ST. MARY'S UNIVERSITY

School of Science, Engineering and Technology
Department of Engineering

Ultra GPS – Indoor Positioning System

By

Nnamdi Jesse Onwuzurike & Leon Harb

Senior Design Project Presented to the Department of Engineering
In Partial Fulfillment of the Requirements
For the Degree of

Bachelor of Science
in
COMPUTER ENGINEERING

San Antonio, Texas
May 2025

Supervising Advisor:

Dr. Djaffer Ibaroudene
PROFESSOR OF COMPUTER ENGINEERING

Dr. Ben Abbott
PROFESSOR OF COMPUTER ENGINEERING

ABSTRACT

The objective of this project is to develop an affordable indoor navigation system for autonomous vehicles where GPS is unreliable or unavailable. The system is intended to meet the requirements of educational environments, providing ±5 cm localization precision and update rates of 5 Hz. This project initially explored multiple localization methodologies, including SLAM (Simultaneous Localization and Mapping), RF-based tracking, and ultrasound systems. We ultimately settled with the use of ultrasound, hence the name UltraGPS. The final design integrates cost-effective hardware with real-time data processing, allowing seamless operation both indoors and outdoors. This work aims to create a scalable solution that enhances robotics education by offering practical, hands-on experience with indoor autonomous systems.

ACKNOWLEDGEMENTS

We would like to thank our supervising professors, Dr. Djaffer Ibaroudene and Dr. Ben Abbott, for their guidance, feedback, and encouragement throughout the duration of this project. We also express our appreciation to Alex Youngs and Hatchbed LLC, our sponsor organization as well as MINDS-i Education, for their support and for providing the opportunity to work on a project with real-world relevance. Finally, we are grateful to St. Mary's University and the Engineering Department for granting access to essential lab facilities and tools, such as the Vicon motion capture system, which were critical to our success.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The evolution of autonomous vehicle technologies has heavily relied on advancements in accurate localization and navigation systems. Outdoor environments benefit from high-precision solutions like RTK-GPS (Real-Time Kinematic Global Positioning Systems), enabling centimeter-level accuracy critical for vehicle control and decision-making. However, these systems are ineffective indoors, where GPS signals are either weak or entirely absent.

As educational institutions, research labs, and development centers increasingly explore autonomous systems, the lack of reliable indoor positioning solutions presents a significant challenge. Many existing indoor localization systems, such as vision-based setups or commercial radio-frequency solutions, are often cost-prohibitive, infrastructure-intensive, or difficult to deploy for small-scale applications.

This project, UltraGPS, aims to address this critical gap by designing a low-cost, deployable, and accurate indoor localization system specifically tailored for small autonomous vehicles operating in indoor spaces. The system leverages ultrasonic technology combined with Arduino microcontrollers, wireless communication, and real-time signal processing to provide reliable relative positioning within a gymnasium or laboratory environment.

Sponsored by Hatchbed, LLC. the UltraGPS project is designed to achieve high accuracy (within 5 cm), rapid calibration (under 10 minutes), and compatibility with existing small-scale autonomous platforms, enabling broader educational and prototyping applications without the need for extensive infrastructure investments.

1.1 COMPANY DESCRIPTION

***Figure 1**: Hatchbed, LLC. Logo*

Hatchbed, LLC is a specialized technology firm providing customized solutions and research and development services for industries focused on autonomous vehicles, robotics, data analysis, AI, and advanced software systems. With over 70 years of combined experience among its team members, Hatchbed has a proven track record of solving the most challenging problems in autonomous vehicle technology and robotics R&D.

The company has developed and invented unique technologies supporting the automation of real-world vehicles — including passenger cars, Class 8 trucks, and low-speed electric vehicles — and created full-stack autonomy software for both on-road and off-road applications. Hatchbed's technical expertise spans critical fields such as localization and mapping, perception systems, vehicle control, motion planning, world modeling, and behavior management.

Their capabilities include advanced technologies like Sensor Fusion, SLAM (Simultaneous Localization and Mapping), object detection and prediction, route planning, ROS integration, Lidar and Radar sensing, machine learning, visual odometry, obstacle avoidance, and multi-sensor calibration.

Hatchbed offers a full range of services, including custom software development tailored to client requirements, adaptation of open-source technologies, and consulting services such as automation technology audits and early-stage engineering support. The company serves clients worldwide, helping them accelerate innovation in the dynamic fields of autonomy, robotics, and intelligent systems.

1.2 PROBLEM STATEMENT

Accurate localization is essential for autonomous vehicles and robotic systems. While RTK-GPS technology provides highly precise positioning outdoors, its signals are unreliable or unavailable in indoor environments such as classrooms, laboratories, and gymnasiums. This limitation creates a major barrier for research, development, and education efforts that seek to demonstrate and test autonomous vehicle systems indoors.

Current indoor localization solutions (such as vision-based tracking systems or commercial UWB systems) tend to be expensive, complex to set up, or require significant infrastructure changes, making them impractical for smaller educational institutions or research teams with limited budgets.

To address this gap, there is a need for a low-cost, easily deployable, and reliable indoor positioning system that can enable autonomous or semi-autonomous vehicles, such as small robotic tractors, to operate accurately indoors without reliance on external GPS signals. Such a system must deliver high accuracy, require minimal calibration time, and be robust enough to function in real-world indoor environments where obstacles, reflections, and varying conditions are present.

1.3 OBJECTIVE

The objective of the UltraGPS project is to develop an affordable indoor navigation system that enables autonomous vehicles to localize and operate effectively in environments where GPS is unreliable or unavailable. The system targets educational applications and aims to provide ±5 cm localization precision with an update rate of 5 Hz, allowing seamless, real-time operation indoors. The objective is to ensure that the system is affordable and that it is easily deployable and usable by students and educators without specialized technical expertise.

1.4 PROJECT REQUIREMENTS

1. The system must provide a 2D real-time localization of the moving tractor.

2. The system must provide positioning accuracy of 5 cm or less.

2. The system must operate within the size of a standard school gymnasium.

3. The system calibration and setup must take less than 10 minutes.

5. The system must use a reliable wired interface (e.g., Ethernet or USB) for transferring data.

6. The system should be compatible with available interfaces like USB (Universal Serial Bus) ports on existing onboard computers (e.g., Raspberry Pi).

7. Update at a minimum update rate of 5 Hz.

8. The system must output position data in NMEA (National Marine Electronics Association) format.

1.5 PROJECT CONSTRAINTS

1. The transmitter system must not interfere with the vehicle's size, profile, or weight in a way that affects performance.

