduate courses, with the possibility that undergraduate students can also attend those courses.

Finally, the authors of this report recommend that there is a larger investment in objective inspection and field assessment of infrastructure to better prioritize the repairs, replacements, and maintenance decisions based on objective data collected in the field.

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APPENDIX 1: PRE-WORKSHOP SURVEY

Pre-Workshop Survey

Infrastructure Management and Maintenance Using New Technologies

1. Which of the following best describes your profession associated with industry?

   ☐ Academia/ Researcher ☐ Industry Professional ☐ Infrastructure owner ☐ Government Regulator ☐ Student

2. In your day to day decisions in bridge management and maintenance, how often do you use new technologies?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

3. How confident are you with using new technologies in bridge management and maintenance?
   (Lowest 1 to Highest 5)

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

4. Why? Why not?
5. How satisfied were you dealing with robots, UASs, Machine Learning, DIC, virtual Tele-presence, Remote sensing?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

6. Why? Why not?

7. For a bridge inspector professional at the job site, how helpful can new technology be to assess the state of infrastructure?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

8. What are the current needs that are unmet by available technologies that you would like to see developed further by researchers?

9. What are the tasks and/or operations that you would see benefiting the most from new technologies in the area of infrastructure management and maintenance?

10. What do you expect to learn from this workshop?

APPENDIX 2: POST-WORKSHOP SURVEY

Tran-SET

Post-Workshop Survey

smilab
Smart Management
Infrastructure Laboratory
THE UNIVERSITY OF NEW MEXICO

Infrastructure Management and Maintenance Using New Technologies

1. Which of the following best describes your profession associated with railroad industry?

   ☐ Academia/ Researcher ☐ Industry Professional ☐ Infrastructure owner ☐ Government Regulator ☐ Student

2. How helpful/useful did you find this workshop? Did it meet your expectations? (Lowest 1 to Highest 5)

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

3. Why? Why not?

4. Will you be interested in attending similar workshops in future? (Lowest 1 to Highest 5)

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

5. You can list the name of the event, society, organization that you benefit most from attending.

6. How comfortable are you introducing new technologies in your future work for infrastructure monitoring and maintenance work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

7. How optimistic are you with current research being conducted in new technologies for infrastructure monitoring and maintenance work?

   ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

8. In your opinion, what kind of technologies related to infrastructure management would be beneficial for Bridge Inspector? List any.

9. Do you prefer inspection-centered technologies, or rather system-centered technologies (management)?

10. What would you recommend should become an alternative/complementary approach to discuss “Infrastructure Management and Maintenance Using New Technologies”?

APPENDIX 3: WORKSHOP SURVEY FEEDBACK

Feedback

Infrastructure Management and Maintenance Using New Technologies

1. What kind of topics relating to infrastructure monitoring and sensor technologies would you like to know more about in future workshops and seminar?

2. In 5 to 10 years what technological advancement in the field of structural monitoring would you like to see in railway and highway bridge monitoring?

3. What suggestions do you have for workshop organizers?

4. What do you think about the duration of the workshop? What would you suggest for future workshops?

5. Do you think the topics were too technical?

6. Would you have liked to have more networking opportunities in the future?

7. What did you miss in this workshop that would have benefit?

APPENDIX 4: WORKSHOP PARTICIPANTS

Table 3. List of participants in the workshop.

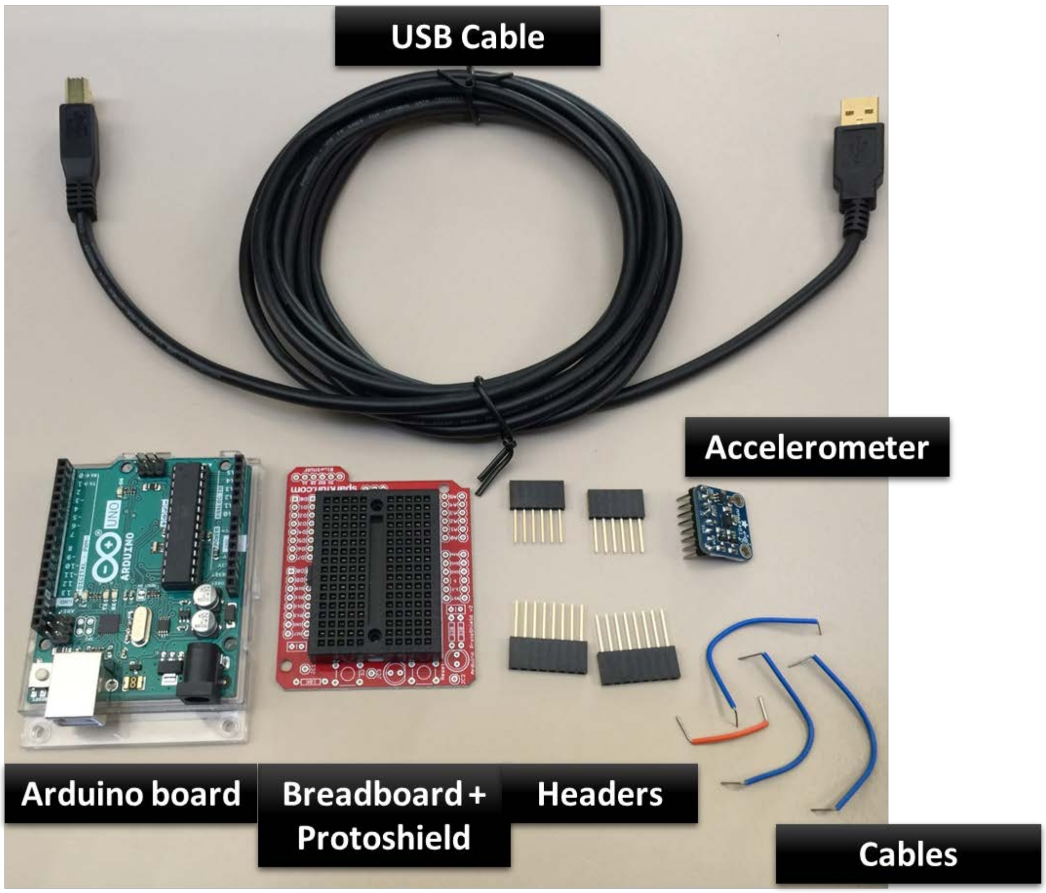
Last Name	Name	Title	Organization
Agüero	Marlon	Master Student in Civil Engineering	University of New Mexico
Alsuhaibani	Eyad	Ph.D. Student	University of Texas at Arlington
Bleser	Walt	President	Sensr
Boraas	Roger	Chief Engineer, Bridge & Structures Division	Federal Railroad Administration
Catbas	Necati	Professor	Univ. of Central Florida
Chao	Sun	Assistant Professor	Louisiana State University
Choe	Doeun	Assistant Professor	Prairie View A&M University
Dhanwani	Kapil	Student	The University of Texas at Arlington
Gul	Mustafa	Assoc. Prof.	University of Alberta
Halling	Marv	Professor	Utah State University
Ham	Suyun	Assistant Professor	University of Texas at Arlington
Kang	Sang-goo	Ph.D. student	University of Texas at Arlington
Kohankar	Zahra	Ph.D. student	The University of Texas at Arlington
Maharjan	Dilendra	Master Student in Civil Engineering	University of New Mexico
Martindale	Todd	Director Bridge Maintenance	Union Pacific Railroad
Mirsayar	Mirmilad	Postdoctoral Research Associate	Texas A&M University
Moreu	Fernando	Assistant Professor	University of New Mexico
Nice	Kaneza	Graduate Research Assistant	The University of Texas at Arlington
Orsak	John	Sr. Engineer	Sensr
Otter	Duane	Scientist - Corporate Research	Association of American Railroads Transportation Technology Center, Inc.
Scola	Sandro	Assistant Chief Engineer Structures	Canadian National Railway
Tehrani	Amin	Ph.D. Student	University of Texas at Arlington
Williams	Steven	Sr. Manager Bridge Inspection	Union Pacific Railroad
Xuelin	Wang	Graduate Research Assistant	The University of Texas at Arlington
Zeinali	Yasha	PhD. Candidate	Southern Methodist University

