Paper ID #54120

UltraGPS: A Low-Cost, Open-Source Ultrasonic Positioning System

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Abstract

We want to raise the bar in high school robotics. In Texas, and likely in many other states as well, high school robotics has reached a roadblock when it comes to autonomous navigation. In many competitions, the autonomous portion sees few, if any, teams successfully completing the required tasks. In modern robotics, it is no longer sufficient for a robot merely be "remote controlled." However, autonomous navigation requires a positioning system but unfortunately, they are not cost-effective. Reliable localization provides the essential foundation upon which higher-level algorithms can be built. This document addresses that challenge by disclosing a simple, open-source, low-cost positioning system designed for use in high school environments to advance the state of educational robotics.

Introduction

Why do we care about positioning? Contemporary robotics is all about autonomy. From self-driving cars to automatically guided rockets, autonomous tasks are the central focus of today's robots. However, high school robotics has been unable to implement autonomous tasks with the same success rate as the rest of the industry. This poses an issue in the preparedness of high school students for college, where the challenge of robotics significantly increases and where autonomous control is a requirement. We need to go from "remote controlled automation", shown in figure 1, to "autonomous navigation" shown in figure 2.

Figure 1: Low-Cost St. Mary's Programmable Car

Figure 2: First Class Quanser QCar Autonomously Navigating Using Optitrack

To achieve "autonomous navigation", the first challenge that must be overcome is calculating the position of the robot in 2D space. Once the position of the robot is known, and with a sufficient refresh rate, other motion parameters like velocity and acceleration can be calculated. This reduces the need for expensive accelerometers, LIDAR [5], and other sensors that are required for a robot to determine its own position. The most popular system used to achieve this is the Global Positioning System (GPS). This system works well in clear areas with a direct view of the sky, where a direct path of the signal from the satellite to the receiver exists. However, in indoor settings, or in areas where large portions of the sky are blocked, GPS is unreliable and often unable to be used for positioning due to the satellite signal not being received in a usable manner by the receiver. Other commercial systems like those made by VICON [2], shown in figure 3, or Optitrack [7], shown in figure 4, can be used for indoor positioning with millimeter accuracy and low latency.

Figure 3: Vicon Positioning Camera

Figure 4: Optitrack Positioning System at St. Mary's Unmanned Aerial Systems Lab

These systems depend on high-speed, high-resolution cameras that use infrared light to track fiducials in their field of view. These cameras, coupled with high-speed networking and powerful computers, allow the system to reach millimeter levels of accuracy and low latency. But just as accurate as these systems are, they are expensive, with purchase costs often reaching tens of thousands of dollars. They also have steep learning curves, depending on the user to already have domain expertise, or be willing to spend a significant portion of time learning about the system. In addition, these systems depend on commercial grade software, adding complexity and cost to the installation and upkeep of the systems.

Alternative positioning systems that are created for academic purposes also exist but have drawbacks that make their widespread use difficult. One example is the positioning system made by [6]. This positioning system combines ultrasonic positioning, inertial positioning, and graph matching to obtain location using a mobile device with an ultrasonic acquisition module. While accurate, this system requires a complex setup of ultrasonic transmitters, Inertial Measurement Units (IMU), and a mobile device. These requirements make the system complex to use in an educational setting. Another example is the system developed by [3] that uses background RF reflections to calculate position. The drawback of this system is that it requires a significant amount of information to be known about the location where the positioning algorithm will be used and requires the training of a Convolutional Neural Network (CNN) that implements the location algorithm. The complexity, domain expertise, and time required to implement these systems make them unsuitable for use at the high school level.

The cost and complexity brought about by indoor positioning systems available pose a challenge in their usage at the high school level. The expense and complexity must be lowered for them to be successfully used as learning platforms in high school curriculums. In addition, a successful positioning system must also be able to be examined, understood, and modified freely by those using it. And must be able to be set up with minimum complexity. A system that meets these criteria is demonstrated in this paper, along with an overview of the software and hardware required to make it.