2. The transmitter system must not interfere with existing onboard sensors.

3. The onboard power system must be able to support the transmitter system without exceeding power capacity.

4. The system must be considered an add-on module, requiring no removal of existing vehicle components.

5. The system must not use prohibited RF bands in the United States.

6. The transmitter system must cost $100 or less per platform.

7. The ground receiver system must cost $500 or less.

8. The ground system must be lightweight, simple to assemble, and require no specialized tools.

1.6 LITERATURE REVIEW

1.6.1 Simultaneous Localization and Mapping (SLAM)

Simultaneous Localization and Mapping (SLAM) Techniques: SLAM is a widely studied method in autonomous navigation. Our research highlights the use of sensors such as LIDAR (Light Detection and Ranging), cameras, and IMUs (Inertial Measurement Units) to map unknown environments and localize robots within them. Studies have shown that SLAM algorithms, when properly implemented, can achieve high accuracy in indoor environments. Recent work by Cadena et al. [16] presents advancements in real-time SLAM, focusing on improving accuracy and reducing computational overhead, which is critical for the application in educational settings where affordable hardware is a constraint.

1.6.2 Radio Frequency (RF)-based Localization

Radio Frequency (RF)-Based Indoor Localization: RF-based localization is another promising method, particularly when GPS is unavailable. In the work by Liu et al. [9], they explore indoor positioning systems using RF signals, such as Wi-Fi and UWB (Ultra-Wideband), achieving sub-meter accuracy in dense environments. These systems demonstrate a high potential for indoor autonomous navigation, offering robustness in environments where line-of-sight may be obstructed by people or obstacles. RF-based positioning systems have the advantage of scalability, which aligns with our goal of supporting multiple autonomous tractors simultaneously.

1.6.3 Real-Time Kinematic Systems

Real-Time Kinematic (RTK) Systems: RTK, commonly used for precision agriculture, has seen advancements in low-cost implementations. In a study by Daniel Janos and Przemysław Kuras [7], these systems-maintained centimeter-level accuracy even under challenging conditions. However, indoor use remains problematic due to reliance on satellite signals, suggesting alternatives like SLAM or RF-based solutions for environments where GPS signals are unreliable.

1.6.4 Ultrasound-Based Localization

Ultrasound-Based Localization: Ultrasound localization systems have also been explored for indoor positioning, offering centimeter-level accuracy. However, research by Faheem Ijaz, Hee Kwon Yang, Arbab Waheed Ahmad, and Chankil Lee [6] investigates ultrasound and inertial sensor fusion for indoor localization, yielding high accuracy. However, as highlighted by their study, environmental noise and reflections make this method less reliable in crowded spaces. This aligned with the project's initial interest in RF or LIDAR-based solutions as more stable alternatives.

1.6.5 Time-of-Flight (ToF) and Trilateration Algorithms

Time-of-Flight (ToF) is a fundamental technique in distance measurement, where the time taken by a signal to travel from a transmitter to a receiver is used to calculate distance. In indoor localization, ToF is often employed with ultrasonic or radio signals to determine the position of an object. Trilateration uses these distance measurements from multiple known points to pinpoint the exact location of the object in two or three dimensions [12].

Key Concepts:

- ToF Measurement: Calculates distance based on signal travel time.
- Trilateration: Determines position using distances from at least three known points.
- Applications: Widely used in GPS, UWB, and ultrasonic positioning systems.

1.6.6 Hybrid Localization Systems

Hybrid localization systems combine multiple technologies to improve accuracy and reliability in indoor environments. By integrating different methods, such as combining RF signals with optical or inertial data, these systems can compensate for the limitations of individual technologies [8].

Key Concepts:

- Multi-Technology Integration: Combines strengths of various localization methods.
- Improved Accuracy: Mitigates weaknesses like signal blockage or multipath effects.
- Examples: Systems combining Bluetooth with Visible Light Communication (VLC) or RF with inertial sensors.

1.6.7 Latency and Real-Time Constraints in Embedded Systems

In real-time localization systems, latency is a critical factor. Ensuring timely data processing and response is essential for the system's effectiveness, especially in dynamic environments [10].

Key Considerations:

- Low-Latency Processing: Essential for real-time feedback and control.
- Efficient Algorithms: Necessary to meet timing constraints.
- System Optimization: Balancing accuracy and processing speed.

2. SOLUTION APPROACH AND PROCESS

2.1 Preliminary Design

At the outset of the project, our team explored multiple design strategies to address the problem of indoor localization in GPS-denied environments. The goal was to create a system that met our objectives of low cost, high accuracy, ease of deployment, and educational accessibility. A broad survey of existing technologies helped inform our initial approaches, which ranged from vision-based tracking systems to radio-frequency solutions and ultrasonic arrays.

Each proposed solution was evaluated using the following criteria:

- Accuracy and consistency of localization
- Cost of components and scalability
- Ease of deployment in a school gymnasium or lab
- Hardware integration with an existing autonomous mini-tractor
- Power consumption and onboard space requirements

2.1.1 First Solution Approach: RF-Based System

Our initial approach to solving the problem of indoor localization for autonomous tractors was to use radio frequency (RF) technology. RF-based systems are commonly used in various localization applications due to their long range and relatively low cost. We considered using radio modules to estimate distances between the tractor and fixed anchors placed around the environment.

This approach was initially attractive because RF modules are readily available, cost-effective, and well-documented in both academic and hobbyist circles. Additionally, RF systems do not require a clear line of sight between the transmitter and receiver, making them more resilient to physical obstructions in indoor environments compared to optical systems.

However, during preliminary research and analysis, we identified several limitations that made RF less ideal for our specific needs. The accuracy of RF-based distance estimation is significantly affected by multipath effects — the phenomenon where signals bounce off walls and objects, leading to inconsistent time-of-flight measurements. In indoor settings like classrooms or gymnasiums, this becomes especially problematic. Furthermore, achieving sub-5 cm precision with RF would require extremely high-frequency timing resolution and complex filtering algorithms, which increase both cost and implementation complexity.

Given these drawbacks, we decided to pivot away from RF and explore more accurate and reliable technologies better suited to short-range, high-precision indoor localization.

2.1.2 Second Solution Approach: Vision-Based System

Our first concept for addressing indoor localization was to implement a vision-based tracking system. Vision systems are widely used in robotics for tasks such as SLAM and pose estimation due to their high spatial resolution and compatibility with existing software libraries like OpenCV and AprilTags. The proposed setup involved mounting overhead cameras in the indoor environment and equipping the tractor with fiducial markers or distinct visual features that could be tracked in real time. These visual inputs would be processed to determine the vehicle's location, which would then be transmitted to a central computer or control unit.

This approach initially appeared promising because it required no additional hardware on the vehicle itself, thus preserving its mobility and simplicity. Furthermore, computer vision solutions can offer sub-centimeter positional accuracy under ideal conditions, and they integrate well with existing SLAM algorithms used in autonomous navigation research.

