Southern Plains Transportation Center
CYCLE 1

# FINAL REPORT

2023–2024

USDOT BIL Regional UTC
Region 6

---

# Increasing Understanding for Weather Emergencies and Enhancing Safety of Different Communities using Wireless Smart Sensors and Human-Environment-Data Interfaces using Augmented Reality (AR)

Southern Plains
Transportation Center

# Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

# Technical Report Documentation Page

<table>
<tr><td colspan="2">1. Report No.<br>CY1-UNM-01</td><td colspan="2">2. Government Accession No.<br>[Leave blank]</td><td colspan="2">3. Recipient's Catalog No.<br>[Leave blank]</td></tr>
<tr><td colspan="4" rowspan="2">4. Title and Subtitle<br>Increasing Understanding for Weather Emergencies and Enhancing Safety of Different Communities using Wireless Smart Sensors and Human-Environment-Data Interfaces using Augmented Reality (AR)</td><td colspan="2">5. Report Date<br>January 27, 2025</td></tr>
<tr><td colspan="2">6. Performing Organization Code<br>CY1-UNM</td></tr>
<tr><td colspan="4">7. Author(s)<br>Dr. Fernando Moreu, https://orcid.org/0000-0002-7105-7843<br>Dr. Su Zhang, https://orcid.org/0000-0002-0396-2518<br>Dr. Kaveh Malek https://orcid.org/0000-0001-9009-2540<br>Ali Mohammadkhorasani, https://orcid.org/0000-0003-3442-8315<br>Mahsa Sanei, https://orcid.org/0000-0002-8373-8806<br>Piedad Miranda, https://orcid.org/0009-0006-8591-0856</td><td colspan="2">8. Performing Organization Report No.<br>R1.1</td></tr>
<tr><td colspan="4" rowspan="2">9. Performing Organization Name and Address<br>University of New Mexico<br>1155 University Blvd SE, Albuquerque, NM 87106</td><td colspan="2">10. Work Unit No. (TRAIS)<br>[Leave blank]</td></tr>
<tr><td colspan="2">11. Contract or Grant No.<br>69A3552348306</td></tr>
<tr><td colspan="4" rowspan="2">12. Sponsoring Agency Name and Address<br>Southern Plains Transportation Center<br>202 West Boyd St., Room 213B<br>The University of Oklahoma<br>Norman, OK 73019</td><td colspan="2">13. Type of Report and Period Covered<br>Final Report (October 2023 – January 2025)</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code<br>[Leave blank]</td></tr>
<tr><td colspan="6">15. Supplementary Notes<br>Conducted in cooperation with the U.S. Department of Transportation as a part of University Transportation Center (UTC) program.</td></tr>
<tr><td colspan="6">16. Abstract<br>This project developed a cost-effective, scalable system integrating Low-cost Efficient Wireless Intelligent Sensors (LEWIS) and augmented reality (AR) to improve disaster preparedness and weather/condition monitoring in different communities. The system was designed to measure rainfall and flooding during significant post-wildfire flood events and provide early alerts to enhance safety and decision-making. Deployed by the Smart Management of Infrastructure Laboratory (SMILab) at the University of New Mexico and validated with High Water Mark LLC, the LEWIS sensors were portable, energy-efficient, and capable of transmitting real-time data via hotspots. They featured solar power with sleep mode functionality, reducing energy consumption by 70%, and were robustly tested in indoor simulations and outdoor deployments in flood-prone areas like Sandia East Mountains and Tinker Town, New Mexico. The project also integrated AR visualization, enabling immersive, real-time displays of rainfall and flood conditions, which were tested and refined through workshops with experts and emergency managers. Community feedback influenced the design of key AR features, such as customizable thresholds, color-coded flooding indicators, and enhanced user interfaces tailored for various settings. The AR platform supported training scenarios and improved decision-making by simulating weather/condition hazards in a risk-free, interactive scenario. This research demonstrated the transformative potential of integrating low-cost sensors with AR technology to enhance disaster preparedness, promote resilience, and address critical challenges in monitoring and emergency response for different communities.</td></tr>
<tr><td colspan="3">17. Key Words<br>Low-cost sensors, augmented reality (AR), disaster preparedness, flood monitoring, community engagement.</td><td colspan="3">18. Distribution Statement<br>No restrictions. This publication is available at www.sptc.org and from the NTIS.</td></tr>
<tr><td colspan="2">19. Security Classification (of this report)<br>Unclassified</td><td colspan="2">20. Security Classification (of this page)<br>Unclassified</td><td>21. No. of Pages<br>63</td><td>22. Price<br>N/A</td></tr>
</table>

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

# INCREASING UNDERSTANDING FOR WEATHER EMERGENCIES AND ENHANCING SAFETY OF DIFFERENT COMMUNITIES USING WIRELESS SMART SENSORS AND HUMAN-ENVIRONMENT-DATA INTERFACES USING AUGMENTED REALITY (AR)

**FINAL REPORT**
SPTC Project Number: CY1-UNM-01

**Submitted by**
Dr. Fernando Moreu (PI)
Dr. Su Zhang (Co-PI)
Kaveh Malek (Graduate Student)
Ali Mohammadkhorasani (Graduate Student)
Mahsa Sanei (Graduate Student)
Piedad Miranda (Graduate Student)
Department of Civil, Construction and Environmental Engineering (CCEE)
The University of New Mexico

**Prepared for**
Southern Plains Transportation Center
The University of Oklahoma
Norman, OK

SOUTHERN PLAINS
TRANSPORTATION CENTER

January 27, 2025

# Acknowledgments

The authors want to thank the following collaborators who supported this research with their input and feedback: High Water Mark LLC; Prospect Solutions LLC; Center for Advanced Research and Computing (CARC) at UNM; Ohkay Owingeh; Halterman Engineering at Montara, CA; Regional Development Consortium of New Mexico. The authors thank the contributions of Hayden Lammons, Isaac May, Guillermo Toledo, Christian Torres, Fabiola Reyes, Jayshel Rojas, and Ronan Reza in the fabrication, analysis, test, and organization of the LEWIS component of this project. The authors thank Elias Mosco on the development of the AR / LEWIS interface.

# Table of Contents

# List of Tables

# List of Figures

# List of Abbreviations and Acronyms

AR ................................ Augmented Reality
CARC .......................... Center for Advanced Research and Computing
CEP ............................ Community Engagement and Participation
DC ............................... Direct current
FOVh ........................... Field of View horizontal
FPS ............................. Frames Per Second
HMD ............................ Head Mounted Device
HWM ........................... High Water Mark, LLC
IDE .............................. Integrated Development Environment
IMU ............................. Inertial Measurement Unit
LEWIS ......................... Low-Cost Efficient Wireless Intelligent Sensors
MQTT .......................... Message Queuing Telemetry Transport
MR ............................... Mixed Reality
PS ................................ Prospect Solutions, LLC
SHM ............................ Structural Health Monitoring
SMILab ........................ Smart Management of Infrastructure Laboratory
UWP ............................ Universal Windows Platform
VR ................................ Virtual Reality

# Executive Summary

The project developed an interface between users and data in the context of cost-effective deployment of sensors designed to collect information on rainfall and flooding during significant post-wildfire flood events. The wireless system was deployed by the Smart Management of Infrastructure Laboratory (SMILab) group at the University of New Mexico (UNM) and validated in collaboration with High Water Mark LLC. With the support of Prospect Solutions, LLC a transportation-focused tool was developed, which could also be applied to other areas related to community, sensors, disasters and decisions. The project proposed the use of Low-cost Efficient Wireless Intelligent Sensors (LEWIS), which were portable and could be installed at minimal cost. These sensors measured both rainfall and flood levels (water elevation) and provided the population with flood alerts 10 to 20 minutes in advance. The LEWIS sensors were connected to the internet via hotspots and were designed incrementally, allowing owners to make modifications as needed.

The focus of the project was to: Design, Build, and Test Post-Wildfire LEWIS Interface with Data and Augmented Reality (AR): The first step of the research group was to design and demonstrate an indoor rainfall/flood data interface system at UNM using simulated indoor rainfall and flooding. The simulation methods (physical or virtual for rain and flooding) were clarified during implementation. The sensors collected rain and flooding data indoors and displayed the data in an AR interface for visualization. The second step was conducted outdoors in the mountains to validate the system's power independence and obtain field data in the event of rain and/or flooding. Even when substantial rain and flooding did not occur, the survivability of the system was tested by maintaining the sensors' connectivity to the server. The expected data collection period was six months. Adapting the sensors to this outdoor location involved minimal costs. The team tested and validated a new connection with LTE in the field. Additionally, a framework was developed to connect rain, flooding levels, and predicted emergency responses using AR. The sensors were optimized for durability, utilizing solar panels and a sleep mode to reduce power consumption by 70%, enabling long-term autonomous operation even in suboptimal sunlight conditions. This framework incorporated AR to enhance decision-making, based on recommendations from Ohkay Owingeh, High-Water Mark LLC and Prospect Solutions LLC. Finally, the research team community feedback was gathered through a workshop held at the HHW LLC, using a mock-up scenario to refine the design of the portal, sensor placement, and tool usability for community emergencies. The PI built on previous successful workshops at this location to engage with the community effectively.

The close collaboration with HWM LLC ensured that the approach was rooted in Native American knowledge, incorporating traditional insights about flooding in the region. The inclusion of AR technology enhanced data visualization, disaster response, and decision-making. The portal design was optimized to improve real-time data interpretation and its application in flood scenarios.

The project demonstrated that the fusion of low-cost wireless sensors with AR technology has the potential to transform disaster response by enabling immersive, real-time scenario-based training, improved decision-making, and enhanced community resilience in different geographical areas. The input from PS assisted to plan a commercial ready approach in the future in collaboration with HWM and other agencies in New Mexico and across the country.

# Chapter 1. Introduction

## Transportation Challenges in Communities in New Mexico

### Natural Disasters in New Mexico

New Mexico has experienced wildfire damage for centuries, but the severity of these events has increased significantly in recent decades. The Pueblos of Cochiti, Kewa, and Santa Clara, were devastated by the fire and subsequent flooding in 2011, 2012, and 2013. These wildfires were caused by the confluence of severe drought, a century of wildfire suppression, and increased human activity in the landscapes. In 2022, an unprecedented early series of wildfires burned large areas of land, increasing the likelihood of more severe downstream flooding. Figure 1 illustrates the impacts of fire and flooding in New Mexico in 2011, when High Water Mark LLC played a key role in emergency response and recovery.

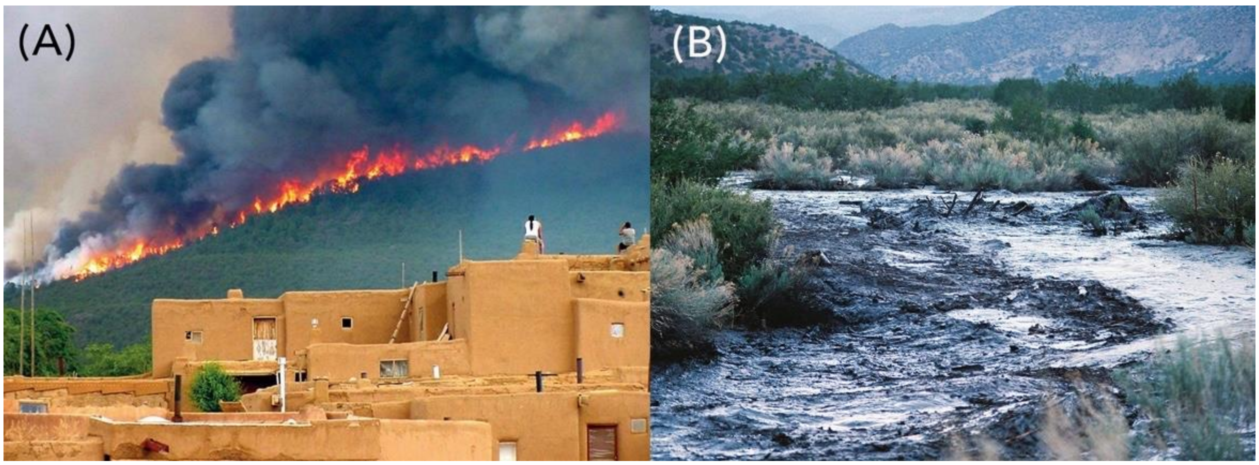



**Figure 1. (A) Members monitor the Encebado Fire from the Taos Pueblo in 2003. (B) Post-wildfire flooding in Cochiti Canyon following the Las Conchas Fire in 2011. (Pictures provided by HWM LLC)**

## Background of the research team with new technologies in relation with effect of weather in transportation for different communities

The SMILab (www.smilab.unm.edu) provides specialized testing equipment including a large hydraulic shake table (9,000 lbs. capacity), seven smaller shakers (110-70 lbs.), three high-precision lasers for displacement monitoring, and two robotic arms for human-machine interaction research. The lab also has advanced equipment for 3D scanning, accelerometer testing, and outdoor sensing.

Figure 2 shows one of the spaces at SMILab available to ensure the growth of this research, specifically the Human-Robot Interaction laboratory at the UNM Center for Advanced Research Computing (CARC). CARC is the UNM campus supercomputing Center and the largest academic computing center in the State of New Mexico, with over 3000 cores, 15 TFlops aggregate compute power, and ~1 PB of RAID5/RAID6 enterprise storage.

The UNM Computer Science Department network infrastructure consists of a switched 1GB backbone, which links the campus network and supports the principal departmental servers.

The CS Department has 4 class C subnets which are segmented into smaller broadcast domains. There are also five 8-core compute servers available for additional processing support. Equipment for parallel processing and real time stream processing prototyping is available through CARC.

**Figure 2. Augmented Reality Laboratory at SMILab, CARC (UNM)**

Systems include dedicated machines, such as the Bethe Xeon Phi/NVIDIA GTX Titan platform for experimental code development in astrophysics and nanoscience, as well as an array of "community" clusters and parallel machines. These include the poblano 256 GB, 64-core SMP system, a shared-memory server for memory-intensive bioinformatics, computational biology, and multiphysics applications; the 200-node Galles 'green' Hadoop/high-throughput Beowulf cluster for bioinformatics and "big data" applications; and five production parallel machines. CARC's resources are available without charge to all faculty, student, and staff researchers at the University. The research team has used the facilities of CARC in the areas of sensor fabrication, sensor programming, AR interfaces, and simulations both virtual and also in the laboratory replicating flooding with AR.

## Low-cost Efficient Wireless Intelligent Sensors (LEWIS)

In recent years, the research team has designed and built prototypes of LEWIS sensors and tested them preliminarily in indoor and outdoor settings. To date, there is no relationship between the rain, flooding, and emergency services decision-making, which is the most important component of an emergency system. Figure 3 shows the LEWIS technology developed by the research team for field deployment.

## Augmented Reality

The new Augmented Reality interface links data measurement directly to decision-making. AR is a tool that has become increasingly more accessible and useful in many domains, from entertainment to instruction. AR enables the operator wearing the Head Mounted Display (HMD) to receive real-time information when necessary and permitting access to datasets or data that are overlaid in front of the user. A key challenge common to AR and any engineering display is to only presenty the information necessary for effective human intervention. This ensures that automation can handle routine tasks, while the operator intervenes only when human judgment is required.

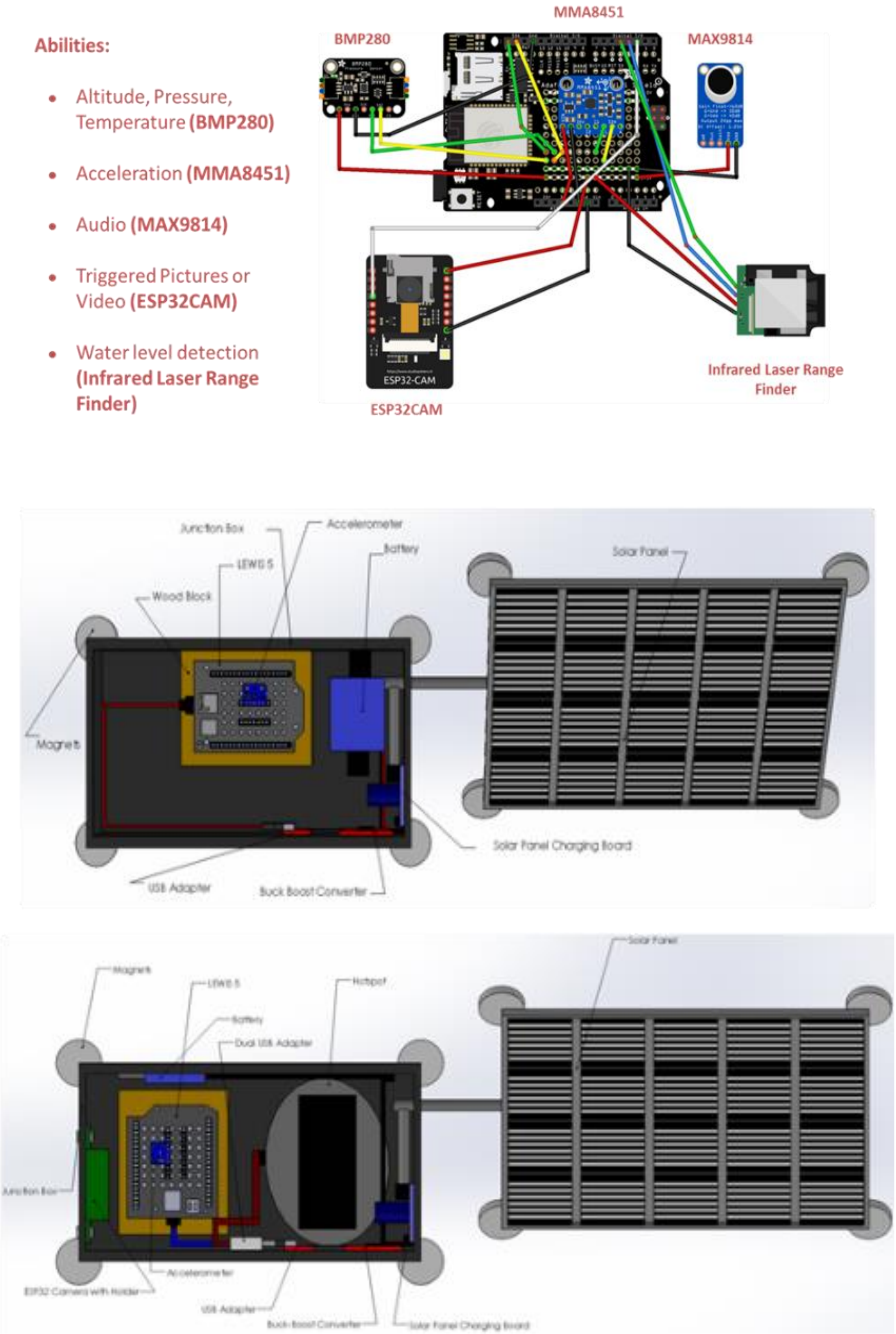



**Figure 3. Previous LEWIS technology for post wildfire flooding monitoring.**

## Augmented Reality and LEWIS

In this project, the team developed a connection between the AR and LEWIS technology to inform and train communities about the flooding data remotely, as well as to enable a new capability to train and inform the user by showing them the effect of such data on their own properties.