Literature Review

Sound positioning systems have been around since creation; one example being the echolocation used by bats. Inspired by these systems, human-made ultrasonic positioning systems have existed since the turn of the millennium [1]. The prime differentiator among ultrasonic systems is their use in commercial or research spheres [4]. Research positioning systems have significant capabilities but often do not leave enough instructions on how to re-create the system or how to use it in a practical sense. Meanwhile, commercial systems are usually cost-prohibitive and complex to use in an educational setting. Two examples representative of research positioning systems that have been published are shown below:

The Cricket Indoor Location System uses RF and ultrasonic pulses produced by beacons that multiple listeners can receive to calculate their position and orientation in a physical space [9]. This research also included a novel method on how to create coordinate assignments that reflect the layout of the beacons without having to know the beacons' location [9]. However, the lack of available hardware and software to replicate the research, along with the cost and complexity, makes it a challenge for the Cricket system to be used at the high school level.

Locate-US is another positioning system that combines an Inertial Measurement Unit (IMU) with an Ultrasound Local Positioning System (U-LPS) to obtain the location of a mobile device with varying degrees of accuracy [6]. The system worked by using an IMU connected via Bluetooth to a cellphone to calculate its position whenever a U-LPS was unavailable. When a U-LPS was available, the IMU was calibrated by an attached acquisition module that received ultrasonic signals from the U-LPS. By placing multiple U-LPS beacons in critical areas, such as hallways, the system was able to track mobile phones with varying degrees of accuracy in indoor settings. High positioning accuracy was obtained whenever the mobile device was in range of a U-LPS beacon, with accuracy decreasing if no beacon was received [6]. While this research presents a useful system for indoor positioning, it depends on the presence of multiple U-LPS beacons and a Bluetooth IMU to obtain accurate positioning data. This makes the system more complex to use compared to the Cricket positioning system and requires more hardware. The increase in complexity and hardware further increases the challenge of its implementation and usage in an educational setting.

Commercial ultrasonic systems, like research ultrasonic systems, have significant capabilities and are easier to use and implement. However, they are much more expensive to acquire and may rely on proprietary software. This prevents their use in an educational setting as their cost is often prohibitive, and the software may not be suitable for teaching at the high school level. Two examples that are representative of commercial ultrasonic positioning systems available in the market are shown below:

Marvelmind has developed a commercial ultrasonic indoor positioning system that is able to achieve an accuracy of ±2 cm [8]. Their system uses stationary ultrasonic beacons that provide known reference positions and mobile beacons that use them to calculate their position and provide real-time location data [8]. Additionally, sensor fusion with the integrated IMU of each beacon can be used to reach refresh rates of 100 Hz and above. While Marvelmind offers a complete, out-of-the-box solution with robust software, its starter set costs 599 euros, placing it out of reach for most high school budgets. Furthermore, the system operates as a "black box," with limited access to the underlying algorithms or raw sensor data, which diminishes its educational value.

Similarly, the 4D1 Precise Indoor Positioning System represents another commercial solution, with the differentiating factor being that this system can deliver millimeter-level 3D accuracy with full 6-degrees-of-freedom [10]. The system uses a network of ultrasonic beacons and wireless trackers that perform on-device sensor fusion with an IMU. The beacons transmit an ultrasonic signal that the trackers receive and use to calculate their position. While 4D1 offers accuracy and scalability for commercial purposes, it is a premium, closed-system solution. The high cost of the specialized hardware (beacon controllers, trackers, and beacons) and the reliance on proprietary software and APIs place it far beyond the budget and educational needs of a high school environment.

Based on the cost and closed-source nature of commercial systems, and the complexity and lack of implementation information of research ultrasonic positioning systems, there is a need for a low-cost, open-source, and straightforward system for use in high school education.

System Development and Design Evolution

UltraGPS evolved from a senior design project whose goal was to develop an affordable indoor navigation system for autonomous vehicles [11]. This project established core requirements of UltraGPS: ±5 cm localization precision, 5 Hz update rates, and compatibility with small autonomous platforms in indoor environments where GPS was unreliable or unavailable [11].

As part of the senior design project, various localization systems were explored before settling on an ultrasonic-based system. Three distinct positioning technologies were evaluated against the project's constraints of cost, accuracy, and educational accessibility.