However, further analysis revealed multiple drawbacks that ultimately made this approach impractical for our specific application. Vision-based systems are highly sensitive to environmental conditions such as lighting variability, shadows, and occlusion from obstacles or people. The infrastructure required — including camera mounts, calibration software, and high-performance processing hardware — significantly increased complexity and cost. These factors conflicted with our core design goals of simplicity, affordability, and ease of deployment in standard educational environments.

As a result, we chose to move away from the vision-based approach in favor of a more robust, low-cost, and portable solution that could operate reliably under a wider range of indoor conditions.

2.1.3 Final Solution Approach: Ultrasonic System

After evaluating various approaches, we selected ultrasound-based positioning as the final solution for our indoor localization system. This decision was driven by ultrasound's proven ability to deliver high-precision distance measurements in controlled environments, particularly over short ranges. For an application like ours—where a tractor must navigate within a confined indoor space—ultrasound offers the accuracy, affordability, and simplicity needed to meet both our technical requirements and budget constraints.

Ultrasound systems work by measuring the time of arrival of acoustic pulses traveling between a transmitter and multiple receivers. Since the speed of sound is relatively slow and predictable compared to electromagnetic signals, precise distance measurements can be achieved without the need for expensive timing hardware. This makes ultrasound a cost-effective solution for achieving our target accuracy of ±5 cm or better.

Another advantage of using ultrasound is its resistance to electromagnetic interference, which can be a major issue in RF-based systems, especially in electronics-heavy indoor environments like classrooms or labs. Additionally, the use of sound waves makes line-of-sight placement easier to manage, and reverberation effects—while present—are generally more predictable and easier to filter out than RF multipath noise.

Our implementation involves placing multiple fixed receivers around the perimeter of the environment, while the autonomous tractor is equipped with a mobile transmitter. This reverse-GPS approach allows us to calculate the position of the tractor in real-time based on the time it takes for the ultrasonic signals to reach each receiver. The system is designed to output standard NMEA-formatted data, allowing for compatibility with existing navigation software used in outdoor systems, thereby maintaining seamless functionality across environments.

Overall, ultrasound offered the best trade-off between precision, cost, power consumption, and implementation complexity, making it the ideal solution for indoor localization in our educational robotics platform.

2.2 DETAIL DESIGN

2.2.1 Functional Decomposition

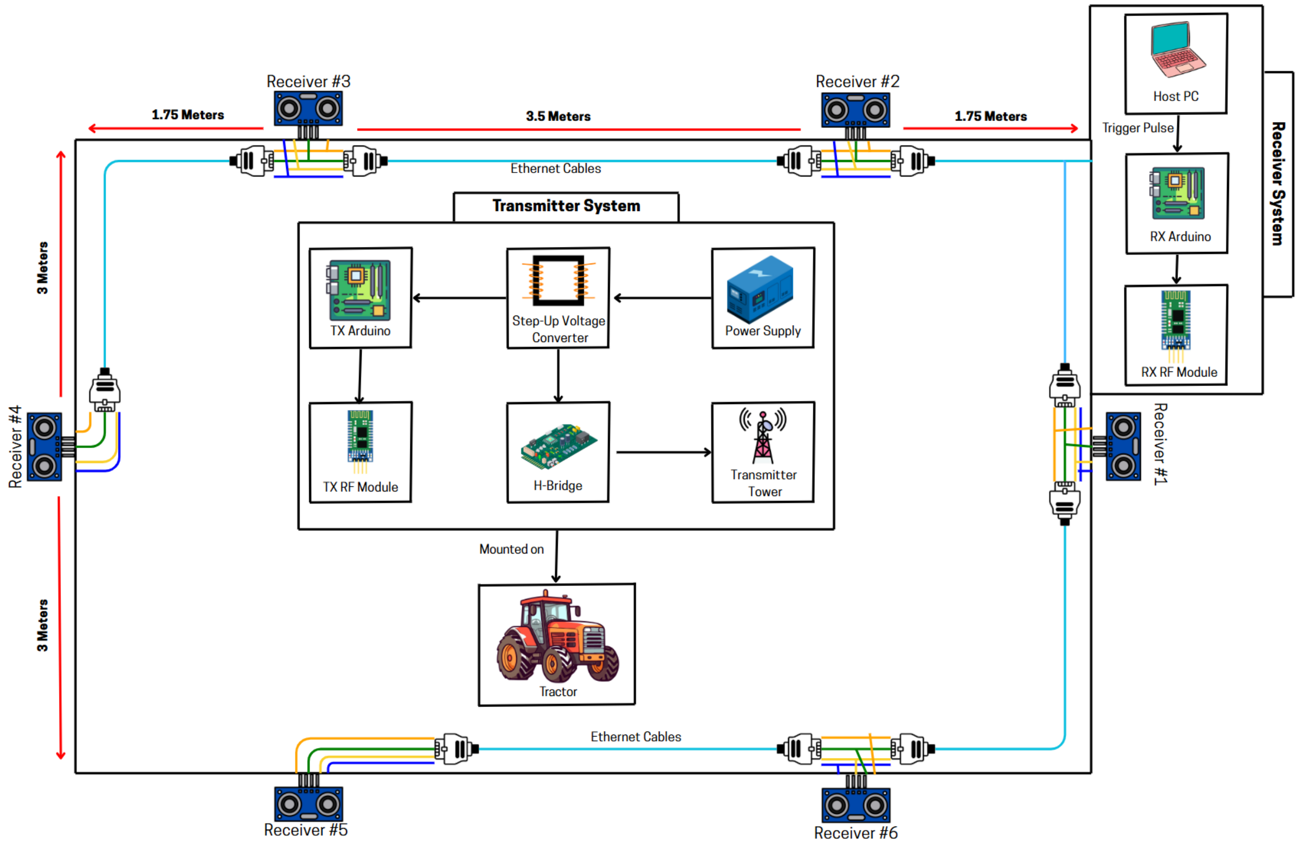

***Figure 2**: System Architecture Diagram*

2.2.1.1 Transmitting Subsystem

This subsystem is mounted on the autonomous tractor and is responsible for emitting ultrasound pulses. A ring of HC-SR04 ultrasonic transmitters is used to broadcast a pulse at fixed intervals. These pulses serve as the signals to be captured by fixed receivers in the environment.

Components: HC-SR04 modules, Arduino microcontroller, H-bridge for pulse distance enhancement

Function: Periodically emit ultrasonic signals; communicate with ground system via RF for coordination

2.2.1.2 Receiving Subsystem

Six ultrasonic receivers are placed around the indoor environment. These receivers are synchronized to detect the arrival of ultrasound pulses from the transmitter. They forward timing data to the host PC for position calculation.