**Figure 4. AR Headset used for this research.**

## Field Deployments in the past

The sensors have been previously deployed near Ohkay Owingeh, only near the Pueblo. However, collecting data in nearby mountainous regions is also valuable. Because these areas have weak internet coverage, an alternative communication solution must be developed to ensure reliable data transmission. Additionally, the algorithm for data sharing needs to be modified so the sensor can share data autonomously and with minor oversight. Figure 5 shows the previous locations of sensors near Ohkay Owingeh that were developed with High Water Mark.
In this project, the team tested the long-term deployment of sensors in the mountains, evaluating their durability in the field and validating their suitability for both public users and private owners.

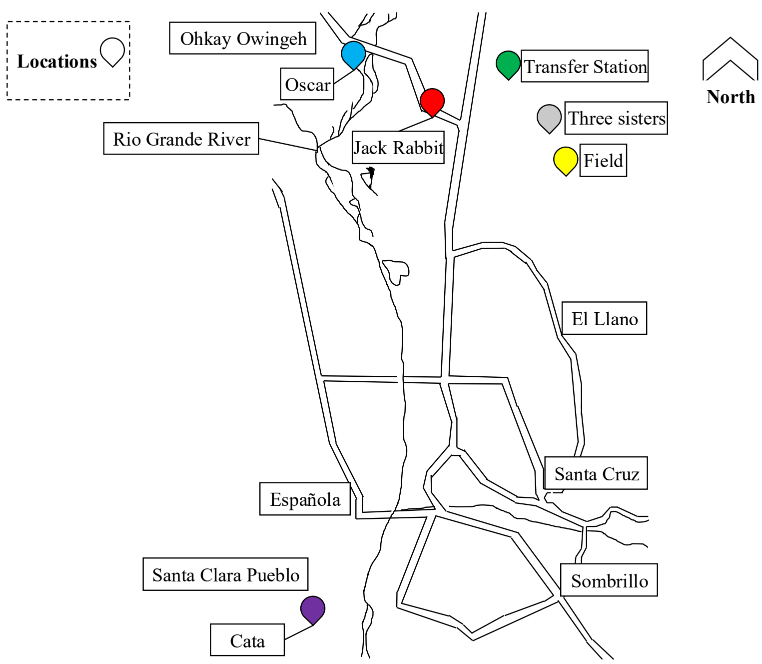



**Figure 5. Previous experience with field deployments of LEWIS by the research team at the University of New Mexico.**

## Collaborations across different academic units, industry, and community experts

Co-PI Dr. Zhang is the associate director of the center for data science in UNM, ASPIRE, and is housed at the Geography Department of UNM. The team of SMILab and ASPIRE developed a new interface that will facilitate the training of communities. This collaboration also supports the practical deployment of sensors and augmented reality systems in real-world emergency and monitoring environments. The strong connection between different academic units, public and private stakeholders ensured the success of the project.

## Stakeholders and their involvement

The following stakeholders were involved in the development of the results shown in this report.

- High Water Mark LLC (HWM): HWM shared datasets from previous wildfire events, including imagery, post-fire flooding records, and documentation of related infrastructure damage during 2022. Additionally, HWM facilitated collaboration with community members in the areas of emergencies and sovereignty of the data being collected. The team met with HWM at the beginning of the project and also at the end, in person, and bimonthly over the phone and virtual video meetings. The project advisers/liaisons were Phoebe Suina and Tom Teagarden, President, and Vice-President, respectively.
- Prospect Solutions LLC (PS): PS provided input for the development of practical implementation of the proposed technology for decision-making processes in the industry and government using this data in relation to the new environment. The use of AR is of interest to advance new interpretation of safety by emergency responders. The input from PS assist in the development of this interface. The team of PS and UNM met monthly. The project advisers/liaisons were Dr. Sharma Allampalli and Dr. Sreenivas Alampalli, President and VP of PS, respectively.
- Regional Development Consortium (RDC): RDC provided input in the context of its regional activities to stimulate the economy with innovation, as well as to connect the proposed effort with fundamental research being developed in the areas of fires, disasters, and decision making using sensors. The meetings were held every 3 months in collaboration with HWM. The project advisers/liaisons were Pat Vanderpool and Greg Dye, CEO and CFO of the RDC.
- Ohkay Owingeh Pueblo (OO): OO provided the input through HWM LLC on the value of connecting data with AR in the simulations held at their main office of HWM LLC. Meetings were held every 2 months and in the headquarters at the start and the end of the project. The leader on this task was Lauren Vigil, employee of HWM LLC, and former researcher at SMILab and involved in sensor deployments and the value of technology to inform emergency responders at OO.

# Chapter 2. Literature Review

## Low-cost sensors

Advancements in digital electronics, wireless technologies, and the widespread availability of internet connectivity have enabled real-time data acquisition through multifunctional sensor nodes and wireless networks (Shanmuganthan, Ghobakhlou, and Sallis 2008). While commercial systems, such as those offered by brands like Vantage Pro2 (2022), are available for infrastructure data collection, they come with significant drawbacks. These systems are often expensive, limited to specific atmospheric measurements, and reliant on proprietary platforms for implementation (Botero-Valencia, Mejia-Herrera, and Pearce 2022). Moreover, they typically require technical expertise for installation and maintenance, as well as extensive wiring for power supply, making them impractical for deployment in remote or hard-to-access areas (Khandelwal and Singhal 2021).

To address these limitations, there has been a growing interest in the development of low-cost, self-assembled sensors. These sensors provide an affordable alternative, offering a high data-to-cost ratio that allows researchers to conduct studies across a wide range of fields and applications without incurring prohibitive expenses (Botero-Valencia, Mejia-Herrera, and Pearce 2022). Their versatility and accessibility have made them increasingly popular in weather and condition monitoring, structural health assessment, agricultural management, and smart city development, among other applications (Ozdagli, Liu, and Moreu 2018). This exponential growth in research and development surrounding low-cost sensors highlights their potential to revolutionize data collection, especially in resource-limited settings, by providing efficient and scalable solutions.

## LEWIS

Academic research continues to expand the use of low-cost sensor technologies across various fields. With the recent decline in sensor equipment costs, the range of applications for information sensing technology has grown substantially (Ayyildiz et al. 2019). For example, Weng et al. developed and validated a real-time structural health monitoring (SHM) system using an integrated wireless network for civil infrastructure. This system enables simultaneous collection and analysis of data from multiple wireless sensing units, which function as a network of analog sensors in real time. The system's performance was further enhanced by incorporating low-cost signal conditioning circuits, and extensive laboratory and field tests demonstrated its feasibility and reliability (Wang, Lynch, and Law 2005).

In another study, researchers equipped a structure with multiple synchronized low-cost LIS344ALH accelerometers to create a system capable of obtaining structural modal data. Although the system's synchronized sampling from multiple nodes produced results comparable to those of piezoelectric sensors, its implementation required cloud connectivity and significant computational resources. Additionally, the performance of an ADXL335 MEMS low-cost accelerometer was evaluated for bridge vibration measurement. This accelerometer, tested under ten harmonic excitation scenarios and on a typical highway bridge, was compared with an instrument-grade accelerometer. The results showed that the low-cost system could successfully identify the dynamic characteristics of the structure. However, only the z-axis was analyzed due to its higher noise density, representing the worst-case scenario (Grimmelsman and Zolghadri 2020).

Another research group proposed a novel data acquisition system by integrating five low-cost accelerometers, achieving high accuracy for low-frequency and low-amplitude acceleration measurements (Komarizadehasl et al. 2021). Despite its low error rate within the frequency range of 0.5–10 Hz, the system presented challenges, including fabrication complexity, reliance on external computing resources, and high noise density. Additionally, it was limited to single-axis acceleration measurements. To address these limitations, the researchers upgraded their system and introduced a new low-cost Adaptable Reliable Accelerometer (LARA) built with Arduino technology. This upgraded system offers improved versatility and reliability for SHM applications, providing a more accessible and practical solution for dynamic structural analysis (Komarizadehasl et al. 2022). The growing body of research on low-cost sensor systems highlights their potential to transform structural monitoring and other fields by providing cost-effective, scalable, and reliable alternatives to traditional high-cost sensors. These advancements make real-time data collection and analysis more accessible, paving the way for widespread adoption in both academic and practical applications.

Researchers selected Arduino for its adaptability and ease of integration with various sensors, such as accelerometers, gyroscopes, and magnetometers, as well as its widespread availability in the market. Arduino's built-in open-source development platform, which supports programming in C, makes it an accessible choice for users. The term "open source" means that all resources related to the board, including design and CAD files, are freely available to the public (Barrett 2013). This allows users to customize the microcontroller's performance via a USB connection, enabling modifications to meet specific requirements. Arduino’s affordability and simplicity make it an ideal tool for both professionals and students to develop microcontroller-based systems that can interact with their environment efficiently and cost-effectively.

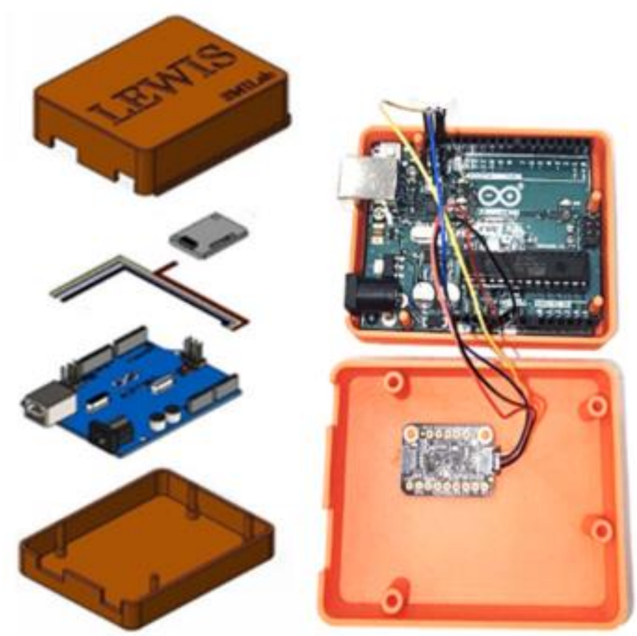



**Figure 6. LEWIS sensor: LEWIS1-γ real photo, (right); LEWIS1-γ 3D model (left) (Sanei, Atcitty, and Moreu 2024).**

The Arduino Integrated Development Environment (IDE) is a user-friendly and intuitive software designed for writing, compiling, and deploying programs onto Arduino boards. These programs, commonly referred to as Arduino sketches, are written in a simplified C/C++ dialect, which follows specific guidelines for organizing code ("Arduino Reference,"). The IDE provides a seamless interface that caters to both beginners and experienced developers, enabling users to write and test code efficiently.

One of the key features of the Arduino IDE is its straightforward layout, which includes tools for error checking, debugging, and code compilation, all integrated into a single platform.
The same ease of use and the integration of new sensors has made possible the development of improved versions of LEWIS sensor with accelerometers, ultrasound as shown in Figure. 7, as well as cameras that integrate wireless monitoring technology for real-time detection.

**Figure 7. LEWIS sensor: Components (left) and in-field inspection setup (right), demonstrating its application for structural monitoring.**

The LEWIS system offers exciting opportunities for engineers and educators to conduct experiments using self-built sensors without requiring advanced knowledge of electrical components. Researchers have trained educators and students to construct LEWIS1 sensors, highlighting its accessibility. Integrating sensor technology into engineering education provides an effective way to enhance the learning experience. By including sensors in the curriculum, students acquire practical skills in real-time data collection and analysis, which are critical for problem-solving and decision-making. This approach fosters critical thinking as students interpret and evaluate data, enabling a deeper comprehension of theoretical concepts. Furthermore, it provides hands-on experience in data collection and analysis, an invaluable skill applicable across numerous disciplines.

## AR technology

In 1990, the term "Augmented Reality" is first introduced (Berryman 2012). Later, Milgram and Kishino (1994) introduced the "Virtuality Continuum," which helped clarify the differences between Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Augmented Virtuality (AV). Figure 8 illustrates the classification of these four concepts. The real environment refers to the physical space where the user is situated, while the virtual environment is made up of computer-generated elements created through technologies like lasers or light. In VR, the user is fully immersed in a virtual world, with no awareness of the real surroundings (Burdea and Coiffet 2003; Zyda 2005). In contrast, MR blends both the physical and digital worlds, allowing the user to interact with both real-world objects and virtual images simultaneously, thus creating a more seamless and immersive experience (Milgram and Kishino 1994; Ohta and Tamura 2014; Speicher, Hall, and Nebeling 2019). MR includes both AR and

AV. AR enhances the real world with interactive virtual elements that are overlaid on the user's view of the physical world [18, 19], while AV manipulates and integrates real objects into a virtual space, allowing for new interactions and possibilities within the virtual environment (Nahon, Subileau, and Capel 2015; Ternier et al. 2012).

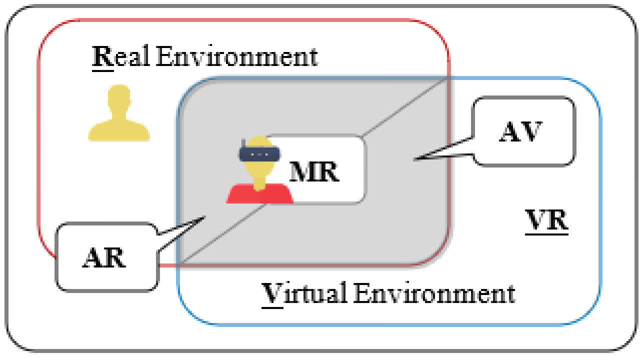



**Figure 8. Classification of the terms Virtual Reality (VR), Mixed Reality (MR), Augmented Reality (AR) and Augmented Virtuality (AV) (Milgram and Kishino 1994).**

The use of AR in this work aims to enhance the inspection process by building on previous research involving AR and computer vision (CV). As illustrated in Figure 4, AR is implemented through holographic HMD lenses from Microsoft, commonly known as HoloLens (Pitsis et al. 2020)These devices can track eye movements, respond to voice commands, and detect hand gestures, with applications in various fields, including medicine. The HoloLens includes a holographic processing unit (HPU) that generates a three-dimensional model of the surrounding environment, utilizing data from an inertial measurement unit, four spatial mapping cameras, and a depth camera. The project will employ Unity (Bayode, Andrew Van der Poll, and Roopnaria Ramphal 2019) and Blender (Petrillo et al. 2018) with Microsoft HoloLens, though the concept can be developed and tested on any AR device.


**Figure 9. AR Interfaces: Headset (left); menu (right).**

## AR applications

The 4th Industrial Revolution is generally considered to have started in 2016, according to (Manda and Ben Dhaou 2019). However, the exact starting point is still under debate, as it is still an evolving process. Moreover, each country may define this starting point differently. For example, Germany is widely recognized as one of the early adopters of the Fourth Industrial Revolution, starting this process in 2011 (Pitsis et al. 2020). Figure 10 illustrates the trend in the adoption of augmented reality (AR) in civil infrastructure, based on data obtained from the number of research articles available in the Web of Science database (2020). Over the past five years (2016-2020), the implementation and development of AR in civil infrastructure applications has shown significant growth compared to the initial years (Aoyama 2019; Cattari et al. 2019; Takara 2019; Petrillo et al. 2018). A thorough and comprehensive analysis for the application of AR in this field is essential to promote its more advanced use. This report presents an updated review of recent studies on AR in civil infrastructure, together with a new classification of its applications.

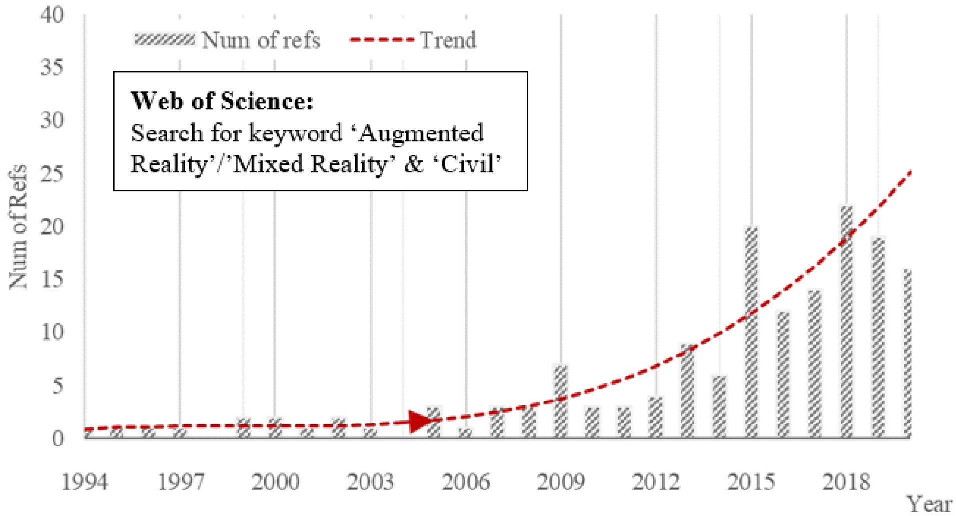



**Figure 10. Trend in the adoption of augmented reality (AR) and mixed reality (MR) in civil infrastructure, based on the number of references retrieved from the Web of Science database.**

Figure 11 illustrates the distribution of existing publications across various countries and regions, based on the same data, it reveals that 40% of the studies originate from the United States and China, accounting for 24% and 16%, respectively. It highlights that these two countries are leading the Fourth Industrial Revolution in the field of augmented reality (AR), as noted by (Manda and Ben Dhaou 2019; Pitsis et al. 2020). This conclusion aligns with recent research studies. (Bayode, Andrew Van der Poll, and Roopnaria Ramphal 2019) pointed out that both the United States and China have launched initiatives, albeit with different objectives, to support the modernization of the industrial production sector. Similarly, (Petrillo et al. 2018) stated that the economic opportunities offered by Industry 4.0 are vast and are expected to significantly impact economies and countries, particularly the United States, China, Germany, and the United Kingdom, by 2030.

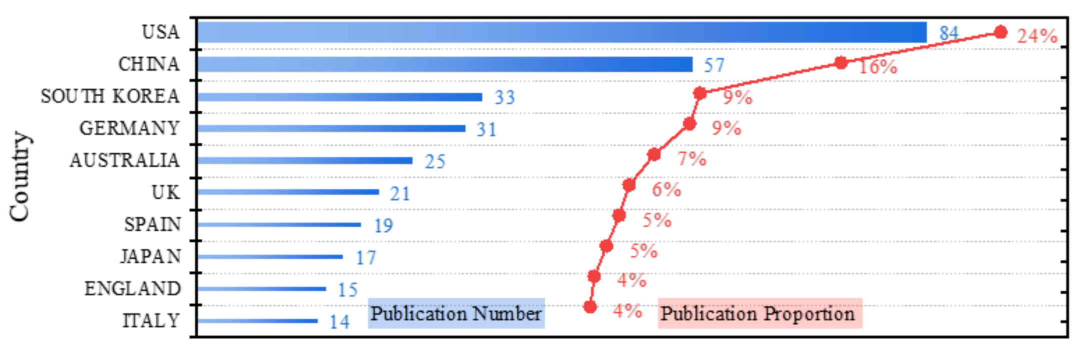



**Figure 11. The number of AR papers in civil infrastructure in different countries/regions (Xu, Jiaqi, and Fernando Moreu. 2021).**

AR refers to an enriched real world with a complimentary virtual world. In the case of Virtual Reality (VR), the real world is replaced by virtual objects and systems (Petrillo et al. 2018). In contrast, AR enhances the real world by anchoring virtual information into the real environment. Figure 12 shows the programming capabilities of the PI, which will be advanced in this project. The PI has developed overlay of models on structural objects to transform the understanding of experiments in the laboratory (Azuma 1997) for engineering decisions, including but not limited to frequency input to shakers, or synchronization of human-machine in real time. The PI has developed an integration of AR and eye gazing with added information.