APPENDIX 5: LOW-COST SENSOR INSTRUCTIONS

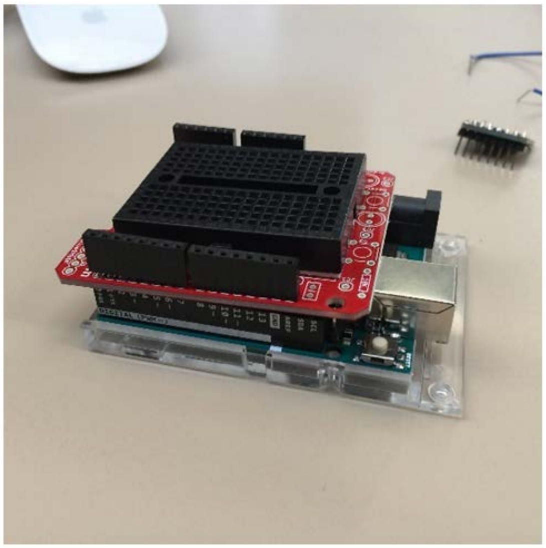
Build your own sensor with Arduino at Classroom

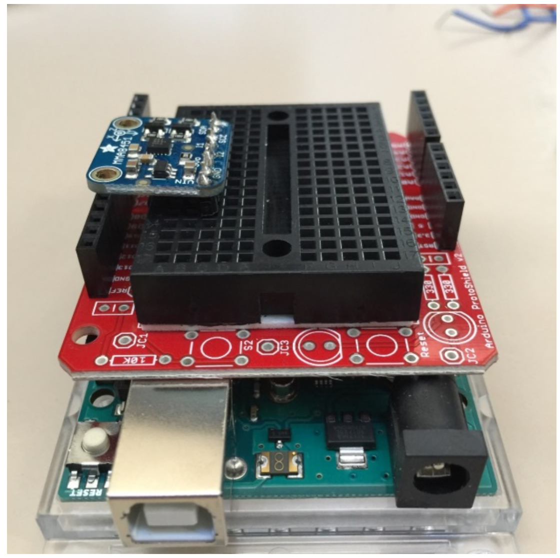
Hardware

1. Open the box to **check the stuff inside**: Arduino board, Bread board, Proto Shield, Accelerometer, Headers, Jumper Cables, USB Cable.

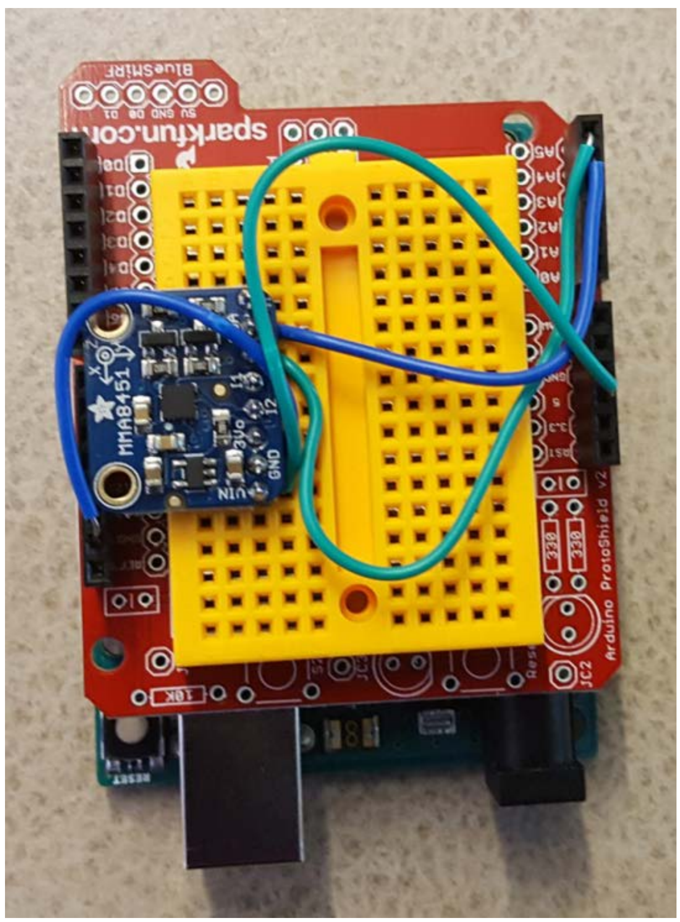


2. (1) **Gluing the breadboard on Proto Shield**, (2) **Insert the four headers** to connect the Proto Shield to the Arduino board (3) **Insert the Accelerometer** to the breadboard (along the longitudinal direction).