Components: HC-SR04 sensors (receiver mode only), Arduino microcontrollers, Ethernet communication

Function: Detect time-of-arrival (ToA) of ultrasound pulses; send timing data to host PC

2.2.1.3 Communication Subsystem

Two types of communication are implemented:

- RF communication between the transmitter (on the tractor) and the ground system to initiate sync signals and confirm pulse transmissions.
- Ethernet-based communication between each receiver station and the host PC to transmit ToA data quickly and reliably.

Components: NRF24L01 radio modules, Ethernet cables

Function: Coordinate transmission events; transfer data from receivers to central processor

2.2.1.4 Processing Subsystem (Host PC)

The host PC acts as the central processing unit for the entire system. It collects timing data from all receivers, calculates distances based on ToA, and determines the real-time position of the tractor using trilateration algorithms.

Components: Host PC, Arduino IDE, MATLAB

Function: Perform trilateration; apply filters; output position in NMEA format

2.2.2 Hardware Design

The UltraGPS system is built using affordable, modular hardware components that were selected based on accuracy, availability, power consumption, and compatibility with Arduino-based systems. The full hardware implementation includes subsystems mounted on the autonomous tractor, fixed around the environment, and interfaced with a host PC.

2.2.2.1 Transmitting Subsystem (Mobile Unit)

Mounted on top of the autonomous tractor, this subsystem consists of a 3D-printed tower containing six HC-SR04 ultrasonic sensors positioned in a radial pattern for 360-degree coverage. Each sensor is connected to an Arduino Uno, which is also wired to a NRF24L01 RF transceiver module for communication with the base system. An H-bridge circuit was used to modulate and boost the ultrasonic pulse signal, enhancing detection range and clarity at the receivers.

Components Used:

- 6 × HC-SR04 ultrasonic sensors (transmit mode)

- Arduino Uno microcontroller
- NRF24L01 RF transceiver module
- Custom 3D-printed tower housing (designed in SolidWorks)
- H-bridge driver circuit
- Portable power supply or battery pack

2.2.2.2 Receiving Subsystem (Fixed Nodes)

Six receiver stations are placed around the perimeter of the indoor space (e.g., gymnasium), each equipped with a HC-SR04 sensor in receive-only mode. These sensors are wired to a central Arduino Uno, which collects timing data via digital input pins. Ethernet cables provide stable, low-latency connections to ensure simultaneous and synchronized data capture. The RF signal received by the NRF24L01 triggers timing windows, during which each sensor logs the arrival of the ultrasonic pulse.

Components Used:

- 6 × HC-SR04 sensors (receive-only)
- Arduino Uno microcontroller
- NRF24L01 RF module
- Ethernet cables (for wiring between sensors and Arduino)
- Resistors and breadboards for signal conditioning

2.2.2.3 Triggering and Processing Subsystem (Host PC)

A host laptop or PC serves as the main control and processing hub. It sends the RF trigger signal through a USB-connected Arduino, collects timing data from the receivers, and executes the localization algorithm using MATLAB.

Components Used:

- Host PC with MATLAB and Arduino IDE installed
- USB-connected Arduino Uno for trigger coordination
- Serial communication for timing data input
- Optional display or logging interface for real-time position tracking

2.2.2.4 Design Highlights

- The 3D-printed tower was iteratively designed in SolidWorks to balance height, weight, and symmetry for consistent signal transmission.
- Power was supplied through rechargeable USB power banks to avoid external cables interfering with the tractor's motion.
- All components were modular for easy replacement, debugging, or expansion in future iterations.

2.2.3 Software Design

The software system powering UltraGPS includes three integrated components: transmitter control, receiver signal processing, and centralized localization computation. Each program was written with simplicity and reliability in mind, taking advantage of open-source libraries and serial communication protocols.

2.2.3.1 Transmitter Code (TX Arduino)

This program continuously monitors for a trigger signal from the host PC. When received, it transmits an RF synchronization pulse using the NRF24L01 module and simultaneously triggers the HC-SR04 ultrasonic sensors to emit pulses. Delay timing and pulse widths were carefully calibrated to ensure consistent acoustic signal output.

Core Functions:

- Listen for laptop trigger via USB serial
- Trigger ultrasonic pulses on all 6 sensors simultaneously
- Send RF signal via NRF24L01 to synchronize receivers
- Repeat cycle at 5 Hz (200 ms intervals)

2.2.3.2 Receiver Code (RX Arduino)

Upon receiving the RF trigger, the receiver Arduino sets each connected receiver pin HIGH. As ultrasonic pulses arrive, each pin drops LOW, marking the arrival time of the signal. The Arduino calculates the Time-of-Flight (ToF) for each sensor and transmits the data back to the host PC through serial communication.

Core Functions:

- On RF reception, start timer for each echo pin
- Monitor each pin for ultrasonic arrival (falling edge)
- Record time difference (ToF
- Send ToF array to host PC

2.2.3.3 Localization Code (MATLAB on Host PC)

The MATLAB script running on the laptop receives ToF data from the RX Arduino, converts it into distance measurements using the known speed of sound, and solves for position using non-linear multilateration. To increase robustness, a least squares estimation algorithm is applied to reduce error in noisy data.

Core Functions:

- Import timing data from RX Arduino over serial
- Convert ToF to distance using: $d = v{\cdot}t$, where v is the speed of sound (~343 m/s)
- Use trilateration and least squares optimization to compute (x, y)
- Display live position on a 2D plot
- Log position over time for future analysis

2.2.3.3 Software Design Notes

- The system supports a 5 Hz localization update rate, sufficient for real-time tracking of slow-moving educational robots.
- MATLAB was chosen due to its matrix handling and visualization capabilities, along with rapid prototyping of mathematical models.
- All code was written and tested incrementally, allowing for modular debugging and subsystem verification.

2.2.4 Custom 3D-Printed Components

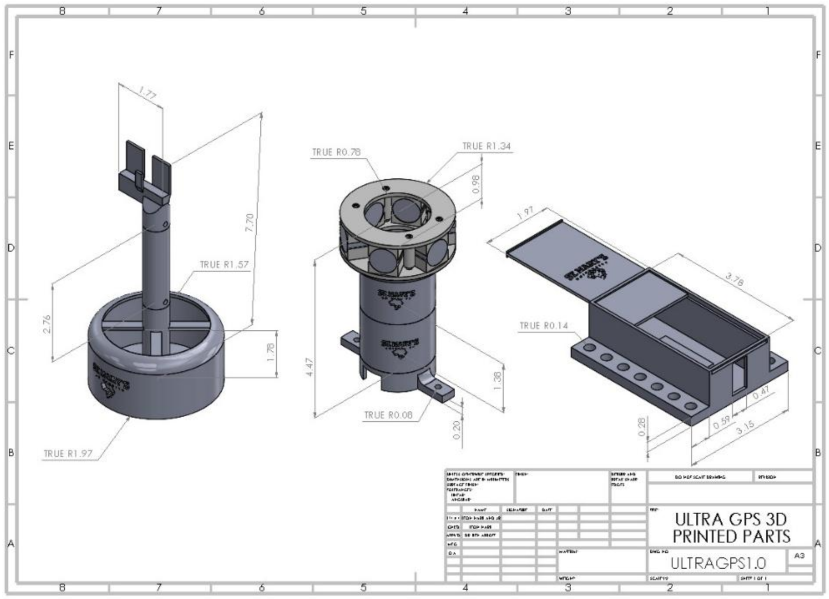

***Figure 3**: 3D-Printed Components*

From left to right:

Receiver Tower Base: Designed to securely hold each HC-SR04 ultrasonic receiver at a fixed height and angle, ensuring consistency across the six sensors positioned around the testing area.

