Position at Response: A Highly Accurate and Low Cost Laser Positioning System

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***Abstract*—Global Positioning Systems (GPS) are widely used in many navigational applications such as vehicles, aircraft and ships to find their speed and position. However, the main drawback of GPS is reliability, especially in an urban environment. Tall buildings reflect the signal and can make the receiver's location appear ten meters or more from its actual position. This paper details a low cost system designed to overcome this accuracy problem. The system utilizes a laser and a network of transponders to locate the vehicle position more accurately than a GPS. The system can work for an indoor application as well. It is easily adaptable to new routes, paths, or destinations. Our preliminary test results show an accuracy within three percent, relative to the distance of the transponders.**

***Keywords*—Laser Navigation, Autonomous Vehicle, Triangulation, Transponder Localization, Positioning, Local Positioning System.**

I. Introduction

Today, Global Positioning Systems (GPS) are ubiquitous, being found on most cellular phones, equipped in many cars as a navigational guide, and in many other applications. The system uses a collection of satellites to trilaterate the position of a base station. Accuracy is guaranteed to be within 6 meters 95% of the time [1]. In a study of over 10,000 smart phones in over 100 countries, GPS had an open sky mean average of 4.9 meters [2]. GPS's inaccuracies only increase with obstructions like trees or buildings.

An autonomous vehicle (AV) needs to reliably determine its location with a better resolution than 6 meters. There are two common methods for doing this, either triangulation, or trilateration, as illustrated in Fig. 1. Triangulation uses angles to determine distance, when two angles and the distance between them are known. Using the laws of sines and cosines, lines can be drawn from the base line at the angles known, and the intersection marks the location. Geometry then finds the distance. Trilateration measures distances not angles. The distance from three known points are used as the radius of three circles, and the circles intersect at the location.

There have been several studies based on the primary concept of trilateration and triangulation. Brooks et al. [3] surveys these navigation methods: Time of Flight, Time Difference of Arrival, and Angle of Arrival. Other methods such as Line Tracking [4] and RFID Mapping [5] are also defined and discussed below.

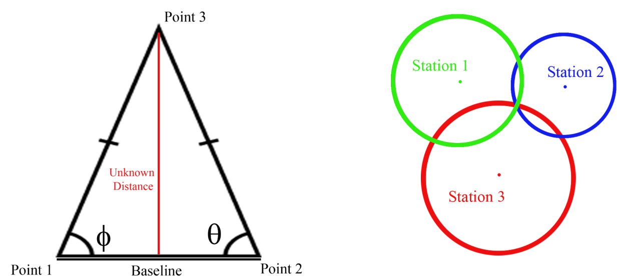

Fig. 1. Triangulation vs trilateration.

Time of Flight (ToF) When used with multiple base stations at known positions, ToF can be used to determine location. Having one base station can determine only distance. After a precise measurement of the time it takes to send a signal at a known velocity, the distance to the base stations are determined. Then trilateration is used to find position. One of the drawbacks to this system is the possibility of interference or multipath propagation of the signal [3].

Time Difference of Arrival (TDoA) This system uses multiple sources of regularly timed signals sent to one receiver. Since the signals locations are known, then by timing the arrival, it is possible to trilaterate position relative to the signal sources. GPS is a specific type of TDoA, using synchronized stationary orbit satellites. It can be completely localized as well, like the system written about by Cheng [6]. TDoA systems without a very accurate clock can have inaccurate distance and position calculations [3], and multipath propagation and atmospheric changes can also affect results.

Angle of Arrival (AoA) AoA finds position in one of two ways. In the first, the base station uses an array of antennas to find the angle of incoming transmissions. This information, used with ToF and trilateration, determines the position in polar coordinates. A second method uses two antenna stations to determine the angle of the incoming signal from each antenna, then uses triangulation to determine the location. One benefit of this second method lies in its angle based system, so no rigorous timing devices are needed. A second benefit is that more stations allow for reduced uncertainty through redundancy. However, the systems accuracy depends on the precision of the antenna's angular resolution [3].

Line Tracking (LT) One form of LT is achieved by burying a wire a few cm deep, and sending a signal through it. The path can be followed using the electromagnetic induction of the wire [4]. This system's main drawbacks are the disruption to existing infrastructure for installation and it's permanence. Optical line tracking is easier to implement, but requires a visible line along the intended path. However, a visual line can be obstructed (e.g. snow) or worn away over time. If the line is lost, the AV cannot move [5].