RF-based positioning was first explored using Wi-Fi or Ultra-Wideband (UWB) signals, which offered operation without requiring direct line-of-sight. However, multipath effects from signal reflections combined with the challenge of achieving sub-5 cm precision caused inconsistent measurements in indoor settings. To compensate for these inconsistencies, expensive timing hardware and complex filtering would be required, which was undesirable in a low-cost system intended for educational use.

The second system explored used overhead cameras and Simultaneous Localization and Mapping (SLAM) algorithms to calculate the position of fiducial markers, similar to the VICON system. While this approach initially appeared appealing due to its accuracy, it soon presented prohibitive computational overhead and significantly increased the cost of the system. Additionally, the dependence on cameras resulted in the system being highly sensitive to lighting variability, shadows, and occlusions. The complexity and cost necessary to account for these challenges resulted in the abandonment of this kind of architecture.

These challenges led to ultrasonic positioning, which offered an optimal balance of accuracy, cost, and implementation simplicity. Ultrasound provides reliable distance measurements over short to medium ranges with relatively simple hardware. Furthermore, basic ultrasonic ranging components are readily available and widely used in the electronics hobbyist community, making them accessible for educational applications.

The initial test setup of UltraGPS, shown in figure 5, was used to test the feasibility of ultrasonic positioning. Using this setup, a MATLAB script was developed to obtain the 2D location of the transmitter tower in the arena. Using this configuration, a MATLAB script was developed to obtain the 2D location of the transmitter tower within the test arena. This prototype successfully demonstrated that common ultrasonic components could be used to develop an ultrasonic positioning system.

Figure 5: Initial test setup in lab

At the conclusion of the senior design project, it was successfully demonstrated that indoor localization using commercially available ultrasonic components was possible. The final system developed during this phase, shown in figure 6, utilized low-cost hardware and was validated by tracking a small RC car throughout the test arena.

Figure 6: Drone Lab Setup

System Overview

UltraGPS consists of four main subsystems: the ultrasonic, receiver, and processing subsystems and the communication infrastructure. These subsystems work in coordination to measure the distance from each transmitter tower (usually attached to a vehicle) to the six receiver towers. Using these distances, the 2D position of the transmitter tower is calculated using trilateration by the processing subsystem. The following sections describe each subsystem in detail.

Transmitter Subsystem

The transmitter subsystem, typically mounted on a mobile robot or vehicle, is built around a custom PCB referred to as the base station. This PCB serves two primary functions; in this subsystem, it operates as a transmitter station that controls an array of ultrasonic transmitters arranged in a radial configuration. The radial layout provides full 360-degree coverage of the emitted ultrasonic pulse by evenly spacing six ultrasonic transducers around a circular, 3D-printed holder.

The base station PCB, shown in figure 8, integrates power management, signal generation, and wireless communication into a single Arduino-attached board. The ultrasonic transmitters are mounted on a transmitter tower, which elevates the array to ensure a clear line of sight to the six receivers. An Arduino connected to the transmitter subsystem generates the ultrasonic pulses and synchronizes their transmission with the receiver network through RF communication.

Receiver Subsystem

Six ultrasonic receivers are positioned around the perimeter of the arena, as shown in figure 7. Each receiver consists of a modified HC-SR04 ultrasonic sensor mounted on a 3D-printed mast (figure 8) and connected to an ultrasonic interface PCB. This interface PCB links each receiver to a base station PCB via Ethernet. The base station PCB, in its second role, serves as the central controller for the receiver subsystem, managing signal routing to the Arduino and providing standardized interfaces that simplify sensor replacement and testing.

Figure 7: UltraGPS Receiver Setup

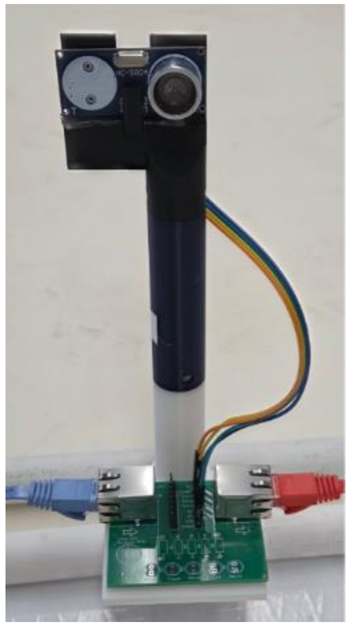

Figure 8: Ultrasonic Receiver on 3D Printed Mast

The six receivers are arranged in a rectangular configuration around the arena to ensure that at least three, and ideally four or more, receivers maintain a clear line of sight to the transmitter at any location within the arena. This geometric redundancy improves position estimation accuracy and enables the detection and rejection of outlier measurements caused by acoustic reflections or environmental interference.