3. (4) Connect **Vin** to **5V** with one cable (5) Connect **GND** to common power/data ground with one cable (6) Connect **SCL** to **A5** (7) Connect **SDA** to **A4.**



4. (8) Connect to the **USB cable** and put your own sensor **in the box.**

You are done with the Hardware. Congratulations!!! Next step is Software

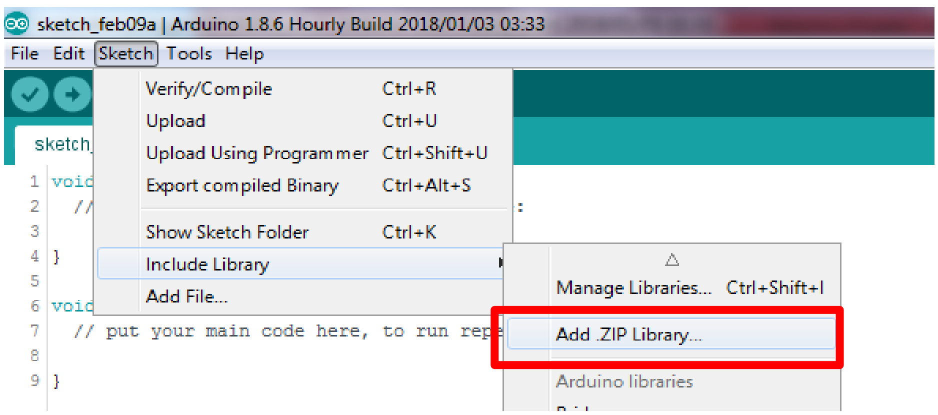
Software

1. Download the ***Arduino IDE Windows installer*** or ***Mac OS X***.

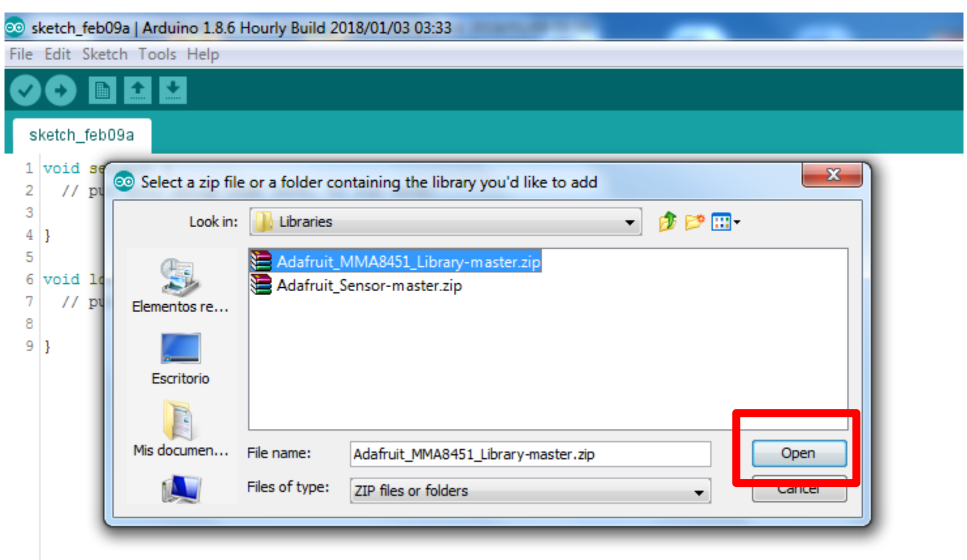
2. **Install** the software on your laptop step by step, using the default install option.

3. Go to page and click on Ardunio code on the left hand side of the screen and download ***Adafruit MMA8451 Library*** and ***Adafruit_Sensor Library***.

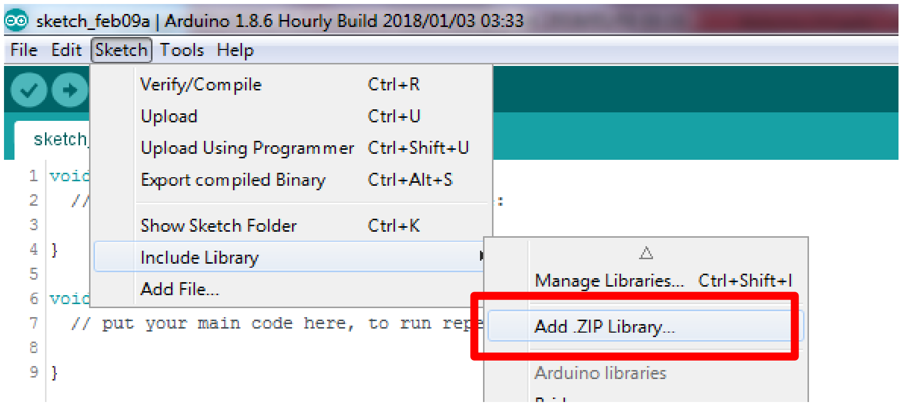
4. Open the Arduino IDE and include the ***Adafruit_MMA8451_Library-master.zip*** library to the software: Under Sketch> Include Library > Add .Zip Library…



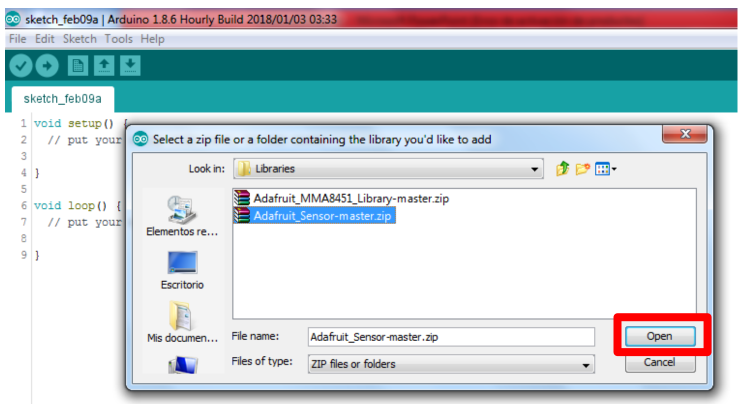
Find the library where you downloaded it.
Select ***Adafruit_MMA8451_Library-master.zip***, click in Open.