**Figure 12. Overlay of AR images on structures:(left) visualization of both model and experiment; (right) results with AR, reality, computer screen, and AR (Aguero et al. 2020). AR obtains better human results in synchronization offset because the human is paying attention to the experiment in real time.**

The use of AR has several applications, most notably for inspection. Typically, areas of increased wear or fracture of a bridge can be marked for inspectors, as shown in Figure 13. This also involves the use of an AR application that uses eye-tracking data to draw a cognitive map to increase the safety of railroaders during field inspections.

**Figure 13. Assisting workers with AR technology (Figure taken by: (left) Jiaqi Xu, (right) Dr. Fernando Moreu).**

The challenge with the immersion of new technologies is the training of workers. Since AR technology is new to most construction workers, effective training is necessary to implement AR technology in an actual construction project. Workers will need to understand basic AR knowledge and the methods of operation of AR devices.

## Literature review conclusions

There is still no platform that effectively connects collected data with decision-makers using an interface in order to enable communities to access, visualize, and understand disaster-related information. A new interface that allows community members to view information within their own environment would provide significant benefit. Equipped by the knowledge of the technology on both sensors and AR, the research team developed a project that integrates sensor simplicity, data visualization, durability under extreme conditions, and community-focused disaster interfaces. This report details the components of this capability, the methodology, results, implementation, and community adoption. The following chapters guide readers in understanding the impact of this research and its potential applications. Strong support from HWM and PS reinforces both the implementation and future direction of this effort, ultimately benefiting communities at high risk from events such as wildfires and flooding.

# Chapter 3. Materials and Methodologies

## Introduction

This project developed a new interface connecting users to data collected by low-cost sensors designed to monitor rainfall and flooding during post-wildfire events. It also enhances people's awareness of the environment using AR visualization. This section includes four key components that form the foundation of this research study: the LEWIS5 sensor, augmented reality, the database, and the connection between the sensor and augmented reality. Each of these components will be explained in detail in the following sections.

## LEWIS5 sensor

This section explains the energy harvesting system designed for low-cost remote sensors with real-time monitoring capabilities, built around two main components: sensor nodes and communication nodes. Sensor nodes are responsible for collecting data from the environment, which in this study, is related to rain and flooding. Communication nodes handle transmitting the collected data to a central monitoring station for analysis and action.

### Outline of the circuit

Figure 14 illustrates how the basic components of the sensor node's energy circuit are interconnected. A photovoltaic panel captures solar energy during the day, which it uses to charge a lithium polymer battery and simultaneously power a microcontroller via a DC-DC converter. The DC-DC converter plays a crucial role by increasing the direct current (DC) voltage from the solar panel to the level required for the Arduino Uno board to function properly. The lithium polymer battery stores the solar energy collected during the day, ensuring the system remains operational at night or in situations where the panel is temporarily shaded. It powers the circuit to transmit the gathered data reliably under such conditions. Moreover, an onboard ESP32 chip, integrated with the Airlift Shield, provides wireless connectivity for seamless data transmission.

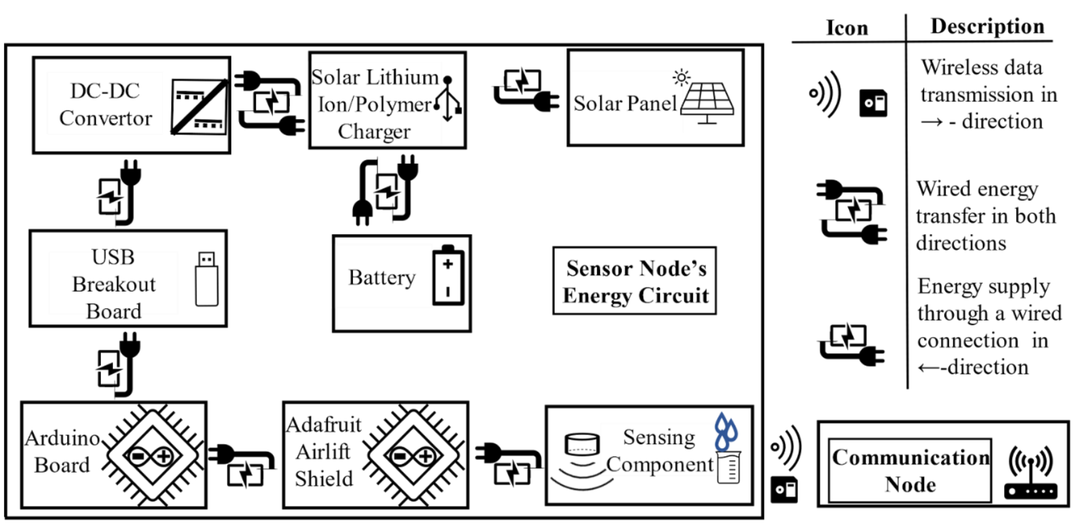



**Figure 14. Outline of the sensor energy circuit.**

## Circuit components

Figure 15 shows a schematic overview of the components and specifications of the sensor node's energy circuit. A 6.22W, 6.5V solar panel serves as the primary energy source, connected to a solar lithium-ion charger. This charger includes a 4.7F capacitor and an MCP73871 microchip, which regulates the voltage. The charger supports both bidirectional energy transfer with a 3.7V lithium-polymer battery and unidirectional energy transfer with a DC-DC converter. On sunny days, the solar panel charges the battery and supplies input to the DC-DC converter at a voltage range of 6V to 6.5V. The converter then steps down this voltage to an output range of 5.4V to 5.6V. At night, the battery powers the circuit by supplying input to the converter within a voltage range of 3.2V to 4.2V. In this case, the converter steps up the voltage to an output range of 5.2V to 5.5V, ensuring the Arduino board receives a safe and consistent 5V supply to operate its 5V logic.

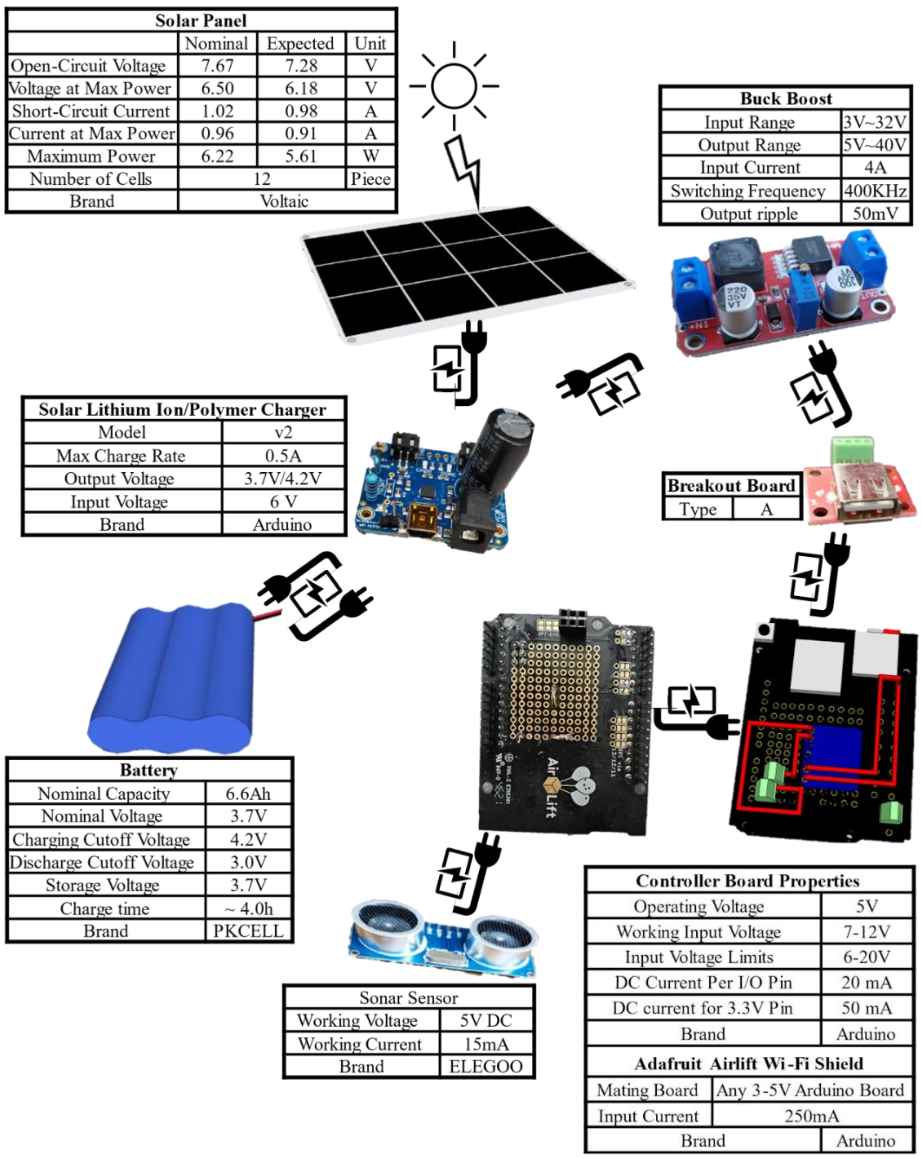



**Figure 15. Energy circuit of the sensor nodes (sonar sensor) components and specifications.**

The Arduino board in this setup has two main components: a rain sensor and an Airlift Shield with an onboard ESP32 chip for wireless communication. While the ESP32 chip is integrated into the Arduino Wi-Fi shield and not depicted separately in the circuit, its role is vital for enabling connectivity. The sonar sensor connects to the Arduino using three connections: a ground pin, a 5V power pin, and two digital input/output (I/O) pins. The circuit diagram for rain sensors closely resembles that of the sonar sensors and is therefore omitted in this section. The primary difference lies in the connection between the Arduino board and the sensor. While rain sensors share the same ground and power input pins as sonar sensors, they use only one digital pin for data transmission instead of two as used by sonar sensors.

## Sensors description

Flooding, recognized as one of the five most severe natural disasters (Naser 2023), significantly threatens social stability and economic progress in flood-prone regions (Naseri and Hummel 2021). The integration of rain and sonar sensors (LEWIS5) offers a new approach to enhance flood prediction. Collecting the necessary data for flood prediction often involves monitoring off-grid, hard-to-reach locations (Zakaria, Jabbar, and Sulaiman 2023). Rain sensors are used to measure real-time rainfall intensity and duration, critical indicators for assessing the likelihood and severity of flooding. Sonar sensors, in contrast, monitor water levels and flow rates in waterways. By combining data from these sensors, the research team created a flood prediction system, which can be used for providing early warnings and mitigating flood damage.

Figure 16a shows the design of rain sensor used in this study, specifically the WH-SP-RG model from MISOL. These rain sensors have a tilting mechanism with components including a rainwater collector, a funnel, a tipping lever, tipping buckets, and reed switches (Savina et al. 2012). Rainwater is collected in the upper section and directed through the funnel toward the tipping buckets. Each tip of the bucket corresponds to approximately 0.28 mm of rainfall and triggers a momentary contact closure with its reed switch. This interaction generates an interrupt pin signal, which is recorded for data processing (www.misolie.net, 2022). Figure 16b schematically presents the water level sensors and their enclosure for electrical components. The ultrasonic measuring unit is mounted on a 3D-printed sonar holder, which is attached to an ABS plastic junction box. This assembly connects to an Arduino board powered by a 3.7V lithium-polymer battery circuit.

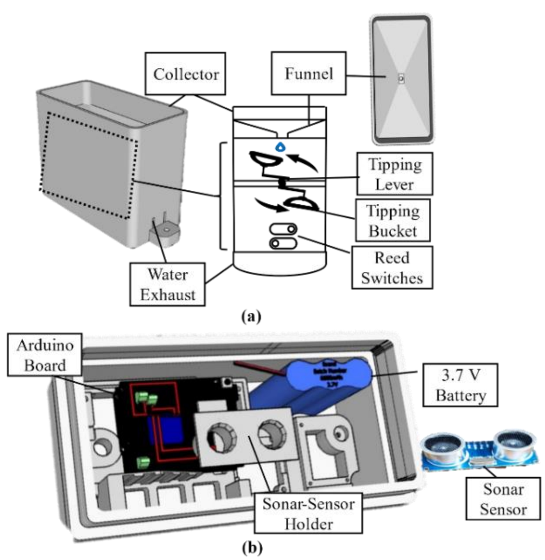



**Figure 16. Rain and sonar illustration (a) rain gauge (b) water level sensor.**

By integrating the data from these advanced sensor systems, this study can better model flooding scenarios and improve the early detection of risks to reduce the damage and loss caused by such disasters.

## Augmented Reality

The research team used Microsoft HoloLens 2nd generation (HL2) to transmit the data obtained from sensor to an enhanced visualization interface in HL2. The Microsoft HoloLens is an AR headset designed to bridge the gap between the physical and digital worlds. The holographic picture created in AR allows seamless interaction within mixed-reality environments (Ungureanu et al. 2020). This device includes several features:

1. Display: A wide, head-mounted stereoscopic screen offering 2K resolution per eye with a 3:2 aspect ratio. It incorporates colored holographic lenses to enhance visualization.
2. Cameras and Sensors: Equipped with a 1 MP depth camera, four visible light cameras, and two infrared cameras. Together, these enable weather and condition sensing and ambient light detection. An Inertial Measurement Unit (IMU), consisting of an accelerometer, magnetometer, and gyroscope, captures user inputs and movement.
3. Audio Features: Five integrated microphones and a speaker system facilitate clear communication between the user and the device.

The HoloLens is powered by a Holographic Processing Unit paired with 4 GB of RAM and 64 GB of storage. Connectivity options include Bluetooth and Wi-Fi. With a lightweight design (566 grams) and a battery that lasts 2–3 hours in active use or up to two weeks in standby mode, it is highly portable and user-friendly. One of the features of the HoloLens is its ability to create holographic data visualizations. These holograms enhance the user's perception by combination of virtual data with real-world surroundings. Users, for instance, can view and interact with these visualizations alongside physical objects, making their analyses more comprehensive. This advanced capability enables users to analyze infrastructure and perform tasks simultaneously within the same physical space. Additionally, multiple users in different locations can collaborate on evaluations, sharing a synchronized virtual environment.

Figure 17 illustrates the device from two angles, highlighting its four depth cameras (two on each side). These cameras enable the HL2 to produce a high-resolution 3D map of its surroundings, ensuring accurate and detailed spatial representations for different applications.

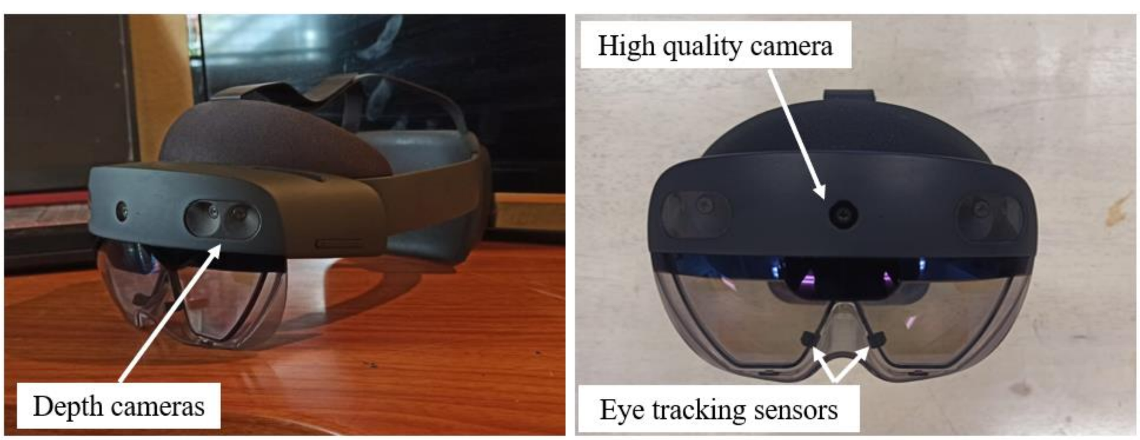



**Figure 17. AR device - Microsoft HoloLens 2nd generation.**

This AR headset is equipped with two eye-tracking sensors that monitor the user’s gaze, along with a high-quality camera capable of taking photos and recording videos of the physical environment. Additionally, it merges real and virtual media, enabling the capture of images and videos of the surrounding environment while anchoring virtual elements on the real world. Table 1 provides this device’s web camera specifications.

**Table 1. Microsoft HoloLens 2nd generation features.**

| Resolution (Pixel2) | Resolution (Megapixel) | FOVh (˚) | Recording Rate (FPS) |
|---|---|---|---|
| 2272 × 1278 | 8 | 64.69 | 30 |

## Database

To achieve the objectives of this study, we developed an AR interface capable of bidirectional interaction with both the user and the data. The interface needed to display holographic representations of the algorithm's analysis results, supported by a database for storing and transmitting information between the algorithm and the AR interface. A dynamic connection was also required to automate processes and ensure a user-friendly experience. For this purpose, the research team employed Wi-Fi technology, which offers high-speed performance and remains functional even in areas without traditional network connectivity. The figure below illustrates the software’s design logic, showcasing its three main components, their roles, and how they interconnect. As shown, the design begins and concludes within the AR headset, indicating that users do not need specialized knowledge to operate the system.

The database creates a two-way communication link between the AR headset and the computer running data analysis. This connection happens in real time, so as sensor data updates, the AR visualization updates automatically, allowing users to see flooding or rainfall changes without needing technical knowledge (Mohammadkhorasani et al. 2023; Moreu and Malek 2023).