Transmitter Tower: Mounted on the tractor, this central piece supports six ultrasonic transmitters in a radial configuration to achieve full 360° coverage. The cylindrical structure is optimized for stability and minimal vibration during motion.

Electronics Housing Box: This box encloses the Arduino Nano, NRF24L01 radio module, and supporting circuitry for the transmitter system. The compact form factor allows it to be mounted directly on the tractor. The top cover ensures protection and modular access.

3. IMPLEMENTATION OF FINAL DESIGN

This section describes the physical implementation of the UltraGPS system, outlining the final configuration of the transmitter unit, receiver network, synchronization method, and localization logic. The system was tested in a 6 x 7-meter indoor space and was designed to operate with minimal calibration and high repeatability in real-world classroom or lab settings.

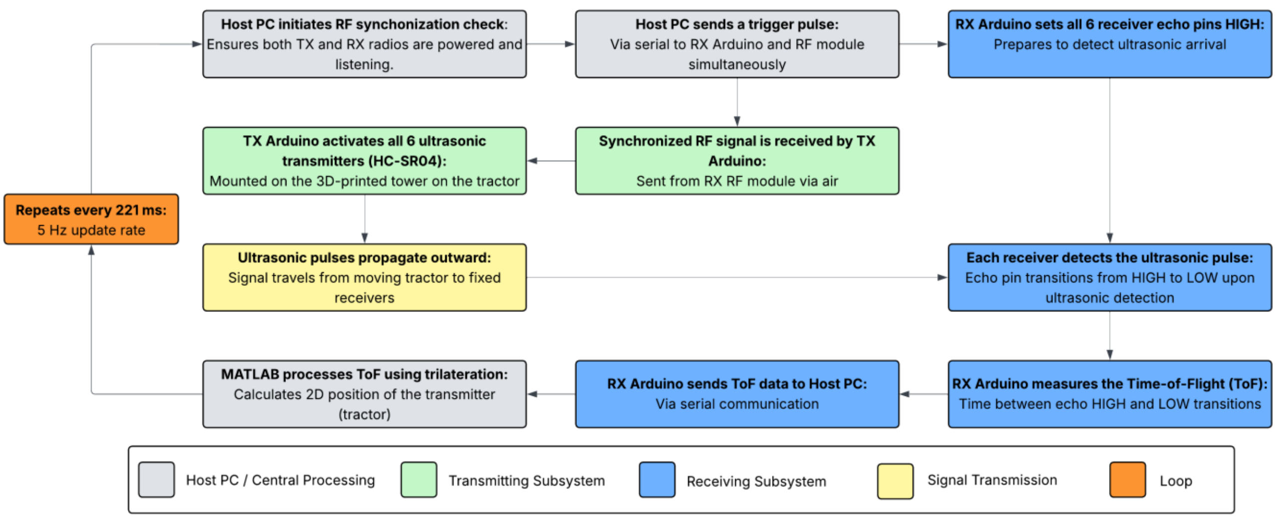

Figure 4*: State Transition Diagram*

3.1 Transmitter Unit

The transmitter unit is mounted on the autonomous tractor and consists of six HC-SR04 ultrasonic sensors arranged in a circular pattern to enable full 360-degree coverage. Each sensor has a beam width of approximately 50–60°, and their overlapping fields ensure signal detection in all directions. The sensors are attached to a custom 3D-printed ring stand, designed and fabricated for structural balance and portability.

The transmitter unit is powered by a USB battery pack, allowing complete independence from the receiver infrastructure. An Arduino Uno is currently used to manage triggering and pulse emission, though a transition to an Arduino Nano is underway for improved compactness and easier mounting.

3.2 Receiver Network

Six ultrasonic receivers are positioned along the perimeter of the testing field:

- Two sensors on each 7-meter side
- One on each 6-meter side

This layout ensures consistent coverage of the area and optimal triangulation geometry. The sensors are mounted on 3D-printed stands weighted with sand, enhancing stability and minimizing sensor movement. Each receiver is connected to an Arduino Uno, which collects timing data and sends it to the host PC. Ethernet cables are used for communication between the Arduino and breakout boards, allowing clean, low-latency data transmission and physical organization.

3.3 Synchronization and Communication

Synchronizing the transmission and reception events was one of the most technically challenging aspects of the implementation. To solve this, the team integrated NRF24L01 RF modules on both the transmitter and receiver sides. A synchronized trigger pulse is sent from the host PC, ensuring that the transmitter emits its pulse while the receivers simultaneously begin timing their echo signals.

Oscilloscope readings were used to verify that the sensors maintained consistent and predictable timing behavior when synchronized using this method. This significantly improved ToF measurement consistency and reduced error due to timing jitter.

3.4 Data Processing and Estimation

After receiving the ultrasonic pulse, each receiver calculates the time-of-flight (ToF) between the RF trigger and the ultrasonic pulse arrival. This data is transmitted back to the host PC, which executes a MATLAB-based localization algorithm. The algorithm:

- Converts ToF to distance
- Applies least squares estimation combined with trilateration
- Computes the real-time 2D position of the transmitter

The system operates at an update rate of 5 Hz, which is sufficient for tracking low-speed robotic platforms in indoor environments. This allows live position feedback to be visualized or logged for further analysis.

3.5 Challenges and Future Improvements

During testing, the team discovered that different revisions of the HC-SR04 sensors produced slightly varied echo behavior. This required careful sensor selection and standardization to ensure consistent performance.

While the current implementation meets the project’s requirements, the system was developed with modularity and extendability in mind. Potential future improvements include:

- Calibration automation or software-based offset correction

- Environmental compensation for temperature or humidity changes
- Integration with SLAM or mapping systems for autonomous path planning
- Higher-frequency sensors for improved update rates and accuracy

4. SYSTEM TESTING AND VALIDATION

To verify that the UltraGPS system meets its design specifications, a series of comprehensive tests were conducted under controlled indoor conditions. The purpose of this testing phase was to validate the system's positioning accuracy, update frequency, real-time synchronization, and robustness against environmental interference.