5. Include the ***Adafruit_Sensor-master.zip*** library to the software: Under Sketch> Include Library > Add .Zip Library…



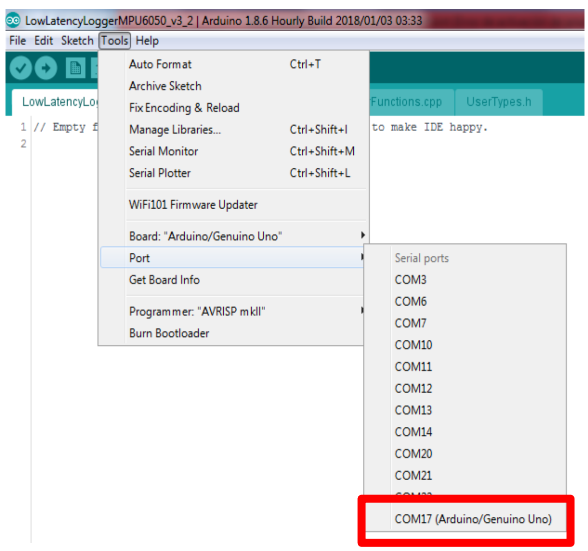
Find the library where you downloaded it.
Select ***Adafruit_Sensor-master.zip***, click in Open.



Restart Arduino app.

6. Plug your Arduino with the USB cable in your computer.

7. Make sure right **COM port** is selected under Tools>>Port.



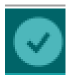
Data Collection and display with Arduino & Matlab

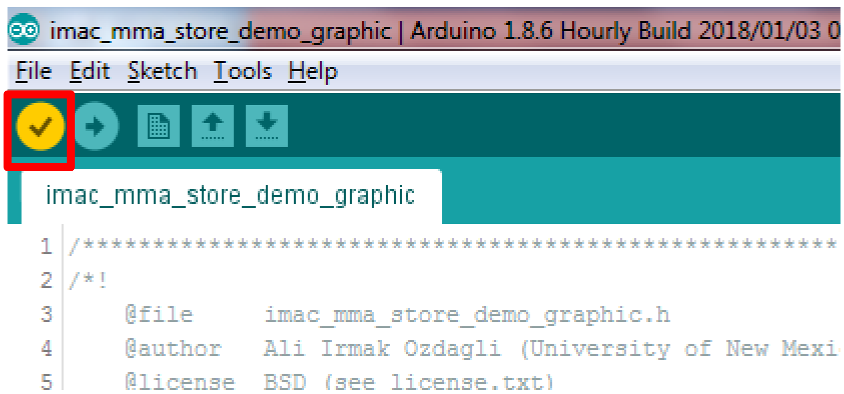
- ❑ Here the tutor will send out the Arduino files and Matlab File by email or USB.
    - ***imac_mma_store_demo.ino*** for data visualization.
    - ***imac_mma_store_demo_graphic.ino*** for real time history.
    - ***example.m***

Data Acquisition – Graphic Mode

A. Plug your Arduino with USB in your computer.

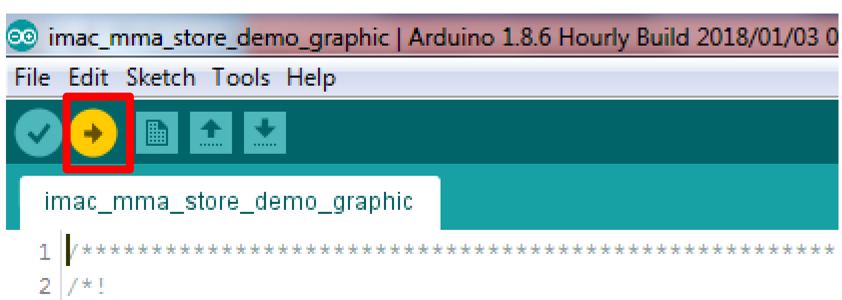
B. Open the ***imac_mma_store_demo_graphic.ino*** code.

C. Click in **Verify** 



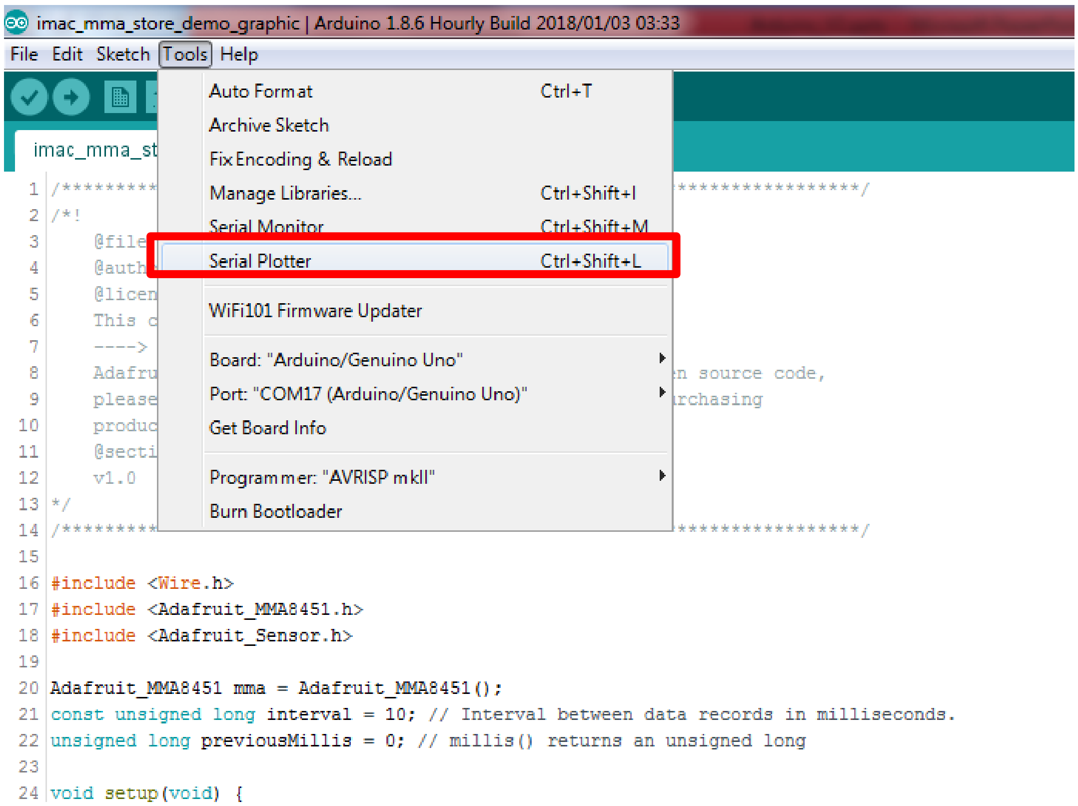
You will receive the following message.