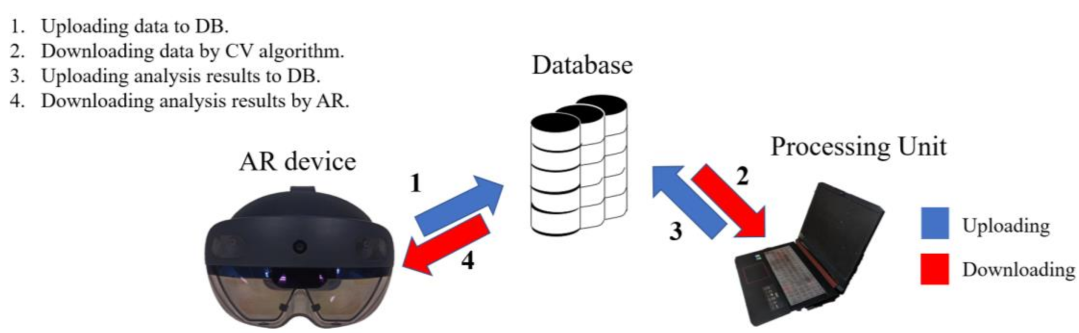



**Figure 18. Schematical connection between AR headset and computer through database system.**

This study introduces an AR-computer communication system that uses a MySQL relational database to address the limited processing power of current AR devices (Xu and Moreu 2021). Many algorithms designed for different purposes cannot run directly on AR devices because of their limited analytical capabilities. Instead, these algorithms rely on external, high-performance processing units. As a result, creating a fast and reliable communication link between AR devices and computers becomes essential. Modern AR devices can gather various types of valuable data, including images, videos, and 3D mappings. This information can then be processed using advanced algorithms for diverse applications. While the focus of this study is on building a connection system specifically for AR headsets and computers, the proposed method is flexible enough to support other devices such as robots and remote sensors, which also require real-time communication with computers. The database developed in this study not only enables the communication between the AR headset and algorithms but also illustrates scenarios that help users imagine emergency cases involving rain or flooding. To ensure its practical application, the database is implemented on a local system and uses Wi-Fi technology for communication.

## Sensor and AR connection

The researchers used the Arduino Integrated Development Environment (IDE) for sensor programming. The Arduino platform, built on open-source software and written in Java, supports all Arduino boards, which simplifies coding and uploading to any compatible board. Additionally, it works with third-party development boards using external cores, making it a highly versatile option.

On the server side, the setup included MySQL and Node.js. MySQL, an open-source database known for its efficiency and global popularity, handled data storage. Node.js, designed to execute JavaScript code outside of web browsers, ran on various operating systems like Windows 10, Linux, macOS, and Windows Server 2008 and newer. Although Node.js is mainly used for building web servers and networking tools, the researchers utilized it to develop a script for receiving sensor data and storing it in the MySQL database. The researchers linked the AR headset to the server using a Unity-based application. This connection enabled data stored in the database to be visualized in the AR headset as water projections. PHP and SQL queries were employed to retrieve the necessary data from the MySQL database. The Unity application, integrated with Visual Studio and coded in C#, facilitated the presentation of this data in an interactive visual format. This experiment focused on data visualizations from a single sensor, but the system is adaptable for future expansions to include a network of sensors.

Previous studies, such as (Zhou, Luo, and Yang 2017), investigated displacement monitoring during tunneling construction by comparing real-time onsite measurements with baseline models to ensure quality. Similarly, (Aguero et al. 2020) demonstrated the integration of AR devices and sensors to combine AR's visualization capabilities with sensors' data collection features. Figures 19 and 20 in their study illustrate the connection process and a practical experiment verifying the effectiveness of AR-sensor integration.

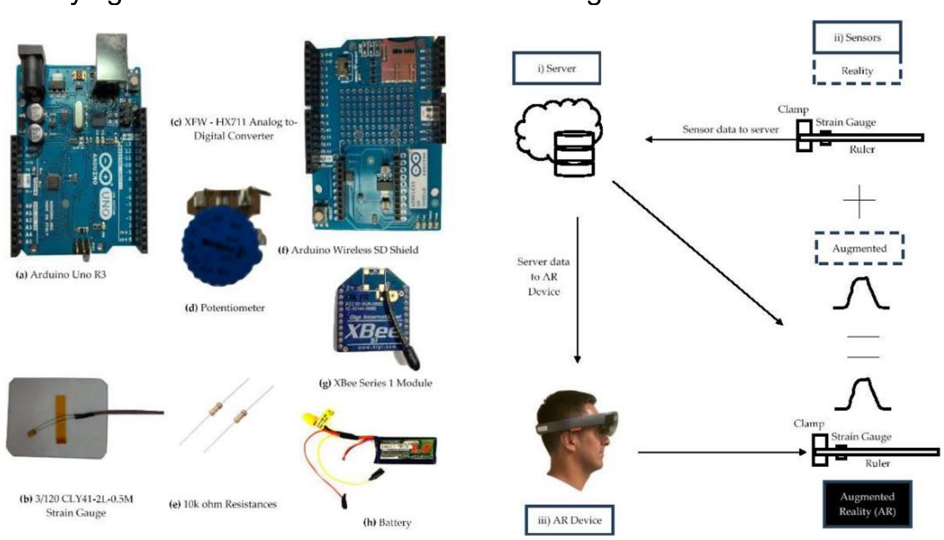



**Figure 19. AR and sensor connection (Aguero et al. 2020)**

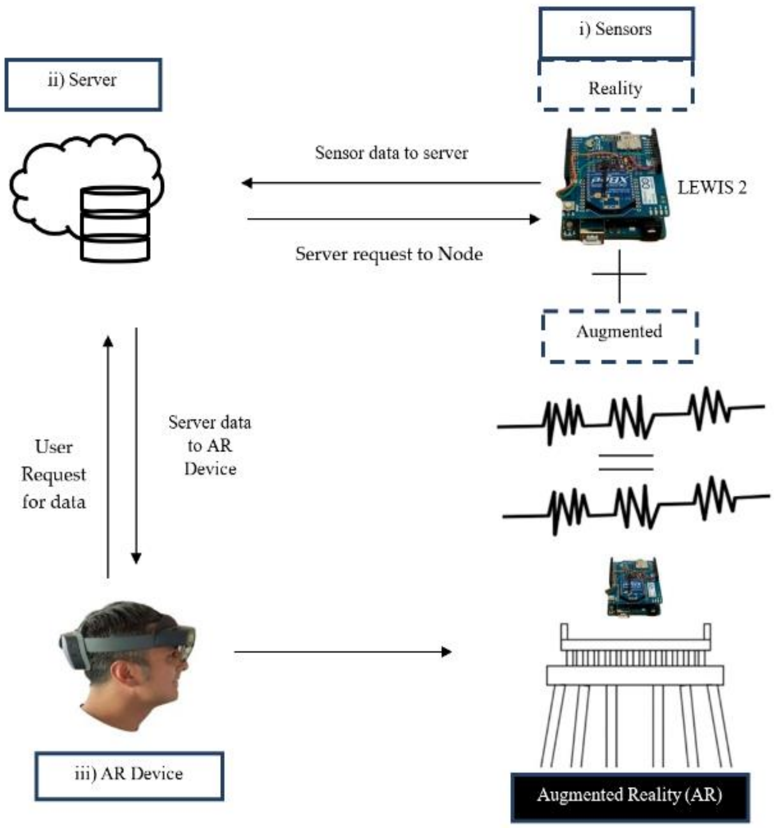



**Figure 20. Experiments of AR and sensor connection (Aguero et al., 2020)**

## Research Tasks

The methodology of this project focused on designing, testing, and deploying a system to enhance disaster preparedness using the integration of sensors and AR. Each task was introduced to address key objectives, from simulating indoor rain and flooding to field deployment and community engagement. The following tasks outline the step-by-step approach and methods undertaken to achieve these goals.

Task 1: Simulating Indoor Rain and AR Visualization
The team simulated indoor rain by testing sensors with graded water measurements to ensure accuracy. A database was created to connect sensor data to an AR application, which displayed dynamic rainfall simulations in Microsoft HoloLens 2. The Unity-based AR app provided immersive rain visualizations, showcasing varying intensities in real-time.

Task 2: Simulating Indoor Flooding and AR Integration
Flood simulations used ultrasonic sensors tested with incremental water levels in controlled settings. The data was integrated into the AR system via a database, allowing real-time visualization of flood progression. The Unity-based AR app depicted dynamic water levels, enhancing user engagement with accurate simulations.

Task 3: Field Deployment for Data Collection

Sensors were deployed in flood-prone areas of Ohkay Owingeh, NM, identified with experts. Solar-powered sensors monitored rainfall and flooding, with data transmitted to validate AR visualizations. The deployments ensured reliable operation in real-world conditions.

Task 4: Power Evaluation of Sensors
The sensors' power consumption was optimized using sleep mode. Solar panel performance under suboptimal sunlight ensured week-long operation. These findings supported the feasibility of sustained deployments in remote locations.

Task 5: Community Feedback Collection
A meeting with disaster management experts provided feedback on the AR applications. Participants evaluated the AR tools' effectiveness and suggested improvements, such as customizable thresholds and enhanced usability for training and emergency preparedness.

Task 6: AR Demonstration Based on Feedback
Refinements to the AR app included color-coded flood thresholds and user-friendly features. Demonstrations showcased real-time flood simulations, emphasizing the applications' value for community training and disaster planning.

Task 7: Drafting Flood Thresholds for AR Integration
Flood thresholds were developed based on community feedback to improve AR simulation accuracy. These thresholds enhanced the system's realism, supporting its scalability for various geographic and weather conditions.

## Conclusion and research contents distribution in the report

The content of the research tasks are distributed in the following chapters in this sequence: Chapter 4 includes research tasks 1-4; Chapter 5 summarizes the conclusions of such efforts; Chapter 6 covers research tasks 5 and 6; Chapter 7 concludes with the efforts of research task 7. Finally, Chapter 8 summarizes the publications, websites, and activities where this research project has been shared.

# Chapter 4. Results and Discussions

## Introduction and tasks description

The following four research tasks describe the development of simulations, hardware, software, and their actual evaluation and are the core of this research project. Each task is outlined within the context of components, development, testing, analysis, and results and inform the subsequent section of implementation, community involvement, and publications (Chapters 6, 7 and 8.)
Tasks 1-4 were developed in laboratory settings to ensure reproducible results and to generate demonstration-ready outputs for community feedback before deploying in the field.

## Task 1: Indoor simulation of rain, and interface with the AR visualization of that rain

In this task the research team objective was to simulate indoor rain and create an interface with AR visualization. The research team began with creating a setup to test rain sensors in controlled lab settings. This involved precisely pouring water into the sensor and examining the data it recorded to ensure it accurately reflected the amount of water collected. The objective was to confirm the sensor's accuracy in reflecting the correct volume of water it received. Figure 21 illustrates a rain sensor and a test setup for measuring sensors' accuracy.

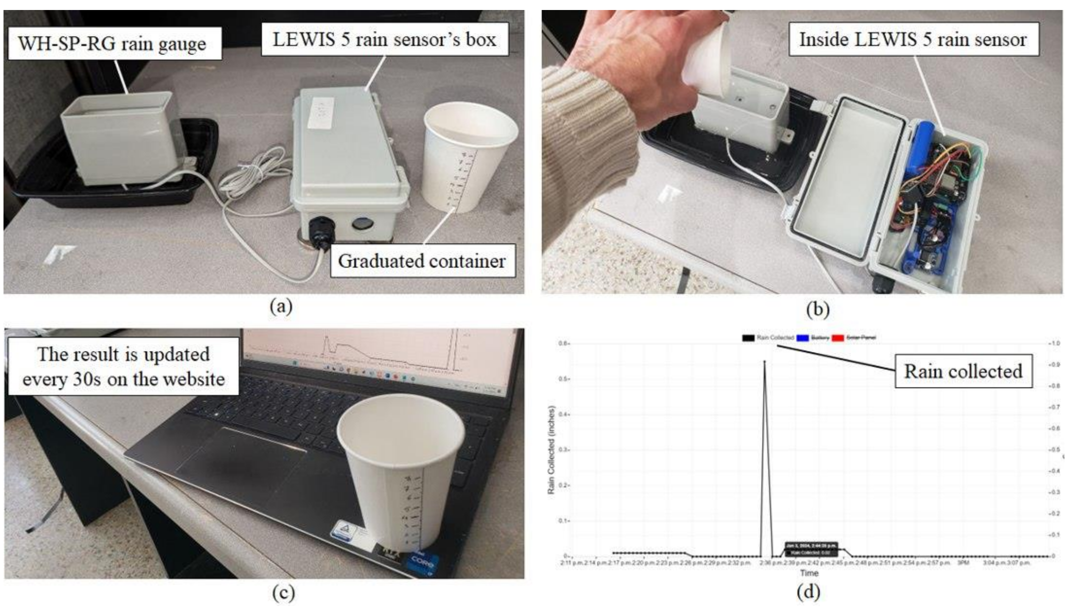



**Figure 21. Indoor simulation of rain (a) rain sensor and graded cup (b) rain simulation (c) results updated on the website (d) simulation result.**

The research team designed the database to establish connections between the rain sensors and AR. This integration with the database will allow the users to capture real-time rain data and store it in the database. Utilizing this connection, users can transmit rain data to the AR headset, enriching the AR visualization experience with dynamic weather simulations. This integration enhances user immersion and interaction with the AR technology, fostering a more engaging simulation of indoor rain scenarios. For further details, refer to Figure 22, which illustrates the workflow of data transmission from rain sensors to the AR headset through the database.

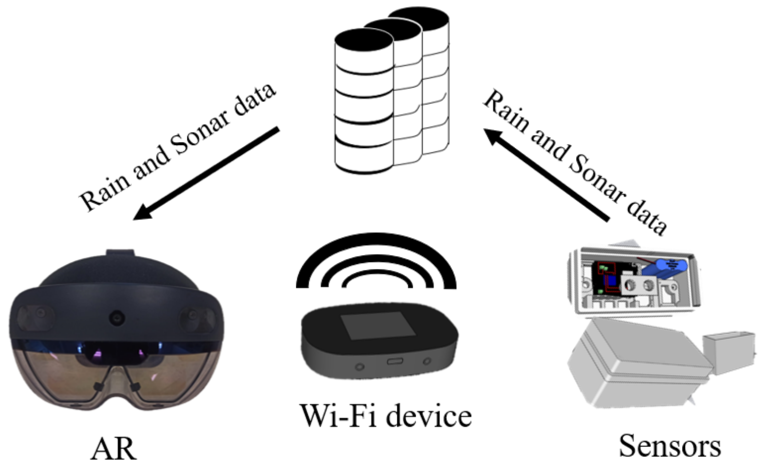



**Figure 22. Workflow of data transmission from rain sensors to the AR headset through the database.**

Finally, the research team developed an AR application on the C#-Unity platform that simulates rain and flooding in an AR headset. This AR app is connected to a dataset receiving information from sensors. Unity3D was chosen for its robust simulation environment, enabling the research team to prototype and interact with virtual worlds using user-defined scripts. Supported by the Unity Engine library and utilizing C# as the core scripting language, Unity3D allows developers to define the behavior of game objects and manage the AR environment effectively. The application was built to be compatible with the Universal Windows Platform (UWP), ensuring deployment on Windows-based AR devices. AR SDKs provide the necessary tools and APIs to enhance the AR development process. However, significant challenges were encountered, particularly regarding library inconsistencies and computational limitations. Advanced mathematical and matrix computation libraries are not fully compatible with the C# interface for AR headset programming, necessitating the use of simpler simulation models for rain and flooding. Figure 23 shows the flowchart of the AR app, illustrating the steps considered for developing this application.

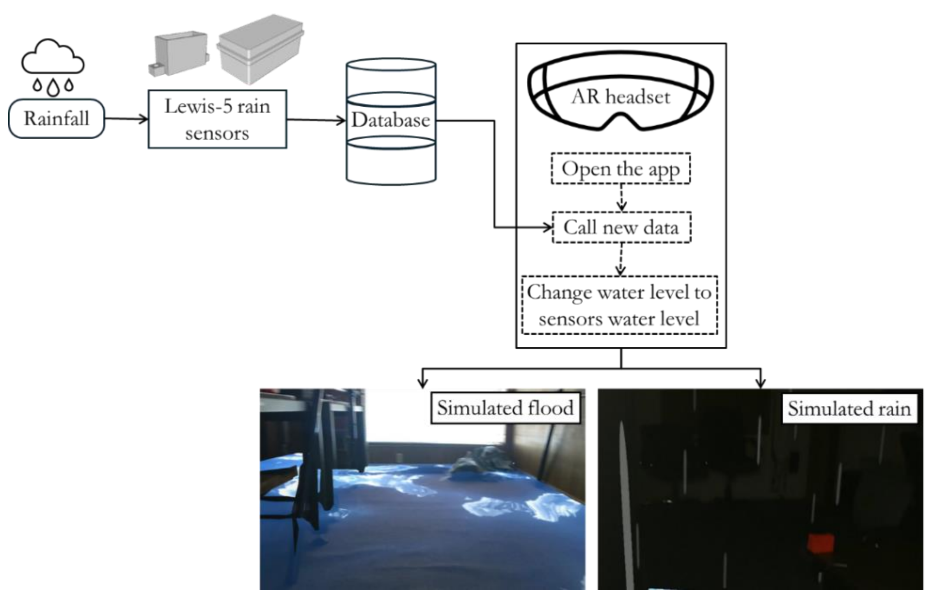



**Figure 23. Flowchart of the steps used for simulating flood and rain simulation in AR headsets.**

The research team further developed an AR application that virtually shows rain by generating virtual water droplets falling from above, allowing users to imagine themselves under a heavy downpour that could cause flooding. This immersive experience helps users feel and understand the impact of heavy rain and flooding. Figure 24 shows a screenshot of the AR rain simulator app, displaying the app's menu and rain droplets. The application can be used in both indoor and outdoor settings, with rain droplets spawning from every direction regardless of where the user looks. The next phase of the project describes how the app simulates flooding caused by virtual rain, giving users a sense of being in a rainstorm that could gradually lead to flooding.

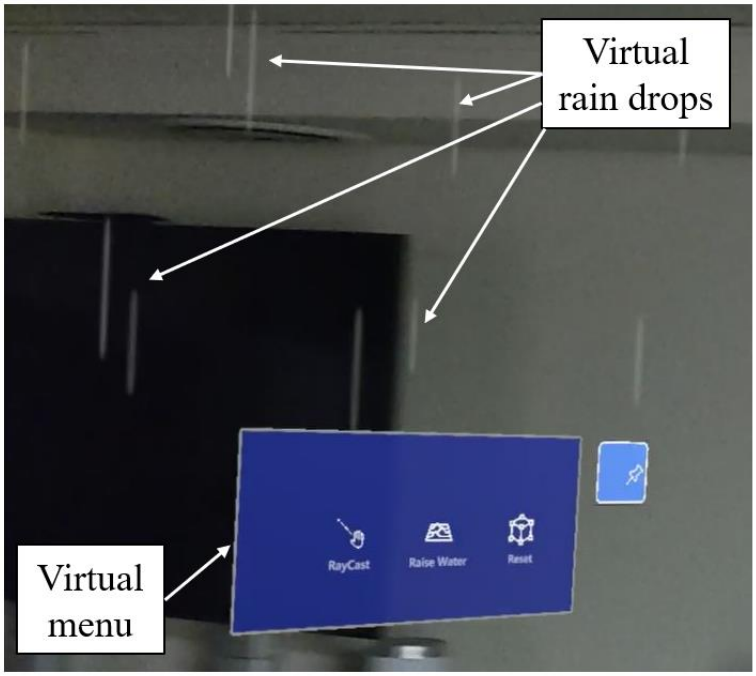



**Figure 24. Rain simulator app showing the menu and rain droplets.**

The rain data was gauged by LEWIS sensors and sent to a SQL relational database running on a Microsoft Azure server. The AR app, which ran on Microsoft HoloLens 2, updated the rain data approximately every 0.02 seconds. This data was then sent to the simulation module of the AR app and translated into the intensity of rain or the speed of flood expansion. These sensors, deployed in the Tinker Town area near Albuquerque, NM, were positioned in out-of-reach areas using tripods and powered by solar panels, enabling remote monitoring of rainfall and flooding. The rain sensors had bowls for collecting raindrops to measure severity, and the sonar sensors faced the ground to collect data from surface runoff, facilitating effective data collection and transmission to researchers.