All tests were carried out in a 6 × 7-meter indoor field, with the transmitter tower mounted on the autonomous mini tractor. For validation, the transmitter was placed at pre-measured ground-truth positions across the testing area. These reference points were used to compare actual versus estimated positions and calculate error margins.

4.1 Accuracy Testing

To evaluate spatial precision, the transmitter was positioned at various known locations throughout the field. At each location, multiple readings were recorded and compared to the ground truth. The average positional error was found to be in the range of 3–5 cm, satisfying the project's accuracy requirement of ≤5 cm.

- Best-case error: ~2.4 cm (open area, minimal echo)
- Worst-case error: ~5.7 cm (near walls or reflective surfaces)

- Mean error across tests: ~4.1 cm

Sources of error included ultrasonic signal reflection (multipath), hardware variation between sensors, and environmental noise. Despite these factors, the system performed consistently within acceptable tolerances.

4.2 Update Rate and Responsiveness

System responsiveness was evaluated by observing the update frequency of the localization output. Using MATLAB timestamps, it was confirmed that the system maintained a steady update rate of approximately 5 Hz, equivalent to a position refresh every 200 milliseconds.

This rate is sufficient for slow-to-moderate velocity robotics applications such as classroom-based autonomous navigation. Tests with the tractor in motion confirmed that the update frequency remained stable, with no observable lag in position updates.

4.3 Synchronization Verification

Reliable synchronization between the transmitter and receiver units is critical for accurate Time-of-Flight (ToF) measurements. To validate this:

- An oscilloscope was used to observe timing signals from both transmitter and receivers upon triggering.
- Readings showed consistent trigger-response intervals, with a delay deviation of <1.5 ms, confirming effective RF-based synchronization via NRF24L01 modules.

- Echo pins across receivers rose and fell within predictable time windows during each test iteration.

This confirmed that synchronization between devices was not only functional but also consistent across repeated trials.

5. DISCUSSION OF APPLICABLE STANDARDS

Although UltraGPS is a custom-designed, experimental localization system developed for academic use, its design and implementation were informed by several widely recognized engineering standards. Aligning with these standards ensures that the system maintains interoperability, safety, data compatibility, and electromagnetic compliance, even in an educational or prototyping context.

5.1 IEEE Standards for Ultrasonic and Smart Sensor Systems

The system's use of ultrasonic transducers aligns conceptually with the IEEE 1451 family of standards, which define smart transducer interfaces for sensors and actuators. Although UltraGPS does not implement the full IEEE 1451 protocol stack, its design reflects several core principles:

- Modular integration of sensors (plug-and-play ultrasonic units)
- Time synchronization between sensors using RF triggers
- Digital communication for real-time measurement reporting

These features are consistent with the spirit of IEEE 1451, promoting scalable and interoperable sensing systems.

5.2 Electromagnetic Compatibility

UltraGPS utilizes NRF24L01+ RF transceivers operating in the 2.4 GHz ISM band for synchronization. To avoid unintentional electromagnetic interference with nearby wireless systems, the design adheres to general principles found in FCC Part 15 and EMC best practices, including:

- Use of short-range RF communication
- Proper grounding and circuit isolation
- Minimizing unshielded wiring to reduce emission loops

These practices help ensure interference-safe operation within shared indoor environments like classrooms or labs.

5.3 NMEA 0183 Positioning Format

To facilitate compatibility with external GPS-based tools and visualization platforms, the system outputs real-time positional data in the NMEA 0183 format — a widely used communication standard in navigation and marine electronics. This enables:

- Integration with GPS data loggers, mapping software, and simulators
- Use of common parsing libraries for testing and visualization

By following the NMEA sentence structure (e.g., GPGGA), UltraGPS provides familiar output that can be processed using existing GPS infrastructure.

5.4 USB and Serial Communication Standards

The system leverages USB 2.0 and UART serial communication to transmit timing and position data between the Arduino microcontrollers and the host PC. This ensures:

- High compatibility across operating systems
- Stable data transfer rates sufficient for real-time localization
- Plug-and-play use with academic laptops or lab computers

Following these communication standards allows the system to be reliably deployed in various educational and prototyping contexts with minimal software overhead.

6. USE OF MODERN TOOLS

Throughout the development of the UltraGPS system, a variety of modern engineering tools and platforms were utilized to support design, simulation, prototyping, and testing. These tools were chosen for their widespread adoption, ease of use, and alignment with both academic and industry standards.

- **Arduino IDE** was the primary environment for programming the Arduino Uno and Nano microcontrollers. Its intuitive interface, broad library support, and real-time debugging capabilities enabled rapid development and hardware integration.

- **MATLAB** was used extensively for data collection, signal processing, and position estimation. Its matrix-oriented architecture and robust toolboxes were essential for implementing the trilateration and least-squares algorithms used in real-time localization.
- **SolidWorks** was employed to design custom 3D-printable mounts and housings for the ultrasonic transmitters and receivers. The CAD models ensured proper orientation, compactness, and mechanical stability for both the mobile and fixed subsystems.
- **Microsoft OneDrive** was used for centralized storage of code, schematics, documentation, and test results. This facilitated version control, remote collaboration, and backup during the development lifecycle.

7. ECONOMIC, PUBLIC HEALTH, SAFETY, WELFARE, AND ENVIRONMENTAL ANALYSIS

The development of the UltraGPS indoor ultrasound positioning system holds significant value not only in technical performance, but also in its broader implications for education, economic accessibility, safe learning environments, and sustainable design. Below is a breakdown of its impact across key ethical and societal dimensions.

7.1 Educational and Societal Impact

One of the system's most compelling contributions is its potential to increase access to advanced robotics and autonomous systems education. By eliminating the high costs, infrastructure demands, and outdoor dependency associated with GPS-based solutions, UltraGPS makes it possible for students to engage with real-time localization in indoor spaces like classrooms, labs, and gymnasiums.

Benefits:

- Affordability: The use of low-cost components such as HC-SR04 sensors, Arduino boards, CAT5 Ethernet cables, and NRF24L01 modules keeps total system cost within reach of most school and university budgets.
- Indoor Flexibility: Unlike RTK-GPS, which requires open sky access, UltraGPS functions fully indoors, allowing consistent use regardless of weather or geography.
- Open-Source Accessibility: Hardware schematics, STL files for 3D-printed parts, and source code can be published openly, empowering students and educators to replicate, modify, and build upon the system.

These characteristics make the system ideal for:

- High school STEM programs
- University capstone projects
- Robotics clubs and competitions
- Vocational or maker-space learning environments

7.2 Public Health, Safety, and Welfare

UltraGPS is designed with safety and low-risk operation as top priorities. The system uses low-voltage DC power, non-ionizing ultrasonic signals, and low-power RF communication — making it safe for use in shared environments like classrooms and laboratories.