D. Click in **Upload**  the code.

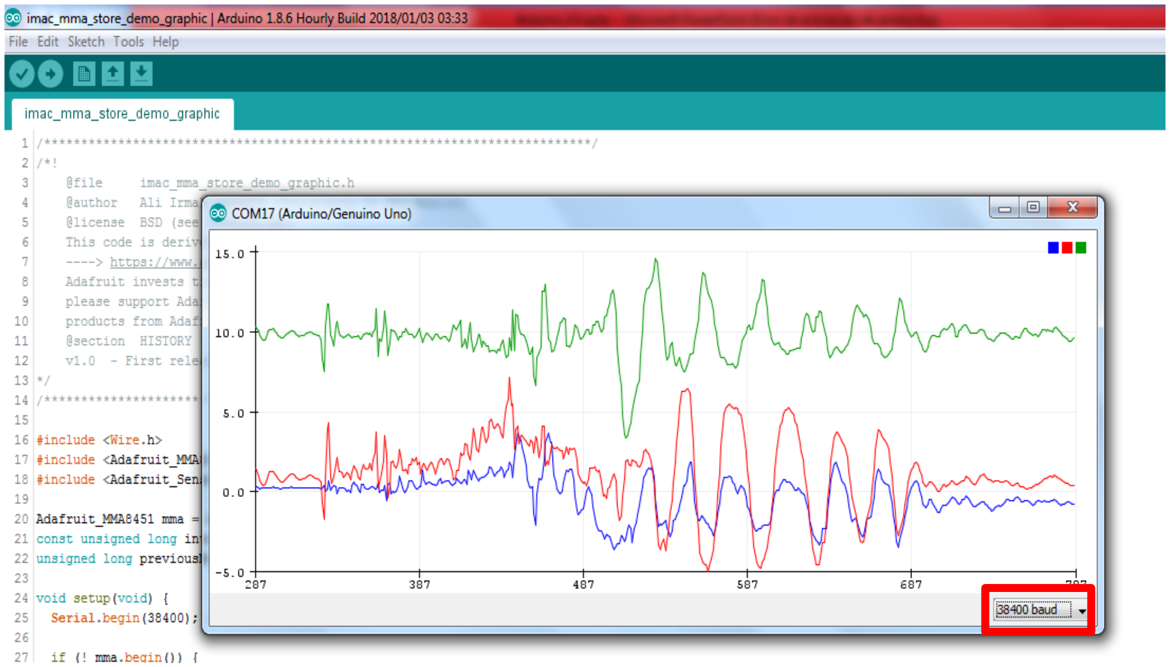


You will receive the following message.

E. Select **Serial Plotter** under Tools>>Serial Plotter



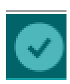
F. Select **38400 baud** from the drop-down list. You can start seeing the plot scrolling.

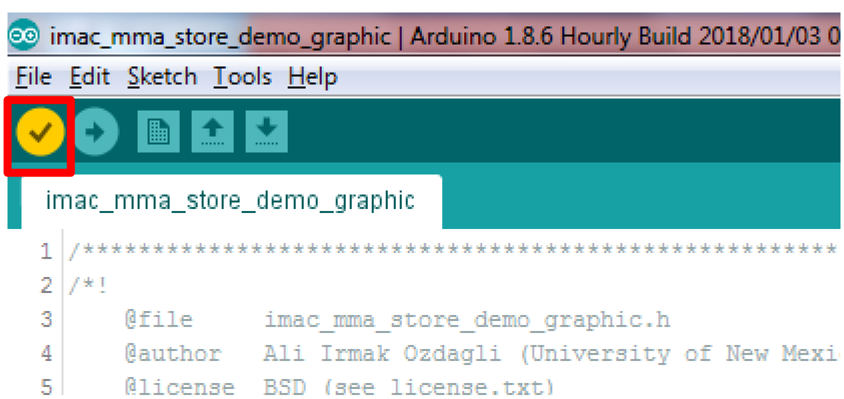


Data Acquisition – Monitor Mode

A. Plug your Arduino with USB in your computer.

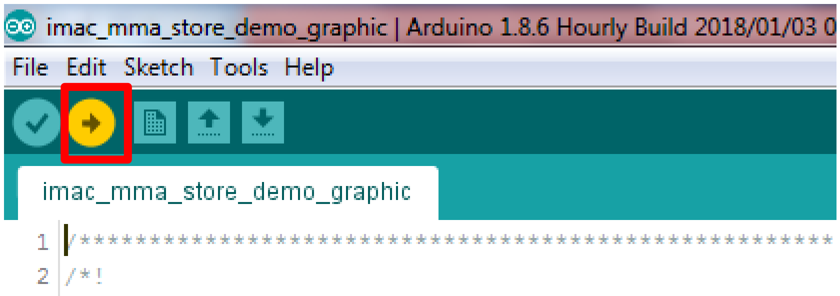
B. Open the ***imac_mma_store_demo.ino*** code.