## Task 2: Indoor simulation of flooding, and interface with the AR visualization

The objective of this task was to simulate indoor flooding and integrate it with AR visualization. In the initial phase of this task, the research team first tested flood sensors in a controlled lab setting, which was described in the previous task. This involved carefully pouring a specific amount of water into a graded bucket beneath the sensor and analyzing the data it recorded.

The bucket was filled gradually to reach the next level, with the sensor constantly collecting data. The experiment description is shown in Figure 25.

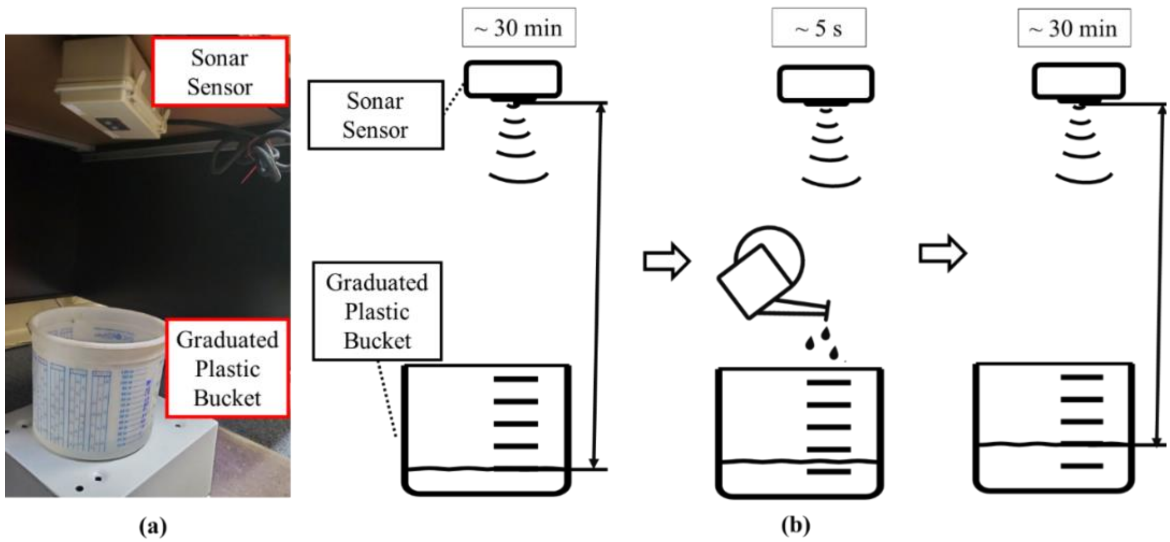



**Figure 25. Experiment description (a) setups (b) process.**

Notably, an ultrasonic sensor was used, capable of accurately measuring the distance to the surface directly in front of it, regardless of whether the material was transparent or opaque. The purpose of this setup was to verify the sensor's precision in determining the actual water level. Figure 26 shows a view of the sonar sensors' components.

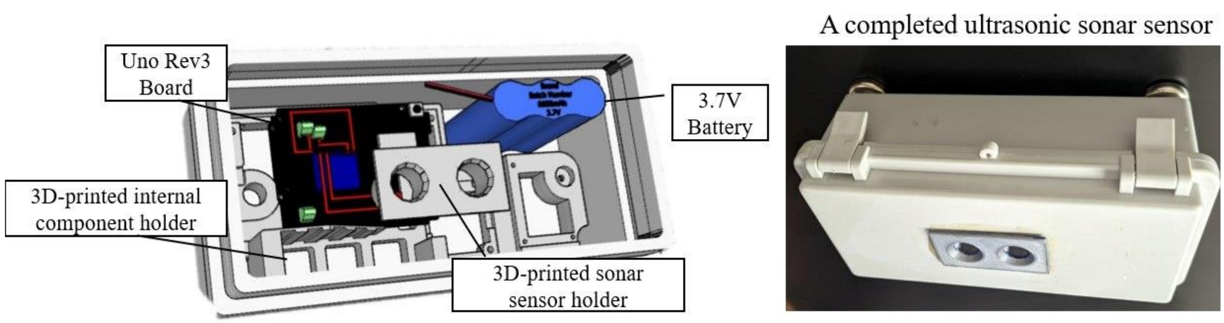



**Figure 26. Components of sonar sensors which were used for flood prediction.**

In alignment with objectives of this project, the research team integrated the flood sensors with the database infrastructure. This connection enabled the real-time transmission of water level data from the sensors to the database. Leveraging this integration, the research team could transmit water level information to the AR headset, enabling the AR visualization with dynamic flooding scenarios. This enhancement added a new dimension to the AR experience, allowing users to visualize and interact with simulated indoor flooding scenarios in real time. For a detailed overview of the database design and its connections with AR visualization, refer to Figure 27, which illustrates the comprehensive structure of the database and its integration with AR and sensors.

To complete the task, the research team developed an AR application in the C#-Unity platform to simulate flood conditions in the AR headset, following the same technical steps as the rain simulation. The AR app connects to a dataset that receives sensor information. Flood data, gauged by LEWIS sensors, is sent to a SQL relational database on a Microsoft Azure server. The AR app, running on Microsoft HoloLens 2, updates flood data every 0.02 seconds. This data is processed by the simulation module of the AR app to reflect the speed of flood expansion.

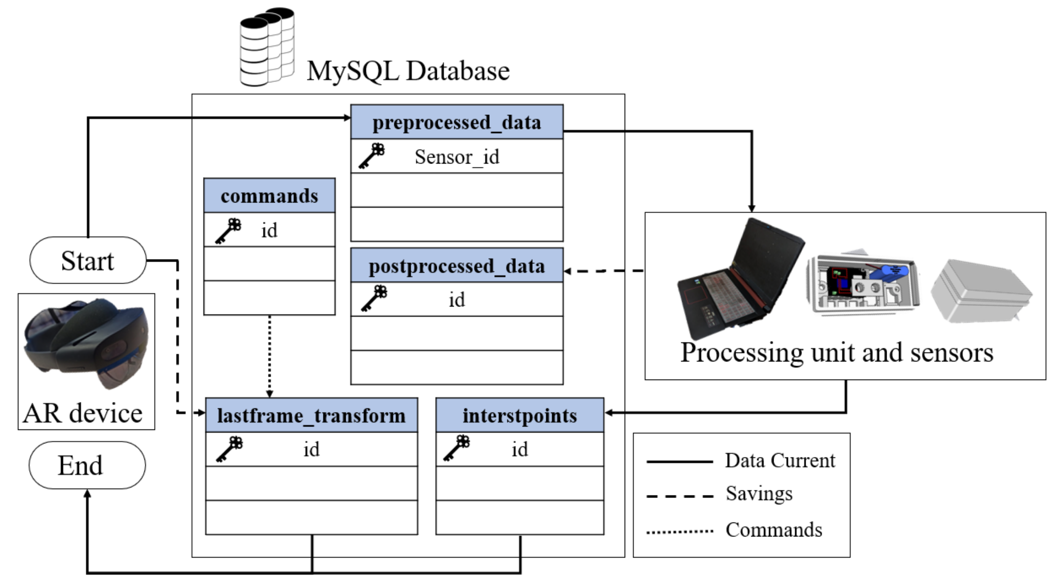



**Figure 27. Database tables and their connections with AR and sensors.**

Figure 28 illustrates the flood simulation in the AR headset. Figure 28 (a) through (e) show the progression of the flood over time, capturing the changes in flood intensity and spread. These snapshots demonstrate the real-time capabilities of the AR app in visualizing dynamic flood conditions based on sensor data.

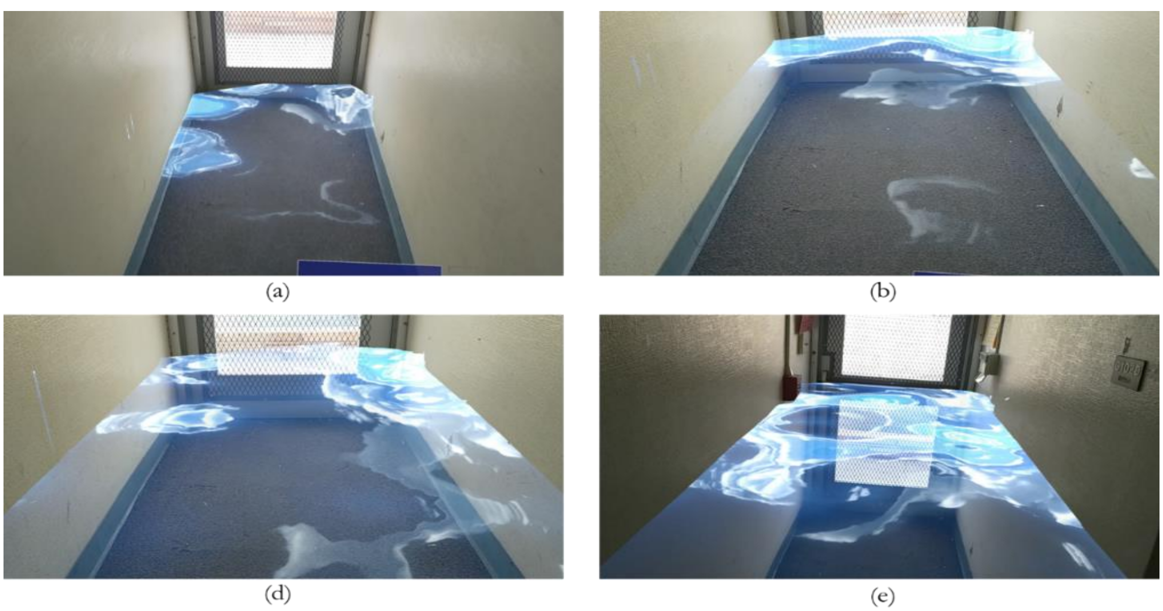



**Figure 28. Instances of flood simulation in AR headset over time, shown in (a) through (e).**

## Task 3: Selection of site deployment for collection of field rain and flooding

The objective of this task was to identify an appropriate deployment site for collecting field data on rainfall and flooding. Previously, similar sensors had been deployed in Ohkay Owingeh, a community in northern New Mexico located near the Rio Grande River. This area is considered remote and faces recurring risks of flooding and wildfires, making it an ideal test environment. Based on geographic assessments, the region was determined to have a high likelihood of flood and post-wildfire events. In the past, the research team deployed sensors in locations presented in Figure 29. These areas included the transfer station, Three Sister, Jack Rabbit, another field location, and the Cata location. In this project, the research team deployed the sensors in East Sandia Mountains (Figure 29), to test the durability of the technology in outdoor environments where there is rain and where the sensor durability can be tested.

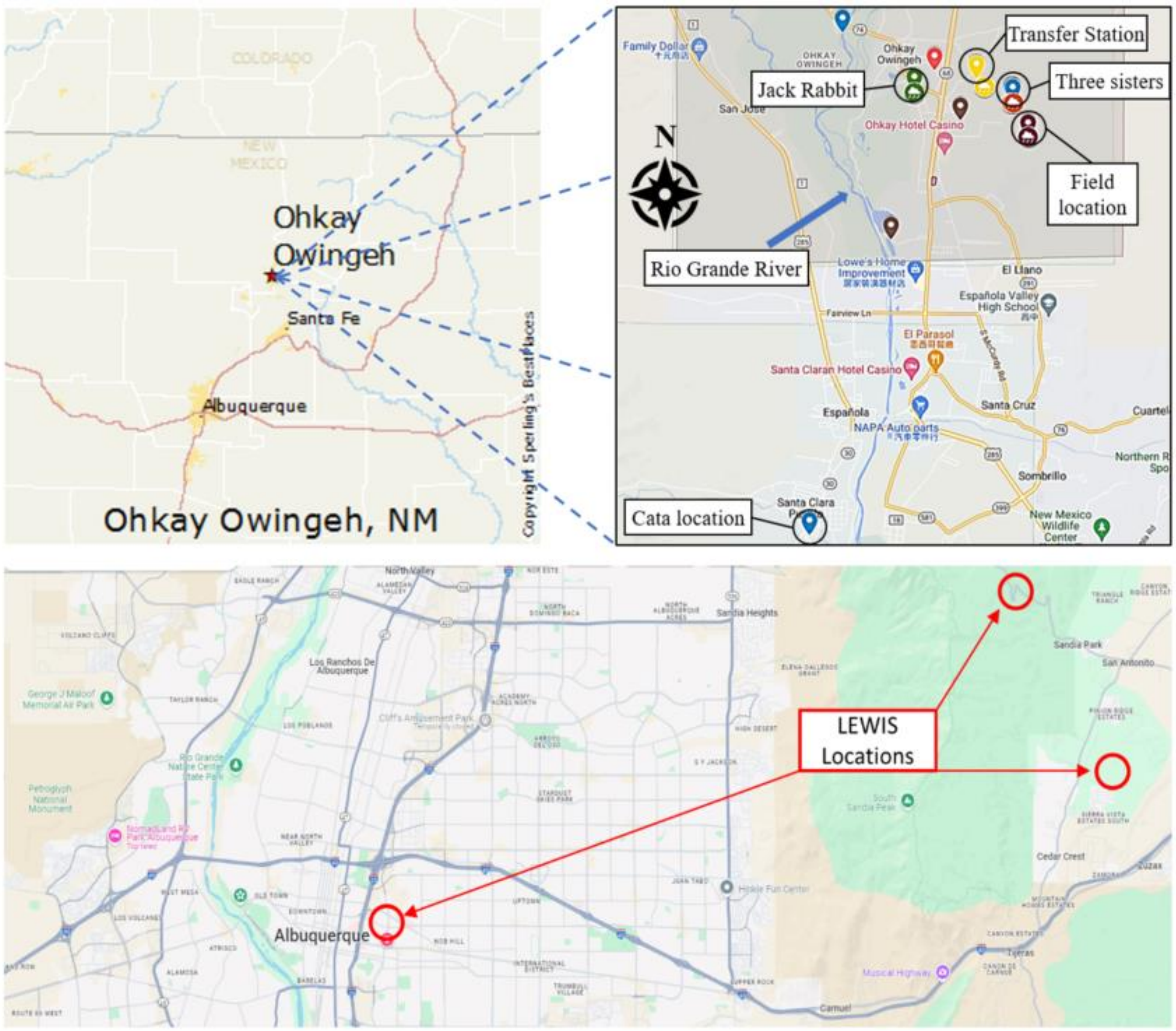



**Figure 29. Areas where sensors were deployed (above) at Ohkay Owingeh for community input; (below) during the durability test of this project.**

## Task 4: Evaluation of the battery to survive outside collecting data for 6 months

The objective of this task was to evaluate the battery's capacity to sustain outdoor data collection for a duration of six months. Our primary objective was to optimize power consumption to ensure the system's operational continuity under various weather conditions. To achieve this, the research team implemented sophisticated power management techniques aimed at minimizing energy usage during idle periods.

A pivotal aspect of the methodology involved partitioning the sensor's activity into two distinct cycles: an active mode and a sleep mode. By strategically activating and deactivating the necessary peripherals on the microcontrollers between sensor readings, we aimed to minimize power draw during periods of inactivity. Figure 30 illustrates the setup used for measuring the amperage and voltage of the batteries during the testing process. Below on the left is the maximum power drawn in amps while performing networking operations during awake mode. On the right is the power drawn in amps during the sleep mode.


**Figure 30. The setup used for measuring the amperage and voltage of the batteries during the testing process. On the left is the maximum power drawn in amps while performing networking operations during awake mode. On the right is the power drawn in amps during the sleep mode.**

To assess the efficacy of power-saving measures, the research team conducted different testing procedures. Initially, the solar panels were removed from two sensors and each sensor was equipped with a fully charged battery.

One sensor remained in an always-active state, while the other was configured to enter sleep mode between sensor readings. Through careful monitoring and data collection, we observed a notable reduction in power loss of up to 70% with the implementation of sleep mode functionality. Furthermore, we conducted tests to evaluate the stability of sensors under suboptimal sunlight conditions. One sensor equipped with sleep mode functionality and a solar panel was positioned behind a tinted window, receiving only 6.5 hours of sunlight daily. Regular voltage readings were performed using a multimeter to assess the sensor's ability to remain operational under such conditions.

The results obtained from the head-to-head voltage loss tests and the suboptimal sunlight test provided valuable insights into the system's performance and resilience. Notably, the sensor equipped with sleep mode functionality exhibited prolonged operational capability, demonstrating promising advancements towards our objective of prolonged outdoor data collection. Moving forward, our focus will be on further optimizing power consumption and enhancing system reliability. Additionally, we plan to transition to a Message Queuing Telemetry Transport (MQTT) model for data transmission, which will enable real-time visualization of data and improve the scalability and robustness of the system. Figure 31 demonstrates the data collected during the head-to-head voltage loss test. Power loss was able to be reduced by 70%.

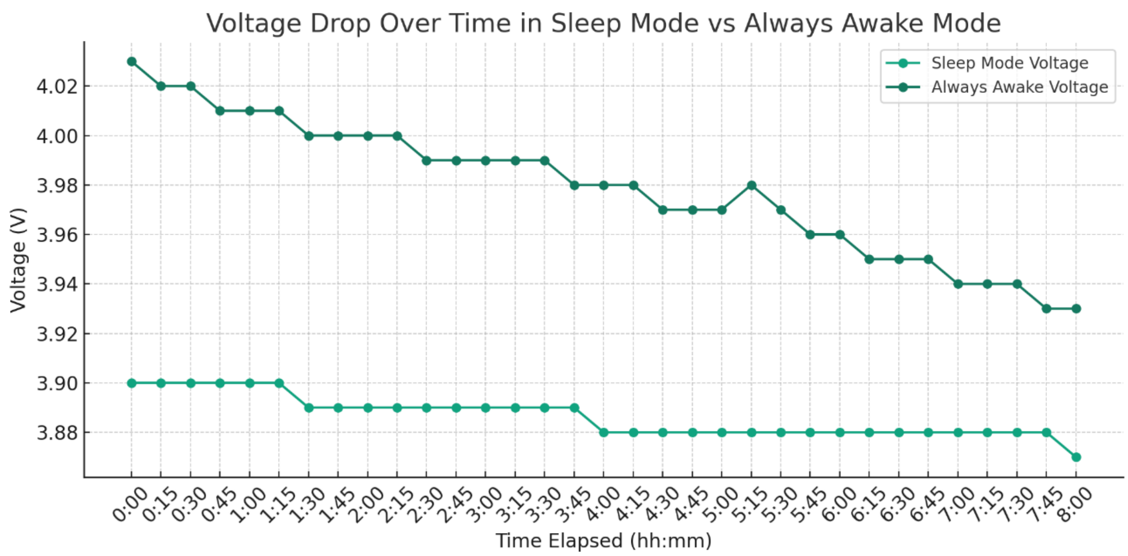



**Figure 31. The data collected during the head-to-head voltage loss test.**

Figure 32 shows the voltage loss data from the suboptimal sunlight test. The sensor was able to remain active with 6.5 hours of suboptimal sunlight for over a week.