Communication Infrastructure

Two types of communication are employed in the system. First, RF communication using nRF24L01 modules provides synchronization between the transmitter and receiver subsystems. When a pulse sequence is requested, the receiver subsystem broadcasts an RF synchronization signal that is received by the transmitter subsystem. This signal simultaneously arms the timing circuits on all receiver sensors in preparation for the ultrasonic pulse emitted by the transmitter. This approach avoids the need for complex time-synchronization protocols while maintaining sufficient timing accuracy between the transmitter and receiver subsystems.

Second, wired Ethernet connections link each receiver sensor to the receiver base station PCB, which acts as the subsystem controller. These wired connections provide a fast and reliable means of detecting the time of arrival of the ultrasonic pulse at each sensor using readily available connectors and cabling.

Processing Subsystem

The processing subsystem consists of software running on a computer connected to the receiver subsystem. This software collects time-of-arrival measurements from all receiver sensors and computes the distance between the transmitter and each receiver. Using these distances and the known positions of the receivers, a two-dimensional position estimate is calculated through trilateration. The resulting 2D position data can then be used by higher-level software modules to support tasks such as autonomous navigation.

System Hardware

Building upon the foundations established in the senior design project, custom hardware and software were developed to prepare the system for educational use and to support continued development. A key enhancement was the transition from breadboard-based prototypes to custom printed circuit boards (PCBs), which significantly improved system reliability, reduced assembly complexity, and provided a more robust platform suitable for classroom deployment.

Two specialized PCBs were designed to support the system architecture. The base station PCB, shown in figure 9, integrates the nRF24 radio module, power regulation circuitry, an Arduino microcontroller, and connections for six ultrasonic receivers onto a single board. Following the common shield or hat design pattern used in the hobbyist community, this PCB mounts directly onto an Arduino, simplifying assembly and reducing wiring errors.

The ultrasonic connection PCB, shown in figure 10, functions as an interface board that enables Cat5 Ethernet cables to connect the receiver towers to the base station. The receiver towers are organized into two groups of three: receivers 1 through 3 are wired together on one side of the arena, while receivers 4 through 6 are wired together on the opposite side. This arrangement simplifies cable routing and improves system organization.