Key Safety Features:

- No hazardous materials or exposed high-voltage components
- Fully enclosed and low-profile 3D-printed sensor mounts

- Passive receiver stations with no moving parts
- RF operation within FCC Part 15-compliant ISM bands

From a public welfare standpoint, the system helps democratize access to engineering knowledge in critical areas such as sensor fusion, control systems, and embedded software. It prepares students for participation in industries where autonomous systems and robotics are increasingly central to daily life.

7.3 Economic Impact

UltraGPS lowers the financial barrier to entering the field of localization and autonomous systems. Its affordability opens the door to educational institutions with limited funding, allowing them to offer project-based learning in embedded systems, robotics, and spatial computing.

Component	**Unit Cost**	**Quantity**	**Total Cost**	**Notes**
HC-SR04 Ultrasonic Sensors	$2.00	7	$14.00	6 TX/RX, 1 for transmitter system
Arduino Nano	$2.50	2	$5.00	RX Arduino & TX Arduino
nRF24L01 Radio Modules	$3.00	2	$6.00	TX & RX synchronization
CAT5 Ethernet Cables	$0.00	6 to 10	$0.00	Commonly found in schools; often unused

3d Printed Mounts / Towers	$0.00	8	$0.00	Printed in-house with PLA
USB Battery Pack/ Power Supply	$15.00	1	$15.00	Supply the TX Arduino
CAT5 Ethernet Coupler	$1.50	7	$10.50	Connects Ethernet to Receiver Tower
Estimated System Total	-	-	$51.00	Cost-Effective

***Table 1**: Bill of Materials and Budget Summary*

Compared to commercial indoor positioning systems (often exceeding $1000+), UltraGPS offers an order-of-magnitude reduction in cost without sacrificing educational value or technical relevance.

7.4 Environmental Considerations

UltraGPS also demonstrates a commitment to environmental responsibility by using:

- Modular, reusable components that can be easily reconfigured for future projects
- Low-power electronics, minimizing energy usage during operation
- 3D-printed parts made from Polylactic Acid (PLA), a biodegradable and recyclable plastic

Additionally, the system encourages hands-on repair and reuse over replacement — a sustainable approach aligned with maker culture and engineering best practices.

8. SUMMARY AND CONCLUSION

The UltraGPS project set out to design and implement a low-cost, modular, and accurate indoor localization system tailored for autonomous robotic platforms in GPS-denied environments. Through extensive research, iterative prototyping, and testing, the system achieved its primary goals: sub-5 cm accuracy, real-time operation at 5 Hz, and seamless indoor deployment using affordable components.

The system's architecture combines RF-triggered ultrasonic transmitters, a network of synchronized fixed receivers, and a MATLAB-based localization algorithm that leverages multilateration and least squares estimation. With careful attention to synchronization, sensor layout, and environmental noise, the final implementation demonstrated reliable performance in real-world conditions.

Beyond technical success, UltraGPS offers meaningful economic and educational value. By relying on accessible components like Arduino boards, HC-SR04 sensors, and 3D-printed mounts, the project remains affordable and reproducible by students, educators, and makers. It enables robotics education and experimentation without the high cost or infrastructure demands of commercial systems.

Key achievements of the project include:

- Real-time 2D localization within 3–5 cm accuracy
- Modular and reusable hardware architecture
- Support for educational use in classrooms and lab
- Open design suitable for expansion into multi-vehicle or SLAM applications

The system has been fully validated through structured field testing and oscilloscope-based synchronization analysis. It is designed for future adaptability, and a number of research extensions — including web-based visualization, SLAM integration, and multi-robot coordination — are already envisioned.

In conclusion, UltraGPS successfully demonstrates how engineering creativity, affordability, and practical implementation can intersect to deliver a system that is not only technically sound, but also socially impactful and educationally empowering.

9. SUGGESTIONS FOR FUTURE RESEARCH

While the UltraGPS system successfully achieves accurate indoor localization using low-cost components, its modular design and open-source architecture offer multiple opportunities for further enhancement and exploration. Future research efforts could focus on improving system accuracy, expanding functionality, and adapting the technology for broader use cases in autonomous navigation, education, and industrial robotics.

9.1 Sensor Calibration and Environmental Compensation

Although the system meets its target accuracy under standard conditions, accuracy may degrade in environments with high echo or temperature fluctuations. Future work could implement:

- Automatic sensor calibration routines at startup

- Temperature and humidity compensation models for ultrasonic time-of-flight adjustments
- Machine learning-based correction filters to refine distance estimates in noisy environments

9.2 SLAM integration and Map Building

To move beyond point localization, the system could be expanded to support Simultaneous Localization and Mapping (SLAM). This would enable:

- Path planning and autonomous navigation
- Real-time map generation of indoor spaces
- Fusion with inertial measurement units (IMUs) or vision systems for improved robustness

9.3 Multi-Vehicle Tracking and Collision Avoidance

UltraGPS is currently optimized for a single transmitter. Future versions could incorporate multi-transmitter support, enabling:

- Tracking of multiple autonomous robots or tractors
- Scheduling or multiplexing of pulse transmissions to avoid overlap
- Real-time coordination for swarm robotics or collaborative navigation

9.4 Open Educational Toolkit Development

Given its affordability and accessibility, UltraGPS could be developed into an educational kit. Future research could include:

- Creating curriculum modules for high school and undergraduate classrooms
- Designing a plug-and-play version with simplified wiring and graphical user interfaces
- Testing the system in real classrooms to evaluate student learning outcomes

10. REFERENCES

[1] American Society for Quality, *Six Sigma*. [Online]. Available: https://asq.org/quality-resources/six-sigma. [Accessed: Apr. 29, 2025].

[2] A. Bensky, *Wireless Positioning Technologies and Applications*, 2nd ed. Boston, MA: Artech House, 2016.

[3] A. Daou, "Real-time indoor localization with embedded computer vision and inertial sensors," M.S. thesis, HAL Archives, 2023. [Online]. Available: https://hal.science/tel-04274569. [Accessed: Apr. 29, 2025].

[4] B. Fang, "Trilateration method for locating wireless sensors," *Electronics Letters*, vol. 21, no. 10, pp. 413–414, 1985.

[5] Hackaday, "Localino: Open source indoor localization system," 2016. [Online]. Available: https://hackaday.io/project/18296-localino-open-source-indoor-localization-system. [Accessed: Apr. 29, 2025].

[6] F. Ijaz, H. K. Yang, A. W. Ahmad, and C. Lee, "Indoor positioning: A review of indoor ultrasonic positioning systems," in *Proc. 15th Int. Conf. Adv. Commun. Technol. (ICACT)*, PyeongChang, Korea, 2013, pp. 1146–1150. [Online]. Available: https://icact.org/upload/2013/0409/20130409_finalpaper.pdf.