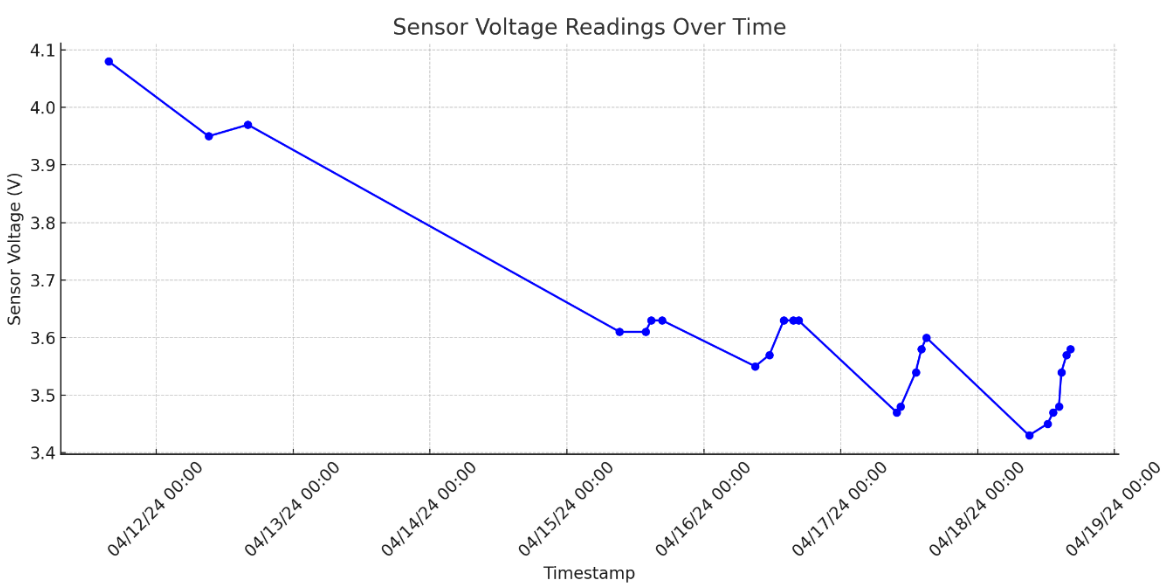



**Figure 32. The voltage loss data from the suboptimal sunlight test.**

We have demonstrated the long-term durability of the sensors in a flood-prone environment, with successful continuous operation for over six months in the East Sandia Mountains. The system has reliably captured rainfall and flooding data throughout this period. To illustrate ongoing performance, Figure 33 presents data from one sensor collected between October 1 and October 7, obtained directly from the system's online interface. This dataset shows uninterrupted transmission. Currently, four sensors remain continuously connected, expanding the scope of our real-time performance assessment. This ongoing monitoring also helps address potential issues such as outlier readings caused by connectivity disturbances or environmental factors including magnetic interference that might otherwise be misinterpreted as sensor errors by non-experts. The system operates autonomously, with solar panels charging the batteries during daylight hours and the batteries providing adequate power during periods of low sunlight. All sensors remain fully active as of January 15.

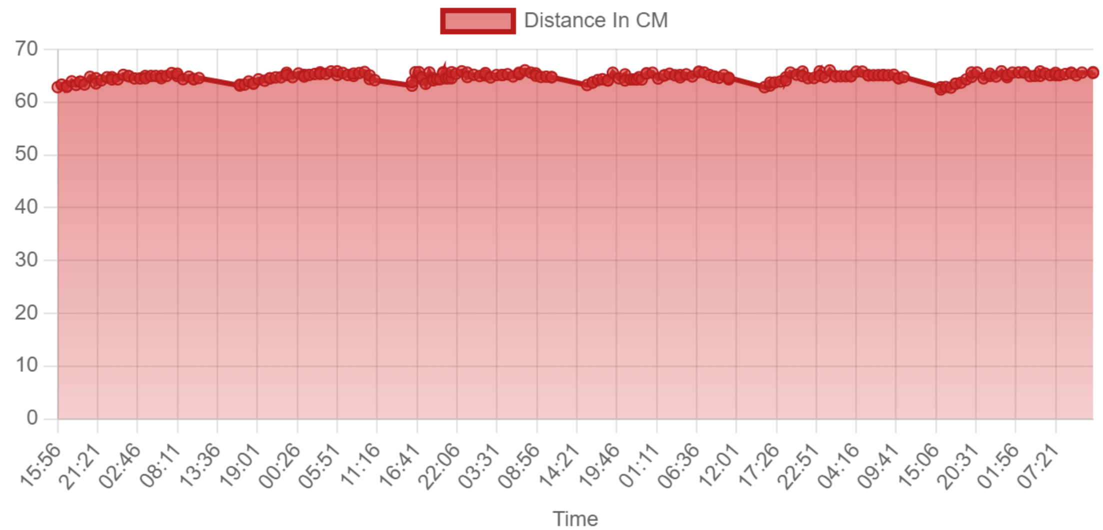



**Figure 33. Screenshot of the website showing the sensor's operation from Oct 1st-Oct 7th.**

## New Hardware Components

The ability to collect rain and flooding data without a hot spot increased the ability of the system to serve remote monitoring. Having gateway runs at roughly 40mA was low enough to maintain power from the solar panel without the need for additional batteries. Figure 34 shows the new gateway.

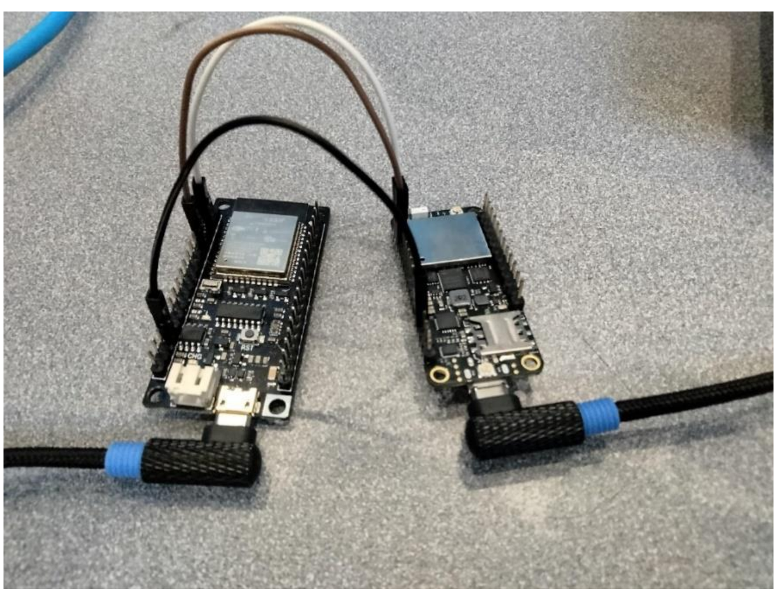


**Figure 34. New LEWIS Gateway.**

## Practical Deployments

The research team tested the new technology at the East Mountains of Sandia to confirm their capability to measure both rain and flooding data (Figure 35).


**Figure 35. Field deployments to collect rain at the East Mountains.**

## Data and results from deployments

Data from multiple rain events was tested and produced successful results. Two different rain events are shown in Figure 36.

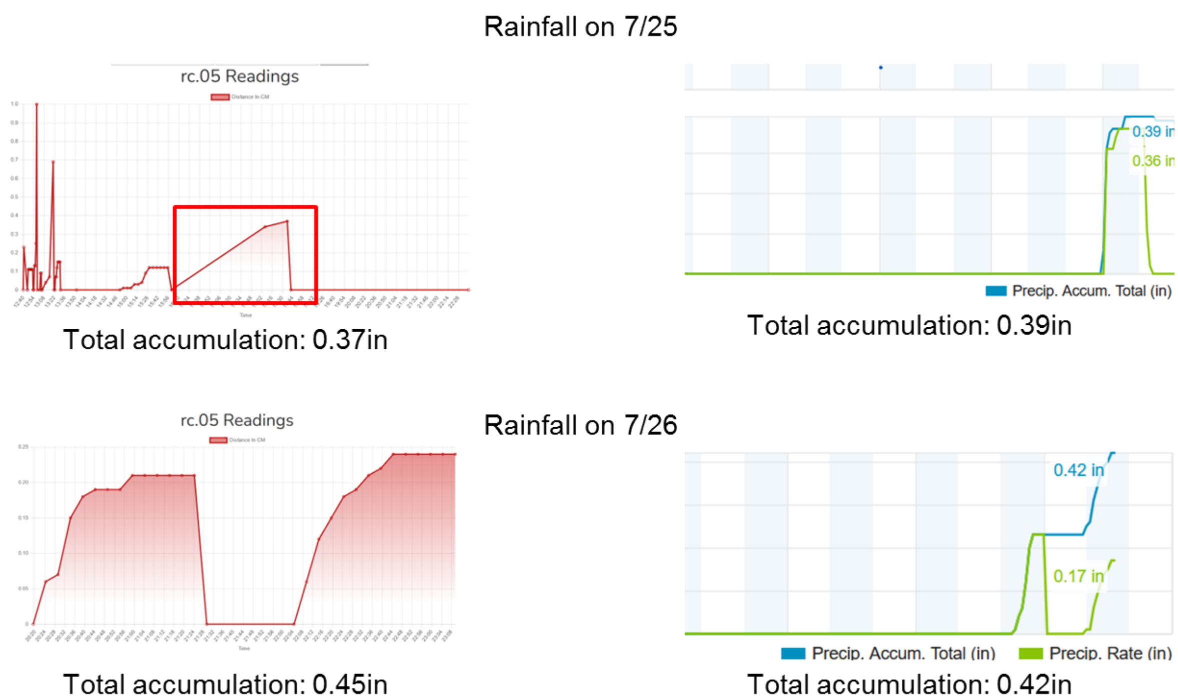



**Figure 36. Rain data collected remotely with LEWIS at East Mountains.**

## Outdoor deployments

The researchers have developed one rain sensor and one sonar sensor in the Tinker Town area near Albuquerque, NM. This step was taken after ensuring the proper functionality of the sensors in indoor settings. The research team decided to deploy the sensors outdoors to ensure their performance in a real-world scenario.

As shown in Figure 37, the rain and sonar sensors are deployed in out-of-reach areas using tripods. Additionally, since these sensors are designed for remote locations, they are powered by solar panels. The rain sensors have rain bowls capable of collecting raindrops to measure the severity of the rain, and the sonar sensors are positioned facing the ground to collect data from surface runoff. This setup enables the sensors to collect and send data on flooding and rainfall to the researchers, allowing for effective remote monitoring.

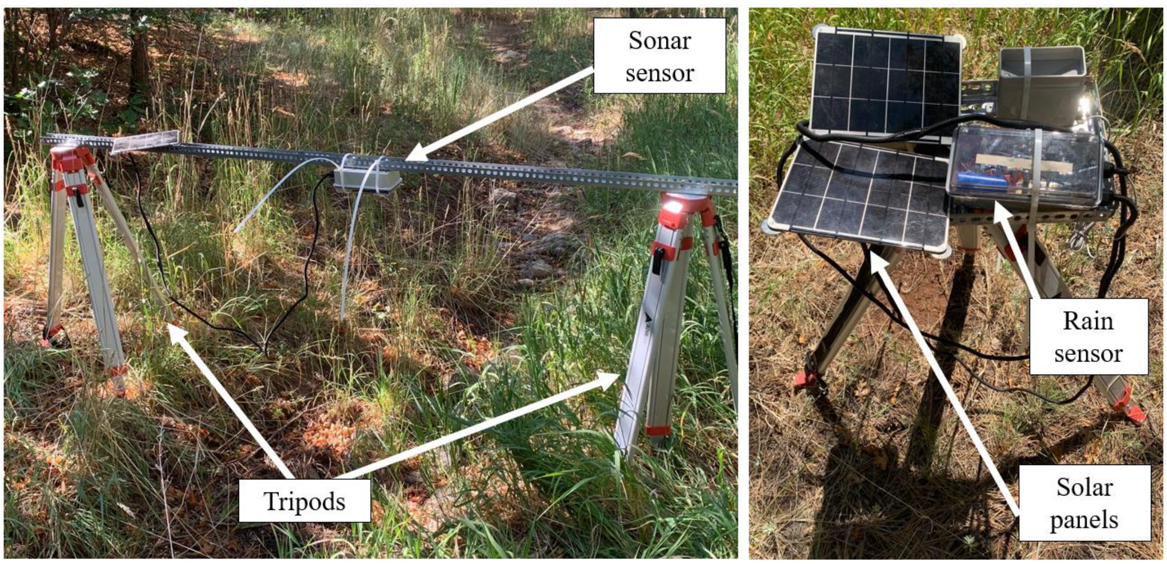



**Figure 37. Sonar and rain sensors deployed in the outreach remote areas to collect data about the rains and possible flooding, Tinker Town, Albuquerque, NM.**

# Conclusions of Chapter 4

The four research tasks were completed on time and enabled the stakeholders to provide input about the sensor data and deployment in terms of durability, accuracy, and value in terms of rain and flooding data. Even though flooding data were not collected in the field, it was demonstrated in the laboratory that the sonar sensor is accurate in measuring the water level remotely. 0The battery and communication systems now operate reliably, ensuring uninterrupted sensor performance. The results presented in this section provide valuable guidance for community engagement and offer critical feedback for selecting thresholds, configuring alarms, and implementing field deployments.

# Chapter 5. Conclusions and Recommendations

## Background regarding the connection with results and community

The research focused on integrating rain and flood simulation technologies with AR applications for enhanced disaster preparedness and condition monitoring. The results highlight the importance of combining technical innovation with community engagement to develop tools that are both effective and user centric. Challenges such as computational limitations and user interface design must be addressed to fully realize the potential of these technologies.

The successful deployment of sensors and positive feedback from community stakeholders show the project's relevance and impact. Future work will focus on scaling these technologies, improving their robustness, and ensuring their accessibility to a broader audience. The findings from this research highlight the transformative potential of integrating real-time data with AR technologies, particularly in the context of disaster preparedness and condition monitoring. The broader implications, challenges, and future directions of this work are described as follows.

## Enhancing disaster preparedness through AR visualization

One of the most important achievements of this project is the successful simulation of rain and flooding events within AR. By integrating sensor data into AR visualizations, users can experience and interact with dynamic weather and condition changes in real-time. This capability is particularly valuable for disaster preparedness, allowing emergency responders, urban planners, and community members to visualize and respond to potential flood scenarios in a controlled, immersive setting. The ability to "experience" flooding without physical risk creates an opportunity for safer, and more effective training.

Moreover, the AR application bridges a critical gap in disaster preparedness by offering a tool that combines weather and condition data, user engagement, and scenario-based learning. This fusion not only improves understanding but also enables different communities to make informed decisions during emergencies. For instance, the incorporation of user-defined flood thresholds and visual signals, such as color-coded severity levels, enhances the app's practical utility. These features enable users to simulate specific risks relevant to their geographic and weather/condition context.

## Addressing challenges in technology development

While the results are promising, several technical challenges occurred that require further attention. The AR simulations faced computational limitations due to inconsistencies in the libraries and frameworks available for C#-based AR programming. This restricted the complexity of the rain and flood simulations, requiring the use of simpler models. Future efforts must prioritize the development of advanced computational frameworks optimized for AR applications, ensuring that the simulations are both accurate and visually exciting.

Another challenge involved the integration of sensors into different settings. Although the sensors worked reliably in controlled settings and during initial outdoor deployments, issues such as connectivity, interference (e.g., magnetic fields), and physical durability were observed. The deployment of sensors in remote, flood-prone areas requires robust hardware capable of resisting extreme weather conditions. Improvements in sensor design, such as enhanced water resistance and extended range, will be essential for long-term usefulness.

## The role of community engagement in technology design

A critical component of this project was to include the feedback and insights of community stakeholders, particularly local experts. Their feedback provided helpful insights that informed both the design and functionality of the AR application. For example, recommendations to use color-coded flooding levels and incorporate flow rate visualizations directly addressed real-world needs, ensuring that the app remains relevant for its intended users.

This collaborative approach highlights the importance of co-creation in technology development. By involving end-users from the beginning, the project ensured that the resulting tools were aligned with practical applications and local priorities. This model of community-engaged research can serve as a model for future initiatives particularly in public safety and weather/condition responsiveness.

## Broader implications for weather/condition monitoring and management

Beyond disaster preparedness, the integration of sensors and AR technologies have broader implications for weather/condition monitoring and management. The ability to collect, visualize, and analyze real-time data on rainfall and flooding offers a powerful tool for understanding and mitigating the impacts of these types of weather events. For instance, the deployment of sensors in flood-prone areas provides critical data that can inform infrastructure planning, water resource management, and hazard mitigation strategies.

Moreover, the scalability of the system provides opportunities for its application in other weather and condition-related domains. The same framework could be adapted to monitor wildfire progression, or drought conditions to address a range of weather and condition-related challenges.

## Reliability and scalability

The project's focus on energy efficiency is another important achievement. The implementation of sleep mode functionality reduced sensor power consumption by 70%, demonstrating the potential for long-term deployments in remote locations. This advancement is particularly important for regions with limited access to reliable power sources. The integration of solar panels further enhances reliability, ensuring that the sensors can operate for extended periods. To scale this system for broader use, the cost of sensor production and deployment must be reduced to ensure accessibility for different communities and levels of resources. Finally, efforts to standardize data formats and communication protocols will be essential for integrating this system with existing weather and condition-related monitoring networks.

## Future directions and opportunities

The results of this research project point to possible future directions:

1. **Advanced AR features:** Incorporating machine learning algorithms into the AR application could enable more complicated simulations, such as predictive modeling of flood progression based on historical and real-time data.

2. **Expanded sensor networks:** Deploying sensors in additional locations, particularly in regions with weather conditions of interest to the various communities, would provide a more comprehensive dataset for analysis and visualization.
3. **Educational applications:** The AR system's immersive capabilities make it a valuable tool for educational purposes, helping communities understand and prepare for weather-related risks. Collaborations with schools and training programs could extend its impact.
4. **Policy integration:** By demonstrating the effectiveness of this technology, the project could influence policy development around disaster preparedness and weather/condition monitoring. Partnerships with government agencies and non-profits could facilitate the adoption of these tools at a larger scale.
5. **Cross-disciplinary research:** Integrating insights from fields such as behavioral science and urban planning could enhance the system's effectiveness and increase its applications.

# Chapter 6. Implementation of Project Outputs

## Introduction to Implementation and Outputs

This chapter summarizes the outcomes of sharing the technical capabilities with public and private stakeholders, gathering input for augmented reality (AR) data, and highlighting the value of these interfaces in establishing thresholds, setting limits, and guiding future developments to benefit communities equipped with this technology.