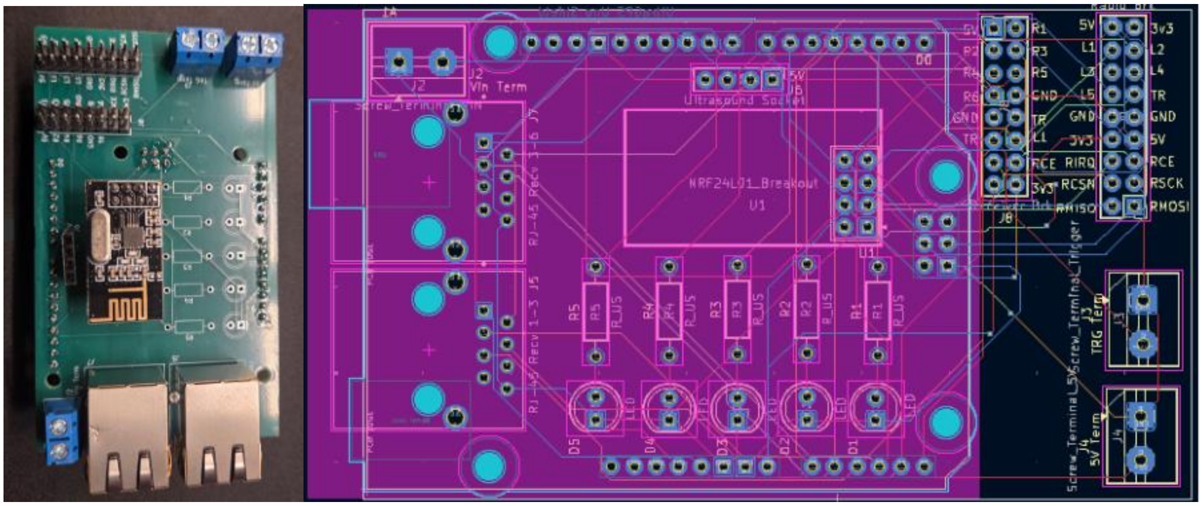

Figure 9: UltraGPS Base Station PCB and Board Layout

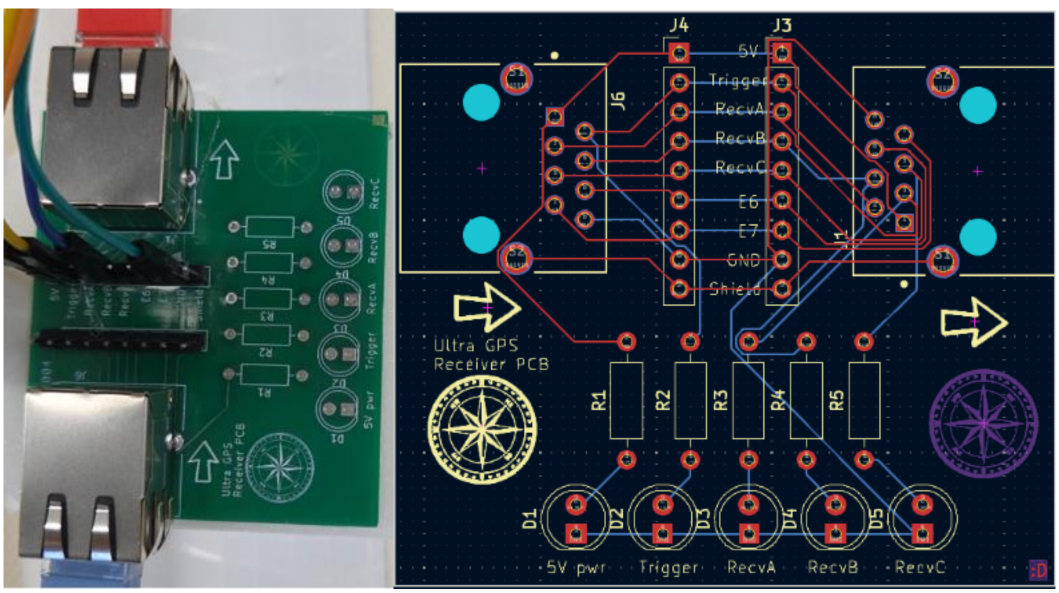

Figure 10: Ultrasonic Connection PCB and Board Layout

System Software

The UltraGPS processing subsystem implements a modular client-server architecture that separates data acquisition from position calculation. It is composed of two main software components:

1) The Broadcast Server interfaces directly with the receiver subsystem via serial connection. It manages pulse timing requests, collects time-of-arrival measurements from

all six receivers, and calculates distances using pre-calibrated constants specific to each sensor.

2) The Control Client connects to the broadcast server through UDP network sockets to request and receive positioning data. It performs trilateration calculations and provides real-time visualization of vehicle position.

This design enables multiple applications to access positioning data simultaneously while separating the hardware interface logic from the user-facing functionality. In addition, the communication methodology between components, illustrated in figure 11, allows the hardware interface to remain stable independent of the control client.

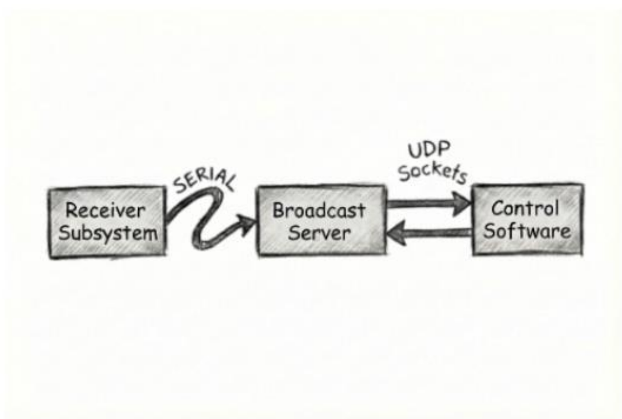

Figure 11: Communication methodology between receiver and processing subsystem components