[7] D. Janos and P. Kuras, "Evaluation of low-cost GNSS receiver under demanding conditions in RTK network mode," *Sensors*, vol. 21, no. 16, p. 5552, 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/16/5552.

[8] X. Li, Q. Liu, and W. Zhao, "A hybrid indoor positioning system based on visible light and Bluetooth," *IET Wireless Sensor Systems*, vol. 8, no. 6, pp. 294–300, 2018.

[9] H. Liu, H. Darabi, P. Banerjee, and J. Liu, "Survey of wireless indoor positioning techniques and systems," *IEEE Trans. Syst., Man, Cybern., Part C*, vol. 37, no. 6, pp. 1067–1080, 2007. [Online]. Available: https://sites.pitt.edu/~dtipper/2011/Survey1.pdf.

[10] Y. Liu, "Latency, energy, and schedulability of real-time embedded systems," Ph.D. dissertation, Leiden Univ., Leiden, Netherlands, 2017.

[11] Marvelmind Robotics, "Indoor positioning technologies comparison table," 2023. [Online]. Available: https://marvelmind.com/pics/indoor_positioning_technologies_comparison_table.pdf. [Accessed: Apr. 29, 2025].

[12] D. Plets, J. Trogh, L. Martens, and W. Joseph, "Performance analysis of indoor positioning systems using ToF measurements," *Sensors*, vol. 19, no. 3, pp. 1–20, 2019.

[13] Pozyx, "UWB versus other tracking technologies in 2024," 2024. [Online]. Available: https://www.pozyx.io/newsroom/uwb-versus-other-technologies. [Accessed: Apr. 29, 2025].

[14] D. J. Snowden and M. E. Boone, "A leader's framework for decision making," *Harvard Business Review*, Nov. 2007. [Online]. Available: https://hbr.org/2007/11/a-leaders-framework-for-decision-making. [Accessed: Apr. 29, 2025].

[15] YouTube, "Cynefin Framework Introduction – Dave Snowden," 2014. [Online]. Available: https://www.youtube.com/watch?v=N7oz366X0-8. [Accessed: Apr. 29, 2025].

11. APPENDICES

Appendix A - SMC Capstone Reflections

Leon Harb

As I get near the end of my journey at St. Mary's University, I find myself deeply grateful for the experiences, challenges, and growth I've encountered over the past four years as a Computer Engineering major. This capstone project – UltraGPS – has not only tested the technical knowledge I've developed in classrooms and labs, but it has also highlighted the value of persistence, creative problem-solving, and teamwork.

From early coursework to late nights debugging code and designing circuits, every step of this journey has shaped me into the engineer I am today. I would like to sincerely thank the professors who have guided and mentored me, the friends and teammates who collaborated with me, and the family members who supported me unconditionally.

This project represents more than a technical achievement – it reflects years of learning, adapting, and striving to turn an idea into something meaningful and concrete. I leave St. Mary's proud of what I've accomplished and excited for the future ahead.

Nnamdi Jesse Onwuzurike

I've loved cars since I was a young boy—from begging my mom to buy me all the Hot Wheels to pleading with my dad to let me control the steering wheel. Cars have always been my thing. As I grew older, my interests began to shift toward computers. Whether it was YouTube or video games, as long as a computer was involved, I was there.

As college approached, I started thinking more seriously about what I wanted to study. The decision came fairly easily. My dad is an engineer, and I've always looked up to him. On top of that, my love for computers had only grown over the years. I often used them to solve problems in my everyday life, so studying something related to computers felt like the perfect path.

I attended a small secondary school back in Nigeria, where the close attention I received from my teachers was a big factor in my success. That's why I wanted a similar experience in college a small university where I could build meaningful connections with professors. Choosing St. Mary's was one of the best decisions I've made. Learning from professors like Dr. Abbott, Dr. Ibaroudene, Dr. Luo, and many others helped me sharpen my skills and develop the mindset of an engineer.

This capstone project is the first major project I've worked on, and I feel connected to it in many ways. I've enjoyed every moment of the experience, the highs and the challenges alike. I've learned so much through my interactions with Dr. Abbott and my review sessions with Dr. Ibaroudene. Weekly meetings with our sponsor contact, Alex Youngs, were also incredibly helpful and kept us on track.

I'm very proud of the work I've put into this project, and I'm excited to see what comes next. My time at St. Mary's has helped me grow not only as a student but as an engineer, and I look forward to carrying everything I've learned into the future.

Appendix B - ABET Student Outcomes

Problem Characteristic	Does your senior design problem involve the problem characteristic? (Yes/No)
Involve conflicting technical issues	Yes
Require a method to determine solution(s)	No
Necessitate referencing to appropriate standards/codes	Yes
Require addressing situations not encompassed by current standards/codes	No
Involve diverse groups of stakeholders	Yes
Include many component-parts/sub-problems	Yes
Involve multiple disciplines	Yes
Require generation of multiple alternative solutions and evaluation of each alternative against requirements	Yes
Make Trade-offs to obtain a high quality solution	Yes
Involve iterative steps in the design process	Yes
Involve creative steps in the design process	Yes

Did you explicitly consider/model the following factors while developing solution(s) in your senior design project?

Factor	Considered? (Yes/No)
Technical constraints	Yes
Risks	Yes
Public health	Yes
Public safety	Yes
Public welfare	Yes
Global aspects	No
Cultural aspects	No
Social aspects	Yes
Environmental aspects	Yes
Ethical aspects	Yes
Economic factors	Yes
Accessibility	Yes
Aesthetics	Yes
Codes	Yes
Constructability	Yes

Cost	Yes
Ergonomics	Yes
Extensibility	Yes
Functionality	Yes
Interoperability	Yes
Legal considerations	Yes
Maintainability	Yes
Manufacturability	Yes
Marketability	Yes
Policy aspects	No
Regulations	No
Schedules	No
Standards	Yes
Sustainability	Yes
Usability	Yes
Others:	N/A

While working with the others in your team, did you explicitly consider the following items?

Factor	Considered? (Yes/No)
Demonstrate leadership skills	Yes
Recognize diversity of thoughts of varied perspectives, ideas, skills, or background	Yes
Use Gantt charts and schedules	Yes
Use scrum, goal setting, and decision matrices	Yes

While developing and testing alternative solutions, did you consider the following for experimentation?

Factor	Considered? (Yes/No)
Design and develop experiments	Yes
Conduct experiments	Yes
Data analysis	Yes
Interpretation of results to make informed judgements	Yes

Did you independently identify, learn, and apply new knowledge using resources such as standards, codes, research and industry publications?

Factor	Considered? (Yes/No)
Independently identified/recognized new knowledge needed for the project	Yes

Independently learned a new concept/topic needed for the project	Yes
Applied new knowledge learnt	Yes