## Task 5: Collection of feedback from the community for emergencies

The direction of experts regarding disasters was included to better understand the potential of this research to assist emergencies. We organized a 1h30m meeting with three experts on disasters in various communities. The research team (PI: Dr. Fernando Moreu, PhD candidates Kaveh Malek, Ali Mohammadkhorasani, and Dr. Jiwi Chong) organized a meeting on October 9th, 2024, with High Water Mark (HWM) LLC as shown in Figure 38.


**Figure 38. A project stakeholder meeting held on October 9th, 2024.**

Attendees included CEO Phoebe Suina, along with environmental engineers Lauren Vigil and Joseph Ganeily. HWM specializes in emergency management, hazard mitigation, and environmental consulting, with a focus on flood recovery and mitigation in the Southwest, particularly in fire-impacted watersheds. To ensure we collected feedback from HWM, we discussed the latest advances in rain and sonar sensors developed in our lab and we collected their opinion from a practical perspective. Phoebe Suina provided professional feedback after discussing our contribution highlighting its strengths, weaknesses, and areas for improvement. Her feedback emphasized the AR potential for training purposes and its ability to visually represent the impacts of heavy rainfall and flooding. However, her team pointed out certain challenges that we need to address to simulate critical weather and emergency situations, suggesting improvements in these areas. We also discussed a website that displays real-time data from sensors deployed in remote areas of New Mexico.

## Task 6: AR demonstration to the community based on feedback

Using the feedback collected during the meeting with HWM LLC, we conducted the AR flood simulation. The developed sensor continuously collect rainfall and water level data and transmit this information to the AR system, allowing users to visualize real-time changes in flood conditions. The demonstration illustrated the potential of the AR app for emergency training, particularly for conceptualizing flooding scenarios in a controlled and safe manner. Figure 39 provides several images of the AR applications that Phoebe Suina tried: the flooding and the fire app demonstration.

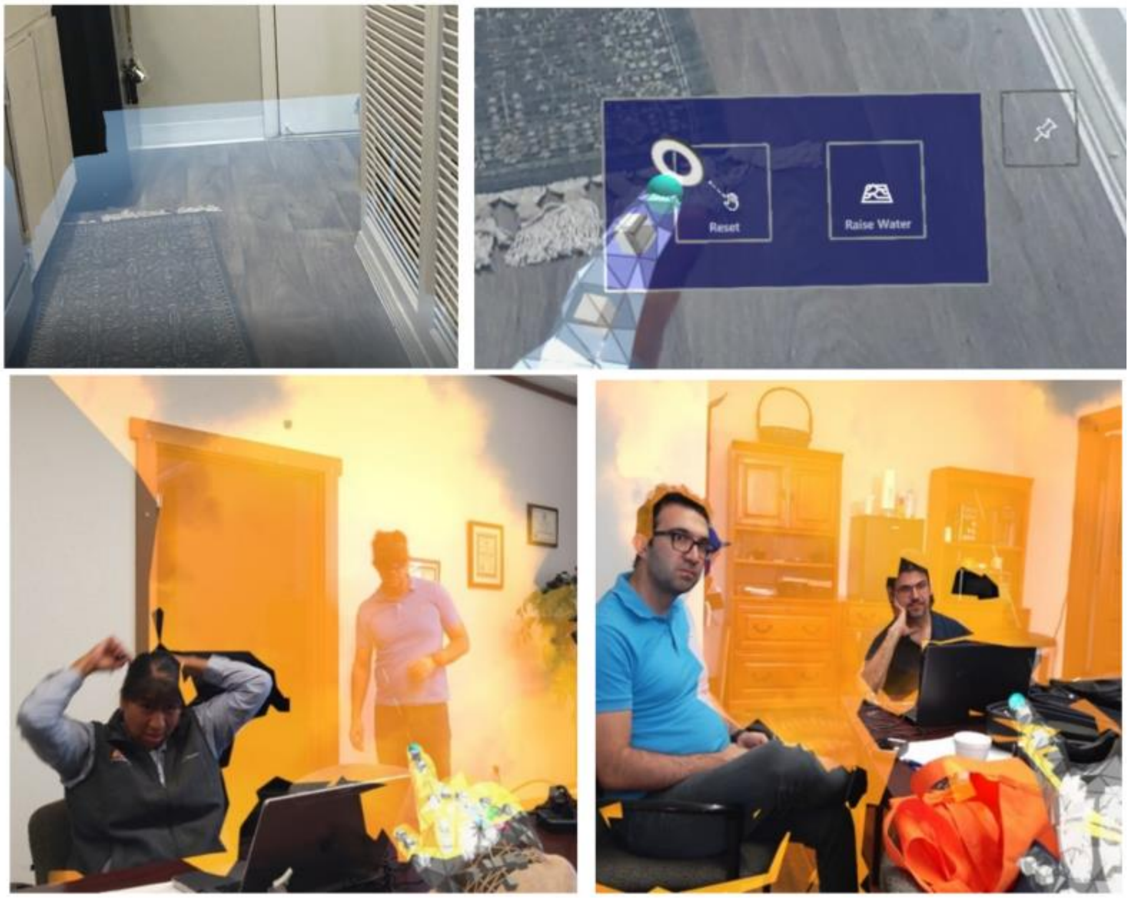



**Figure 39. Demonstration of the AR emergency application (flooding and fire simulator).**

Key strengths noted by the participants included the app's practical application for training purposes and its capacity to clearly demonstrate the consequences of heavy rain and rising water levels. However, they also noted that the app's user interface could be more intuitive for educational use.

Recommendations for further development included refining the user experience and incorporating customizable flood thresholds based on specific river or weather conditions. We also presented an AR fire application to show the potential of AR for simulating emergency situations.

Table 2 summarizes the HWM points of view after testing the AR app. This table provides bullet points of all the strengths, weaknesses and recommendations provided by HWM personnel. The limitations and the recommendations were recorded by the research team to improve the application for future development.

**Table 2. Summary of the HWM team's feedback and recommendations.**

| | |
|---|---|
| Strengths | • The app is well-suited for training, offering a safe platform to conceptualize flooding scenarios.<br>• It effectively illustrates the impact of heavy rain and subsequent flooding in a straightforward manner.<br>• There is substantial potential for improving the app to enhance disaster preparedness and training capabilities. |
| Weaknesses | • The app currently lacks the ability to simulate certain weather-related challenges. |
| Recommendations for Future Development | • Use colors to show the intensity of the flooding using feet, not inches:<br>i. 0-1.5 feet: green<br>ii. 1.5-3 feet: yellow<br>iii. >3 feet: red<br>• Make the system to show the flow of flooding in cubic feet per second (CFS) unit.<br>• Develop sensors and test AR app outdoors especially good if those can be tested in Ruidoso and Gallinas (USGIS station).<br>• Improve the app's user-friendliness and accessibility, especially for educational purposes and training sessions.<br>• Incorporate flood threshold features to simulate rising water levels in rivers more accurately. |

Figure 40 shows the USGIS Gallinas station's website. The research group has decided to deploy the sensors there for finalizing the project based on the emergency expert's opinion. This site was recommended by Phoebe Suina after trying the AR applications and Phoebe suggests that we connect the LEWIS data and validate it with the gage height in future research.

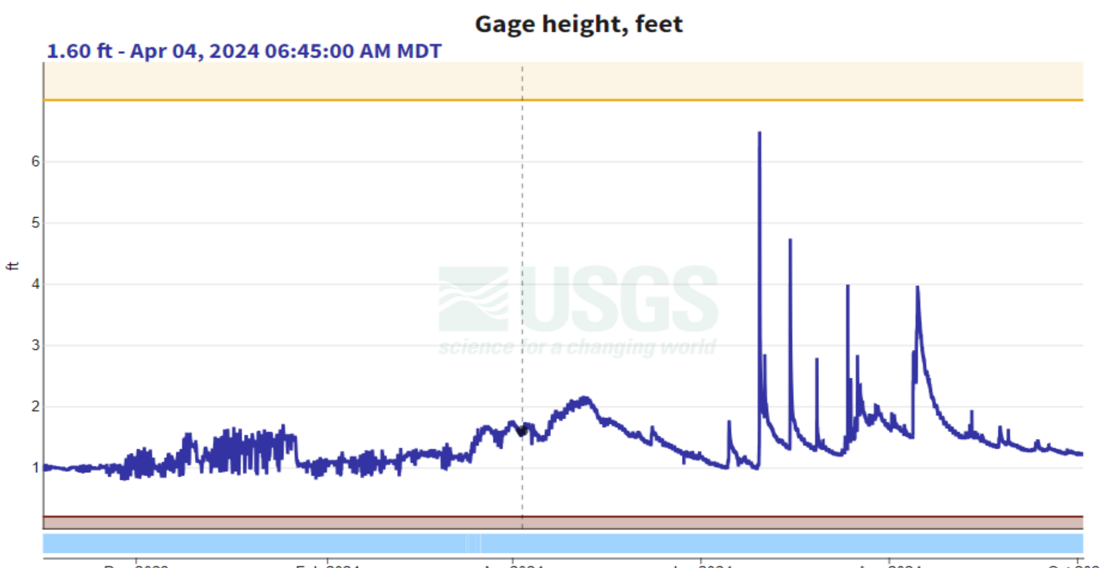
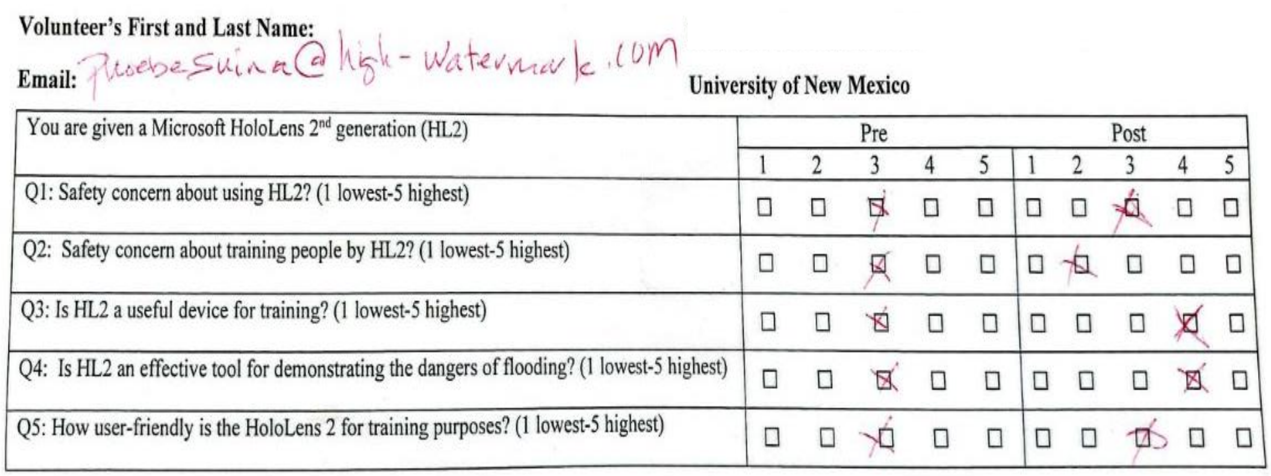



**Figure 40. Gallinas USGIS station website (https://waterdata.usgs.gov/monitoring-location/gallinas)**

The participants completed a comprehensive questionnaire before and after using the AR app, providing feedback on the safety, usefulness, and user-friendliness of the HoloLens 2 for training purposes. Figure 41 includes an example of a complete questionnaire that reflects the feedback provided by participants on the use of the AR app.

Here is the summary of the questionnaire analysis:

- Safety concerns about using HoloLens 2: 60% felt it was safe, unchanged after using the app.
- Safety concern about training people with HoloLens 2: 60% felt it was safe before, but only 40% felt so after using the app.
- Is HoloLens 2 a useful device for training? 60% agreed before, and 80% agreed after using the app.
- Is HoloLens 2 an effective tool for demonstrating the dangers of flooding? 60% agreed before, and 80% agreed after using the app.
- How user-friendly is HoloLens 2 for training purposes? 60% felt it was user-friendly, unchanged after using the app.


Volunteer's First and Last Name:

Email: PhoebeSuina@high-watermark.com

University of New Mexico

| You are given a Microsoft HoloLens 2nd generation (HL2) | Pre | | | | | Post | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| Q1: Safety concern about using HL2? (1 lowest-5 highest) | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ |
| Q2: Safety concern about training people by HL2? (1 lowest-5 highest) | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ |
| Q3: Is HL2 a useful device for training? (1 lowest-5 highest) | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ |
| Q4: Is HL2 an effective tool for demonstrating the dangers of flooding? (1 lowest-5 highest) | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ |
| Q5: How user-friendly is the HoloLens 2 for training purposes? (1 lowest-5 highest) | ☐ | ☐ | ☒ | ☐ | ☐ | ☐ | ☐ | ☒ | ☐ | ☐ |

**Figure 41. An example of a filled-out questionnaire by the High-Water Mark LLC team, providing their professional feedback on the AR flooding app's effectiveness, user-friendliness, and safety concerns before and after using the app.**

## Practical value of the developed technology

### Prospect Solutions LLC input

Prospect Solutions LLC has supervised the progress of the research project and provided direction on the areas that need to be developed to transition from research results to commercial ready technology, which will increase the impact of this collaboration in low cost technologies and emergencies responses.

### Meetings, directions, and updates

The team briefed PS on the start of the project and regularly with the new progress on the LEWIS technology, which has evolved from a laboratory product to a sensor that can be installed remotely and does not need a hot spot for data sharing. The research team devoted the attention to the sensor simplification following PS directions and recommendations. The new product was shared with PS leadership in Summer 2024 to receive more direction. PS conducted an evaluation of the progress and recommended SMILab new simplifications for the second half of the project. PS met with SMILab at the end of the project and discussed the directions for commercial ready development, technical and commercial barriers, and suggestions for a more advanced simplification of the technology for community users.

### Directions for commercial ready development

According to PS, the following are necessary steps for the implementation of this technology and were asked from SMILab:

- The hardware and software have to be finalized so they can be used and accessed by potential buyers and tested before they decide to implement them.
- The Intellectual Property of the technology needs to be clarified with potential buyers, as that is the most valuable piece, in case they want to choose to own it or simply use it.
- The cost of the sensor and the AR needs to decrease as it is not clear which entity would be able to purchase them.
- A project schedule for implementation with companies interested in acquiring and testing this technology would be needed.
- A decision whether to implement this technology in an existing company or to develop a new company would need to be made to advance this technology forward for public and private users.

In summary, although the technical aspect of the technology has been proven to be successful and convinced HWM and PS, the next step would involve a further simplification and the development of a business model in coordination with potential stakeholders, UNM Rainforest, New Mexico and entrepreneurs across the country.

## Conclusions

The direct involvement of HWM and PS assisted in collecting input on the value for commercialization, emergencies, decisions, as well as the user interface changes. Stakeholders also provided recommendations to enable this tool to contribute to disasters assessment and management by different communities. The following chapter summarizes commercialization opportunities.

# Chapter 7. Technology Transfer and Community Engagement and Participation (CEP) Activities

## Task 7: Preliminary draft community-informed thresholds of flooding using AR

Based on the professional feedback provided by HWM LLC, the research team began drafting preliminary flood thresholds to be integrated into the AR flooding simulation. These thresholds, based on input from engineers and community leaders, account for local conditions and weather variables. Initial estimates suggest water level thresholds between one and a few feet, depending on the specific area. These thresholds will be integrated into the AR system to enhance the realism of flood simulations and improve their applicability for disaster preparedness training.

The meeting also revealed valuable insights regarding how the AR app could better reflect real-world flood hazards, and additional improvements are planned to ensure the app can simulate flood conditions across various geographic locations. These thresholds will serve as a foundation for future updates to the AR app, enabling a more accurate and location-specific simulation of flood risks.

Phoebe Suina is recommending that the team deploys sensors and AR interfaces in Ruidoso in Southern New Mexico. Figure 42 shows two disasters shared by Phoebe Suina at Ruidoso where they recommend we try to deploy sensors and an AR interface outdoors to see water levels that the community can evaluate and understand.

(a)

(b)

**Figure 42. Ruidoso potential deployment suggested by HWM LLC for threshold sharing at a real location: (a) near residential housing; (b) across the village.**

# Chapter 8. Invention Disclosures and Patents, Publications, Presentations, Reports, Project Website, and Social Media Listings

## Introduction

The project's advancements and findings were actively disseminated through a variety of platforms, ensuring that the knowledge and innovations reached a broad audience. This strategy included academic publications in renowned journals, presentations at key industry conferences, and detailed reports that provided insights into the research process and outcomes. These publications served not only to share the findings with the scientific community but also to establish a foundation for future research in similar domains. Additionally, presentations at conferences and workshops provided opportunities to engage with peers, gather feedback, and foster collaborations that extended the project's impact and applicability.

## Project data website (available during the project)

A project website (https://lewisdata.org/) was created to serve as the central hub for information, updates, and resources related to the project. It featured an interactive interface showcasing real-time data from the sensors. Alongside the website, the project maintained an active presence on various social media platforms. These channels were utilized not just to inform and update the public and stakeholders about the project's progress and events but also to engage with a wider community. Interactive posts, informative content, and community engagement initiatives on these platforms played a crucial role in raising awareness about the project, driving conversations around weather and condition monitoring technology, and promoting the importance of community involvement in such initiatives.

## Conferences

Two conference articles were presented by research team:

- Smart Sensing Technology and its Aid in Flood Data Analysis for Northern New Mexico
- Low-Cost Efficient Wireless Intelligent Sensor (LEWIS) Deployment for Community Driven Decision Making

## Journal Publication

This was also an opportunity to gather feedback for the forthcoming publication 'Developing an Affordable Wireless Ultrasonic Sonar Sensor System for Early Flood Detection and Autonomous Monitoring in Ohkay Owingeh' by Ali Mohammadkhorasani et al.

## Media

Below are events that included publications, presentations, and social media

- New Mexico high schoolers presented projects at annual STEM challenge: high school students were mentored by SMILab in their Augmented Reality project to reduce anxiety in the cafeteria lunch led by the high school students of Zuni. More than 400 high schoolers gathered at the UNM Student Union Building Saturday to present their projects at the annual New Mexico Governor’s STEM Challenge.

https://www.kob.com/new-mexico/new-mexico-high-schoolers-present-projects-at-annual-stem-challenge/

- A Civil Engineering Class at the University of New Mexico gave a new meaning to reaching higher, What's Cool in Steel, Modern Steel Construction, American Institute of Steel Construction (AISC), December (2023)

# References

Aguero, Marlon, Dilendra Maharjan, Maria del Pilar Rodriguez, David Dennis Lee Mascarenas, and Fernando Moreu. 2020. “Design and Implementation of a Connection between Augmented Reality and Sensors.” *Robotics* 9 (1): 3. https://doi.org/10.3390/robotics9010003.

Aoyama, Kazuma. 2019. “Novel Display Using Percutaneous Electrical Stimulation for Virtual Reality.” In *Human Interface and the Management of Information. Information in Intelligent Systems*, edited by Sakae Yamamoto and Hirohiko Mori, 3–14. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-22649-7_1.

“Arduino Reference.” n.d. Accessed October 27, 2022. https://www.arduino.cc/reference/en/.