C. Click in **Verify** 



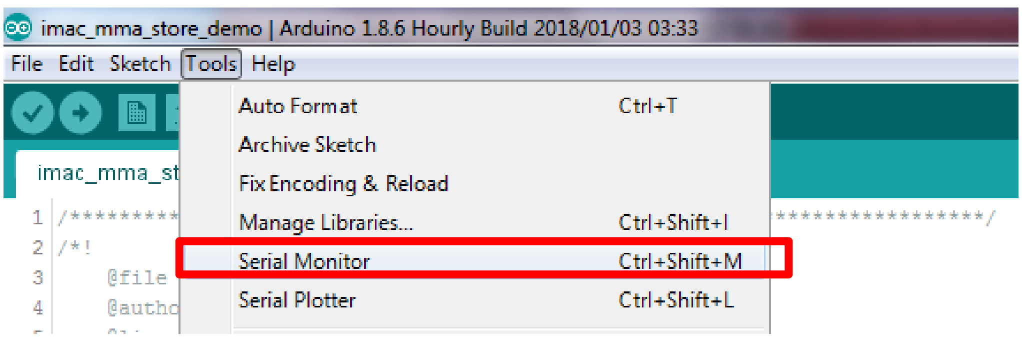
You will receive the following message

D. Click in **Upload**  the code

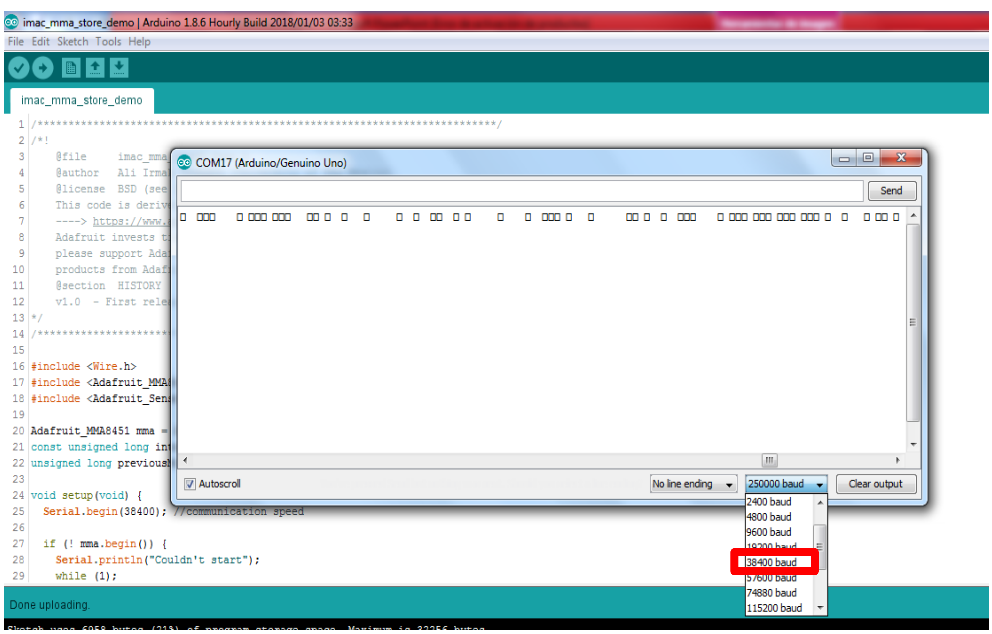


You will receive the following message.

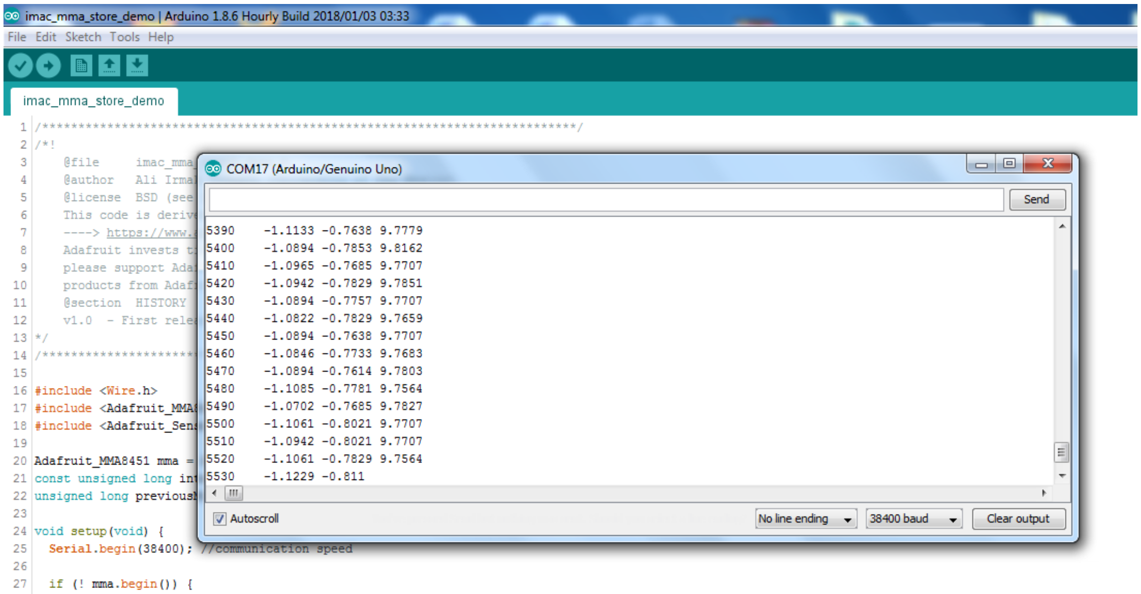
E. Select **Serial Monitor** under Tools>>Serial Monitor



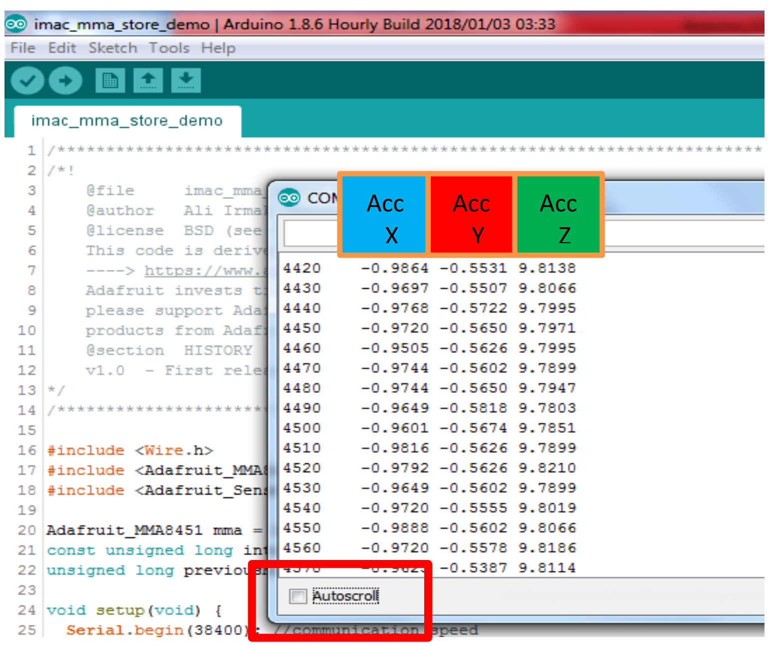
F. Select **38400 baud** from the drop-down list.



You can start seeing the data scrolling.