2D Position Data Flow

The data acquisition process to obtain a 2D position follows a synchronized sequence:

1) The control client requests a position update from the broadcast server
2) The broadcast server sends a pulse trigger command to the receiver subsystem via serial
3) The receiver subsystem broadcasts an RF sync signal and records time-of-arrival data
4) Time-of-arrival measurements are returned to the broadcast server
5) The broadcast server calculates distances and broadcasts them via UDP
6) The control client receives distance data and computes 2D position using trilateration

The broadcast server opens three UDP ports: one dedicated command channel for receiving requests, and two data channels that broadcast raw time-of-arrival values and calculated distances respectively. The control client uses the data provided by the sockets to create a real-time position tracking window that displays the vehicle's current location on a 2D map of the arena. The receiver positions are shown as fixed reference points, while the transmitter position updates as soon as position data is calculated, enabling immediate feedback during system testing and use.

Position Calculations

UltraGPS employs a two-stage approach to calculate the 2D position of the transmitter tower from the measured distances to each receiver. This method combines an initial estimate using Ordinary Least Squares (OLS) with a refined solution obtained through Non-Linear Least Squares (NLS) estimation.

The first stage calculates an initial position estimate by linearizing the positioning problem. Given the measured distances d_i from the transmitter to each of the six receivers with known positions (x_i,y_i), the relationship between the transmitter position (x,y) and each receiver can be expressed as:

$$d_i^2 = (x - x_i)^2 + (y - y_i)^2$$

Where (x,y) represents the unknown transmitter position. Expanding this equation yields:

$$d_i^2 = x^2 - 2x * x_i + x_i^2 + y^2 - 2y * y_i + y_i^2$$

By taking the difference between consecutive receiver measurements, the quadratic terms $(x^2 + y^2)$ can be eliminated, resulting in a linear system of equations. This results in a linear system of equations of the form:

Where $p = [x,y]^T$ is the position vector to be solved, **A** is the matrix formed from the receiver coordinates, and **b** contains the linearized distance measurements. The OLS solution is obtained using the pseudoinverse:

This analytical solution provides a reliable initial estimate that is typically within a few centimeters of the true position under low-noise conditions. However, the linearization process introduces approximation errors, particularly when measurement noise is present or when the transmitter is located near the edge of the receiver network, where geometric dilution of precision becomes significant.

In the second stage, the initial estimate is refined using a Non-Linear Least Squares approach that directly minimizes the residual error between the measured and predicted distances without linearization. Using the OLS solution as an initial guess, the NLS algorithm minimizes the cost function

$$C(x,y) = \sum_{i=1}^{6}\left(d_i - \sqrt{(x-x_i)^2 + (y-y_i)^2}\right)^2$$

This optimization problem is solved using the Levenberg-Marquardt algorithm. At each iteration, the algorithm computes the Jacobian matrix of the residuals with respect to the position coordinates and updates the estimate:

$$p_{k+1} = p_k - (J^T J + \lambda I)^{-1} J^T r$$

Where **J** is the Jacobian matrix of the residuals with respect to the position coordinates, **r** is the residual vector, $\boldsymbol{\lambda}$ is the damping parameter, **I** is the identity matrix, and **k** denotes the iteration number. The algorithm continues until convergence is achieved.

The NLS refinement compensates for errors introduced by the linearized OLS formulation and improves robustness in the presence of measurement noise or partial receiver visibility. As a result, this two-stage approach yields more accurate and stable position estimates, particularly in noisy environments or when some receivers experience degraded signal reception.

Conclusion

In conclusion, we have shown that the path to advanced, autonomous robotics in education need not be prohibitively expensive or complex. Our system, UltraGPS, provides a viable, open-source foundation for high school programs to transition from simple remote control to the core challenges of autonomous navigation. Its fusion of low-cost ultrasonic positioning with open-source software creates an accessible and adaptable platform. We hope this work will inspire a community-driven effort to extend its capabilities, fostering innovation in ways that extend far beyond our initial scope. As we prepare for its public release in May 2026, our goal is to empower a new generation of engineers, pushing the boundaries of educational robotics to infinity and beyond.

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