Ayyildiz, Cem, H. Emre Erdem, Tamer Dirikgil, Oguz Dugenci, Taskin Kocak, Fatih Altun, and V. Cagri Gungor. 2019. “Structure Health Monitoring Using Wireless Sensor Networks on Structural Elements.” *Ad Hoc Networks* 82 (January):68–76. https://doi.org/10.1016/j.adhoc.2018.06.011.

Azuma, Ronald T. 1997. “A Survey of Augmented Reality.” *Presence: Teleoper. Virtual Environ.* 6 (4): 355–85. https://doi.org/10.1162/pres.1997.6.4.355.

Barrett, Steven F. 2013. *Arduino Microcontroller Processing for Everyone!* Synthesis Lectures on Digital Circuits & Systems. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-79864-1.

Bayode, Abiodun, John Andrew Van der Poll, and Rohith Roopnaria Ramphal. 2019. “4th Industrial Revolution: Challenges and Opportunities in the South African Context.” In . Johannesburg (SA). https://doi.org/10.17758/EARES8.EAP1119285.

Berryman, Donna R. 2012. “Augmented Reality: A Review.” *Medical Reference Services Quarterly* 31 (2): 212–18. https://doi.org/10.1080/02763869.2012.670604.

Botero-Valencia, J. S., M. Mejia-Herrera, and Joshua M. Pearce. 2022. “Low Cost Climate Station for Smart Agriculture Applications with Photovoltaic Energy and Wireless Communication.” *HardwareX* 11 (April):e00296. https://doi.org/10.1016/j.ohx.2022.e00296.

Burdea, Grigore C., and Philippe Coiffet. 2003. *Virtual Reality Technology*. John Wiley & Sons.

Cattari, Nadia, Fabrizio Cutolo, Renzo D’amato, Umberto Fontana, and Vincenzo Ferrari. 2019. “Toed-in vs Parallel Displays in Video See-Through Head-Mounted Displays for Close-Up View.” *IEEE Access* 7:159698–711. https://doi.org/10.1109/ACCESS.2019.2950877.

Grimmelsman, Kirk A., and Navid Zolghadri. 2020. “Experimental Evaluation of Low-Cost Accelerometers for Dynamic Characterization of Bridges.” In *Dynamics of Civil Structures, Volume 2*, edited by Shamim Pakzad, 145–52. Conference Proceedings of the Society for Experimental Mechanics Series. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-12115-0_19.

Khandelwal, D.d., and Mohit Singhal. 2021. “Developing a Low-Cost Weather Monitoring System for Data-Sparse Regions of the Himalayas.” *Weather* 76 (2): 60–64. https://doi.org/10.1002/wea.3647.

Komarizadehasl, Seyedmilad, Fidel Lozano, Jose Lozano-Galant, Gonzalo Ramos, and Jose Turmo. 2022. “Low-Cost Wireless Structural Health Monitoring of Bridges.” *Sensors (Basel, Switzerland)* 22 (July). https://doi.org/10.3390/s22155725.

Komarizadehasl, Seyedmilad, Behnam Mobaraki, Haiying Ma, Jose-Antonio Lozano-Galant, and Jose Turmo. 2021. “Development of a Low-Cost System for the Accurate Measurement of Structural Vibrations.” *Sensors* 21 (18): 6191. https://doi.org/10.3390/s21186191.

Manda, More Ickson, and Soumaya Ben Dhaou. 2019. “Responding to the Challenges and Opportunities in the 4th Industrial Revolution in Developing Countries.” In *Proceedings of the 12th International Conference on Theory and Practice of Electronic Governance*,

244–53. ICEGOV ’19. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3326365.3326398.
Milgram, P., and F. Kishino. 1994. “A Taxonomy of Mixed Reality Visual Displays.” *IEICE Transactions on Information and Systems*, December. https://www.semanticscholar.org/paper/A-Taxonomy-of-Mixed-Reality-Visual-Displays-Milgram-Kishino/f78a31be8874eda176a5244c645289be9f1d4317.
Mohammadkhorasani, Ali, Kaveh Malek, Rushil Mojidra, Jian Li, Caroline Bennett, William Collins, and Fernando Moreu. 2023. “Augmented Reality-Computer Vision Combination for Automatic Fatigue Crack Detection and Localization.” *Computers in Industry* 149:103936.
Moreu, Fernando, and Kaveh Malek. 2023. “Human-Machine Interfaces Using Augmented Reality.” *STRUCTURAL HEALTH MONITORING 2023*, no. 0. https://doi.org/10.12783/shm2023/36970.
Nahon, David, Geoffrey Subileau, and Benjamin Capel. 2015. “‘Never Blind VR’ Enhancing the Virtual Reality Headset Experience with Augmented Virtuality.” In *2015 IEEE Virtual Reality (VR)*, 347–48. https://doi.org/10.1109/VR.2015.7223438.
Naser, M. Z. 2023. “Machine Learning for All! Benchmarking Automated, Explainable, and Coding-Free Platforms on Civil and Environmental Engineering Problems.” *Journal of Infrastructure Intelligence and Resilience* 2 (1): 100028. https://doi.org/10.1016/j.iintel.2023.100028.
Naseri, Kasra, and Michelle Hummel. 2021. “Development of a Bayesian Copula-Based Nonstationary Framework for Compound Flood Risk Assessment” 2021 (December):NH15D-0471.
Ohta, Yuichi, and Hideyuki Tamura. 2014. *Mixed Reality: Merging Real and Virtual Worlds*. 1st ed. Springer Publishing Company, Incorporated.
Ozdagli, A. I., B. Liu, and F. Moreu. 2018. “Low-Cost, Efficient Wireless Intelligent Sensors (LEWIS) Measuring Real-Time Reference-Free Dynamic Displacements.” *Mechanical Systems and Signal Processing* 107 (July):343–56. https://doi.org/10.1016/j.ymssp.2018.01.034.
Petrillo, Antonella, Fabio De Felice, Raffaele Cioffi, Federico Zomparelli, Antonella Petrillo, Fabio De Felice, Raffaele Cioffi, and Federico Zomparelli. 2018. “Fourth Industrial Revolution: Current Practices, Challenges, and Opportunities.” In *Digital Transformation in Smart Manufacturing*. IntechOpen. https://doi.org/10.5772/intechopen.72304.
Pitsis, Tyrone S., Sara L. Beckman, Martin Steinert, Luciano Oviedo, and Bettina Maisch. 2020. “Designing the Future: Strategy, Design, and the 4th Industrial Revolution—An Introduction to the Special Issue.” *California Management Review* 62 (2): 5–11. https://doi.org/10.1177/0008125620907163.
Sanei, Mahsa, Solomon Atcitty, and Fernando Moreu. 2024. “Low-Cost Efficient Wireless Intelligent Sensor (LEWIS) for Research and Education.” *Sensors* 24 (16): 5308. https://doi.org/10.3390/s24165308.
Savina, M., B. Schäppi, P. Molnar, P. Burlando, and B. Sevruk. 2012. “Comparison of a Tipping-Bucket and Electronic Weighing Precipitation Gage for Snowfall.” *Atmospheric Research*, Rainfall in the urban context: forecasting, risk and climate change, 103 (January):45–51. https://doi.org/10.1016/j.atmosres.2011.06.010.
Shanmuganthan, S., A. Ghobakhlou, and P. Sallis. 2008. “Sensor Data Acquisition for Climate Change Modelling.” In . https://www.semanticscholar.org/paper/Sensor-data-acquisition-for-climate-change-Shanmuganthan-Ghobakhlou/a2f21c98ebdcb14da954d9aa487cc01b9cc13997.
Speicher, Maximilian, Brian D. Hall, and Michael Nebeling. 2019. “What Is Mixed Reality?” In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–

15. CHI ’19. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3290605.3300767.
Takara. 2019. “Alex Kipman’s Grand Vision for How Holograms Will Change Our Lives.” *Adafruit Industries - Makers, Hackers, Artists, Designers and Engineers!* (blog). November 25, 2019. https://blog.adafruit.com/2019/11/25/alex-kipmans-grand-vision-for-how-holograms-will-change-our-lives/.
Ternier, Stefaan, Roland Klemke, Marco Kalz, Patricia Van Ulzen, and Marcus Specht. 2012. “ARLearn: Augmented Reality Meets Augmented Virtuality.” *JUCS - Journal of Universal Computer Science* 18 (15): 2143–64. https://doi.org/10.3217/jucs-018-15-2143.
Ungureanu, Dorin, Federica Bogo, Silvano Galliani, Pooja Sama, Xin Duan, Casey Meekhof, Jan Stühmer, et al. 2020. “HoloLens 2 Research Mode as a Tool for Computer Vision Research.” arXiv. https://doi.org/10.48550/arXiv.2008.11239.
Wang, Yang, Jerome Peter Lynch, and Kincho H. Law. 2005. “Validation of an Integrated Network System for Real-Time Wireless Monitoring of Civil Structures.” *Ann Arbor*, no. 1001 (January), 48109.
Xu, Jiaqi, and Fernando Moreu. 2021. “A Review of Augmented Reality Applications in Civil Infrastructure During the 4th Industrial Revolution.” *Frontiers in Built Environment* 7. https://www.frontiersin.org/articles/10.3389/fbuil.2021.640732.
Zakaria, Muhammad Izzat, Waheb A. Jabbar, and Noorazliza Sulaiman. 2023. “Development of a Smart Sensing Unit for LoRaWAN-Based IoT Flood Monitoring and Warning System in Catchment Areas.” *Internet of Things and Cyber-Physical Systems* 3 (January):249–61. https://doi.org/10.1016/j.iotcps.2023.04.005.
Zhou, Ying, Hanbin Luo, and Yiheng Yang. 2017. “Implementation of Augmented Reality for Segment Displacement Inspection during Tunneling Construction.” *Automation in Construction* 82 (October):112–21. https://doi.org/10.1016/j.autcon.2017.02.007.
Zyda, M. 2005. “From Visual Simulation to Virtual Reality to Games.” *Computer* 38 (9): 25–32. https://doi.org/10.1109/MC.2005.297.

# Appendix A: SPTC FoT 2024

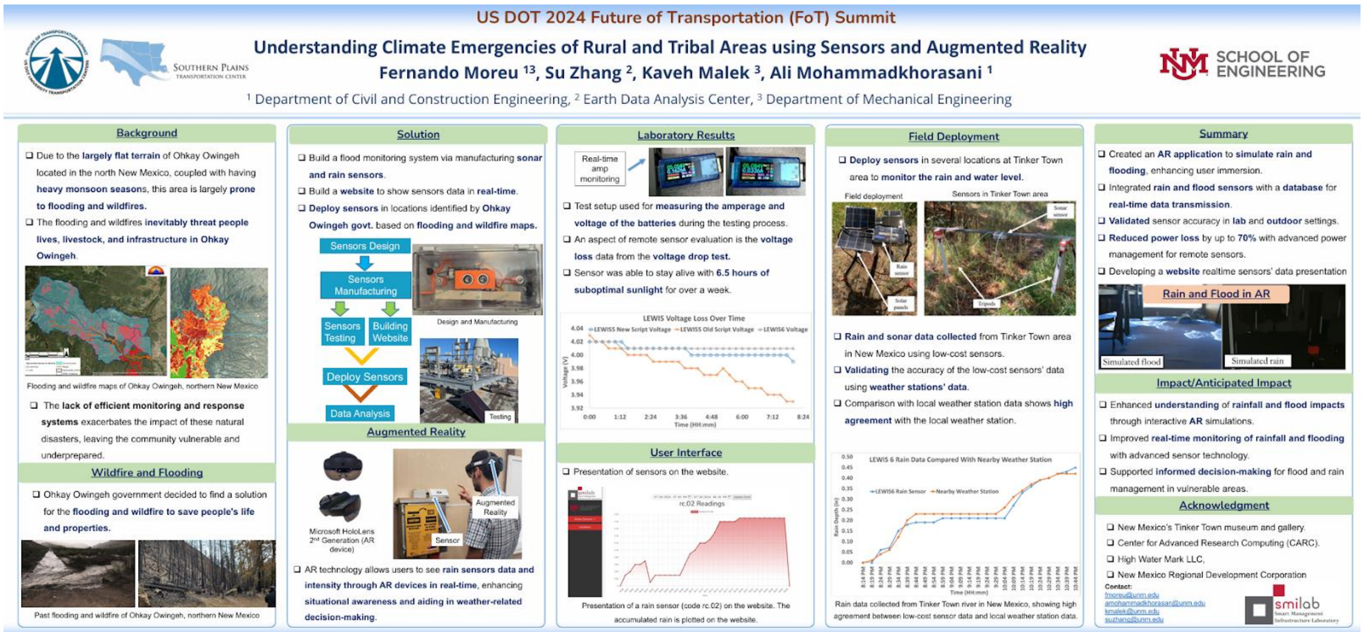



**Figure 43. Sensors and Augmented Reality to improve real-time monitoring of rainfall and flooding.**

# Appendix B: Project presentations at TRB 2025

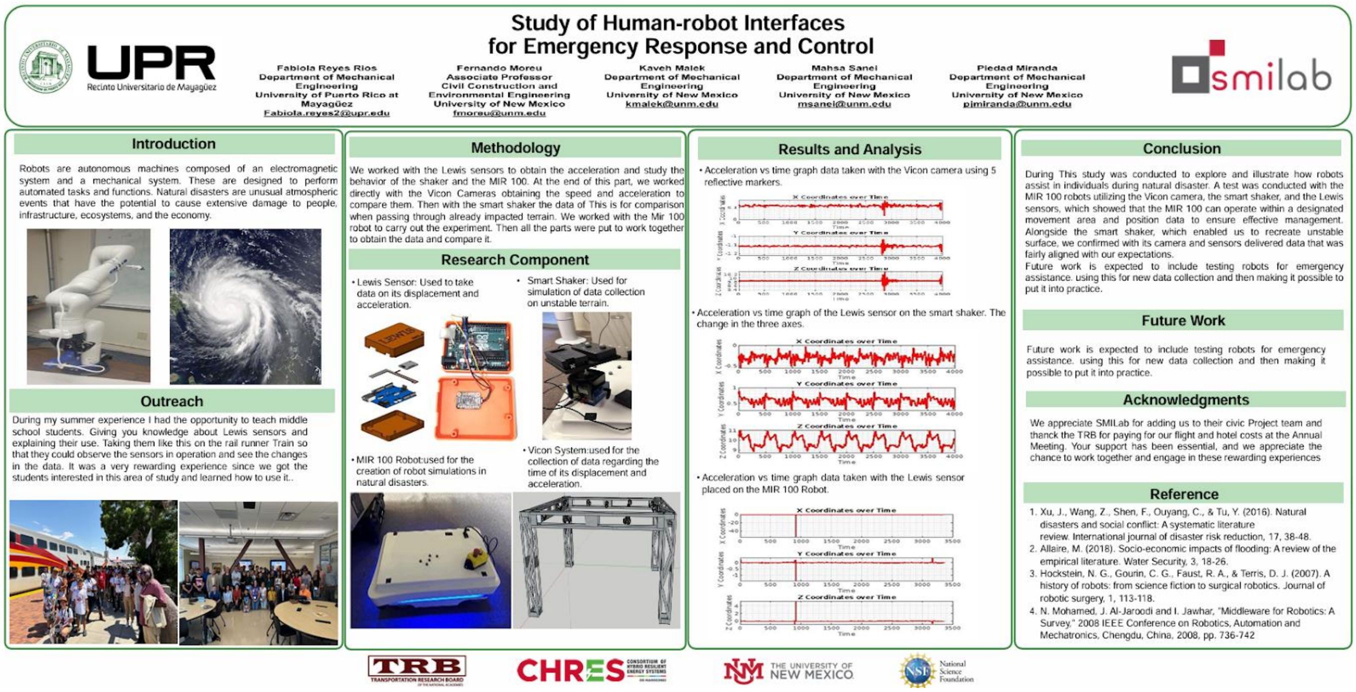



**Figure 44. Human-robot Interfaces for Emergency Response and Control.**

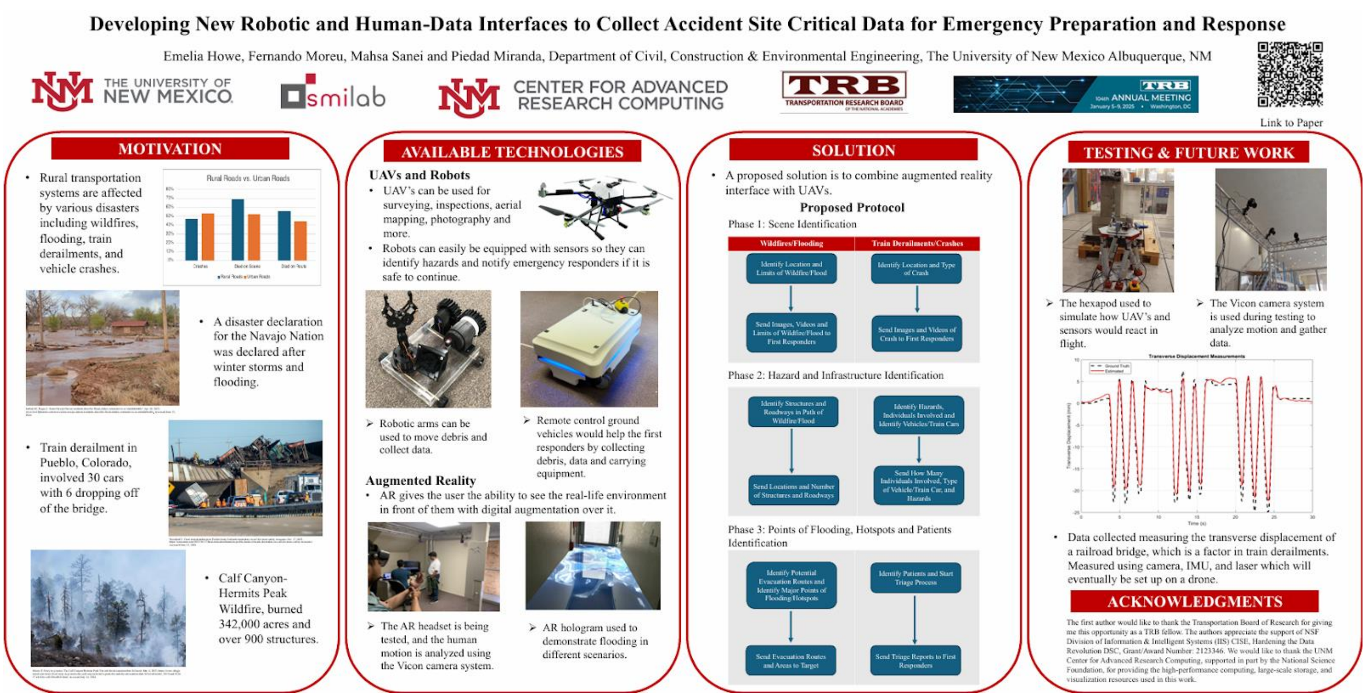



**Figure 45. New Robotic and Human-Data Interfaces for emergency preparation and response.**

Southern Plains
Transportation Center

The University of Oklahoma | OU Gallogly College of Engineering
202 W Boyd St, Room 213A, Norman, OK 73019 | (405) 325-4682 | Email: sptc@ou.edu