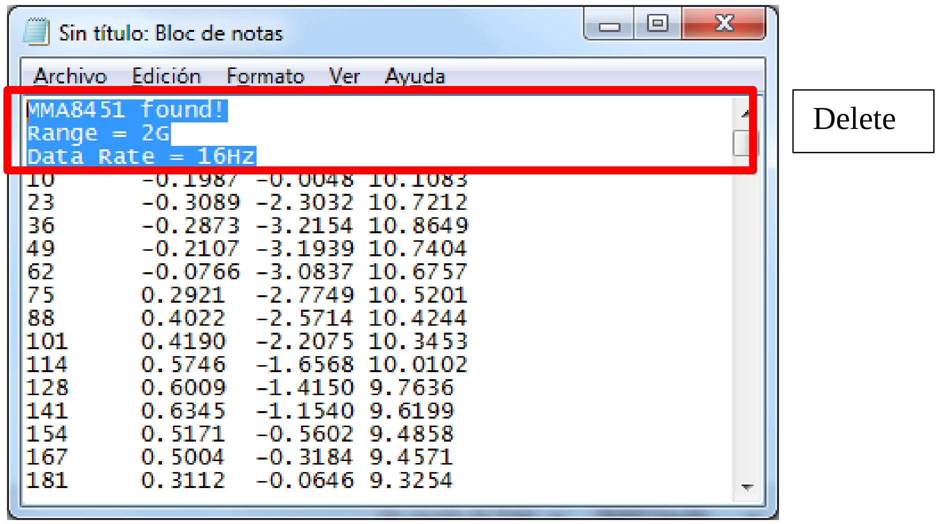


G. In order to stop data collecting, **disconnect** the Arduino from the computer and uncheck **Auto scroll**.

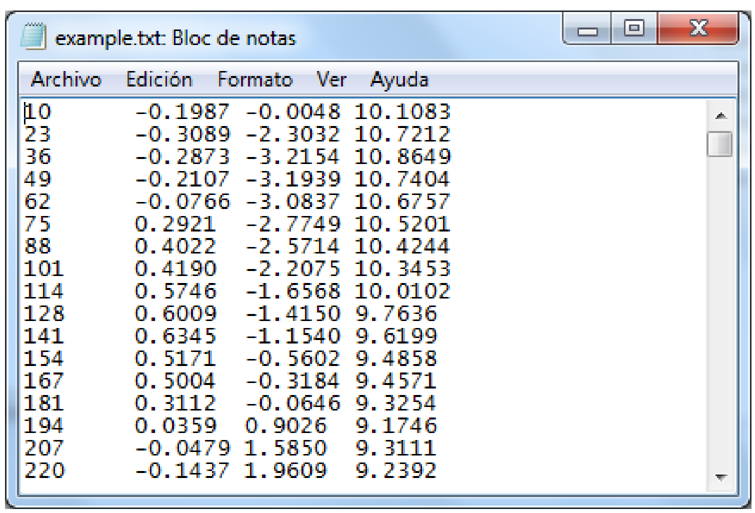


Save Data Processing

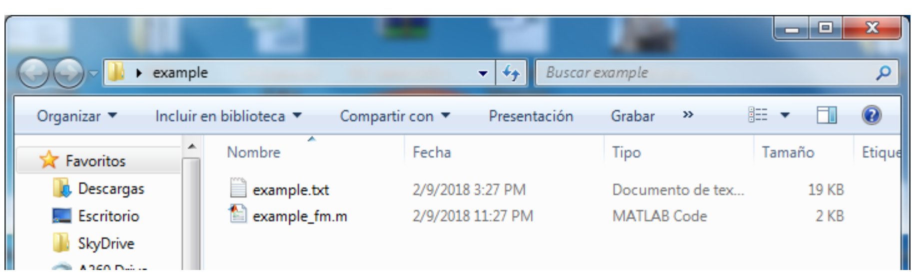
H. Click the surface of software, **control/command + A** to choose all, **control/command + C** to copy, open **Notepad** on your computer and control/command + V to paste. (Remember to delete first several lines after pasting since there are some useless data at first)



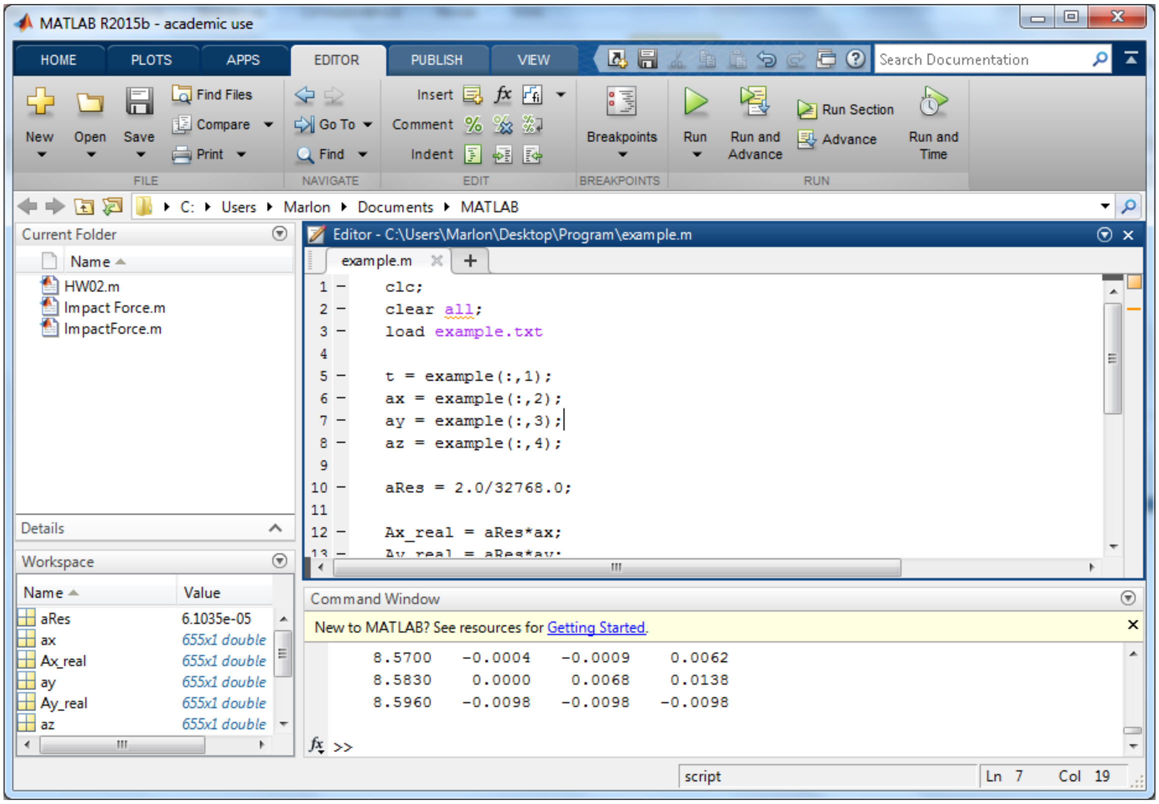
I. Save the File – ***example.txt***



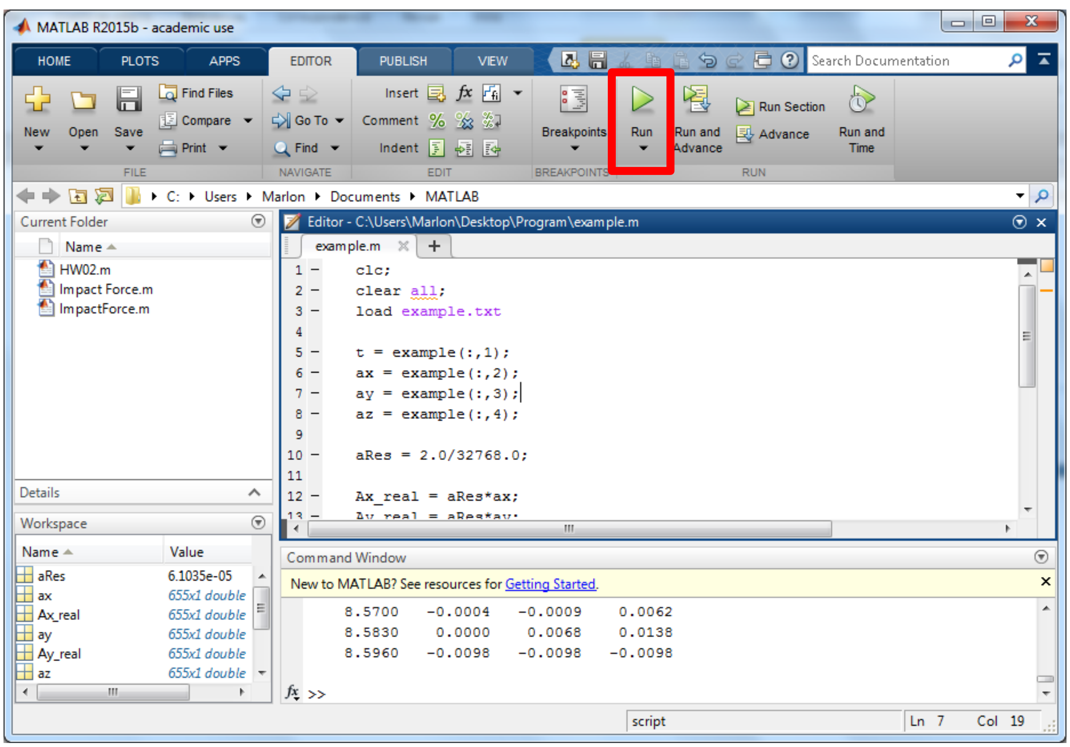
J. Create a folder called **example** and put there the files ***example.txt*** and ***example_fm.m***



K. Open the Matlab file – ***example_fm.m***

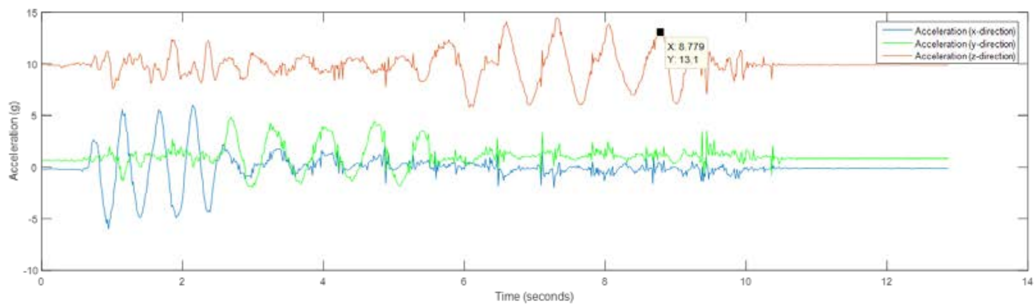


L. Click in **Run**

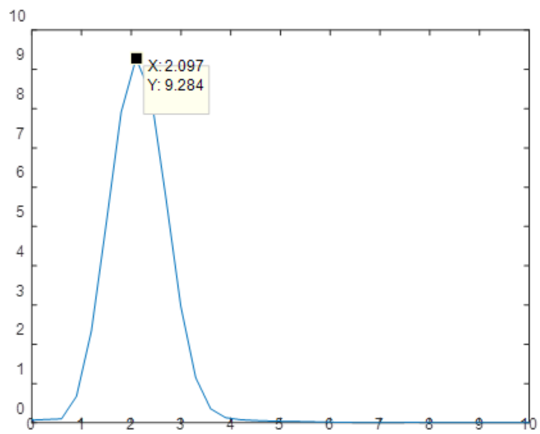


M. This is the final result:

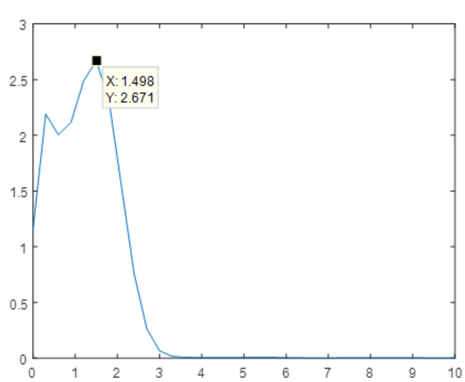
Accelerations:



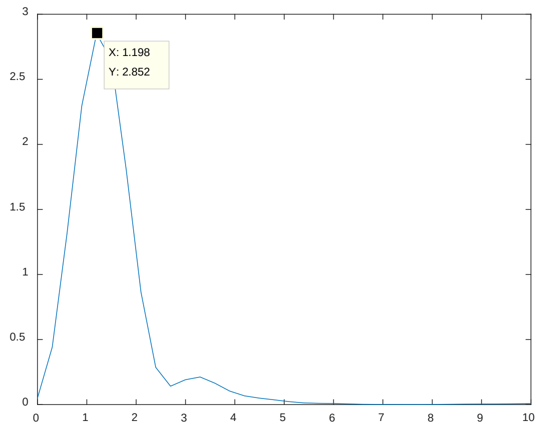
Frequency acceleration x:



Frequency acceleration y:



Frequency acceleration z:



Reference 1, **Reference 2**