RFID Mapping (RM) This form of location is most commonly used in warehouses. RM embeds a grid of radio frequency identification (RFID) chips in the floor (or ceiling) [5][7], to allow AVs to traverse to specific bins and collect materials, or have the bins move to desired locations [8]. This method while effective also requires drastic infrastructure disruptions to install or expand.

Position at Response (PaR) PaR is a new method for triangulation. Unlike the systems listed above, PaR is low cost and doesn't require any precision timing of signals (like ToF or TDoA), antenna beamforming (like AoA), or infrastructure changes (like LT and RM). Instead it uses an motor encoder to track the position of a laser it is rotating. As the laser sweeps across transponders with known locations, they return an identifying signal by transceiver. The position at the response is sent to a microcomputer to triangulate the location. Additionally, it is designed to be easy to setup, maintain, and determine or change existing routes.

The rest of the paper is organized as follows: In Section II, the system overview and the triangulation method are detailed. In Section III, testing and results are discussed, along with some problems of the PaR system, and how it compares to other methods. Section IV discusses future work and conclusions.

II. System Description

This system was designed at the Oklahoma State University to provide accurate location data for an autonomous golf cart giving campus tours. However, the system will work any environment, indoors or out, with almost no infrastructure changes needed. Furthermore, it has user friendly software designed for easy adaptability in route changes; whether temporarily (i.e., for construction) or permanently. It was developed to be easily installed, maintained and adjusted by laypeople.

The system naturally divides into four parts: The laser base, the transponders, the location software, and the Graphical User Interface (GUI) as can be seen in Fig. 2.

1) **Laser Base**
This central component contains a laser diode, an encoded motor, and processing hardware. A laser is decollimated into a vertical line and rotated about the z-axis. The motor's encoder data is sent to a Raspberry Pi. The base also has an Inertial Measurement Unit (IMU) to track magnetic north and the yaw (rotation about the z-

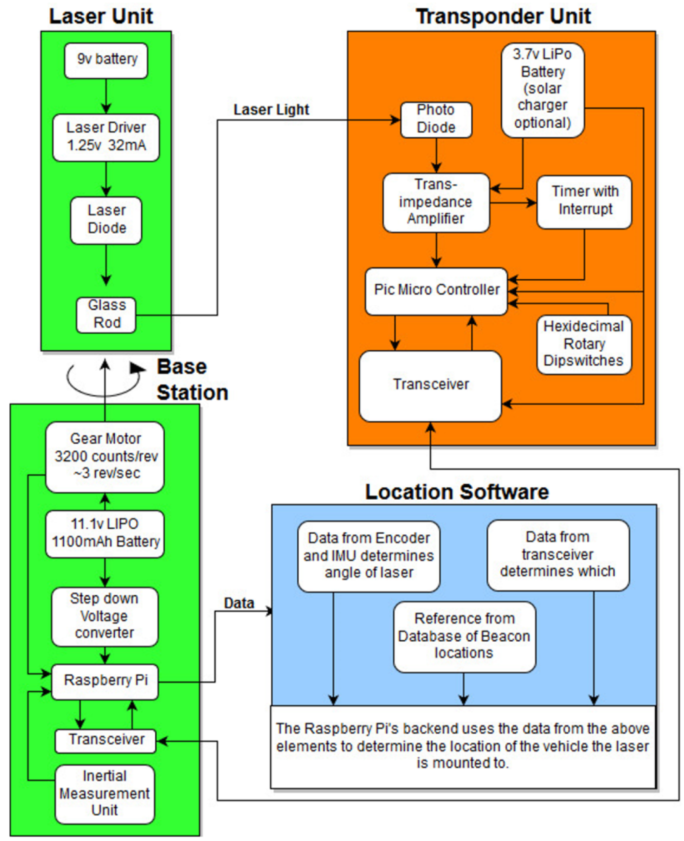

Fig. 2. System overview.

axis), which it relays to the Pi. The laser base uses a transceiver to receive signals from the transponders.

2) **Transponders**
As the rotating laser sweeps across photodiodes on each transponder, a small current is sent through a Trans-Impedance Amplifier (TIA). This triggers a PIC microcontroller to read the values from the user set ID for the transponder, and transmit this ID back to the laser base. The ID is user defined by rotary hexadecimal switches on the casing.

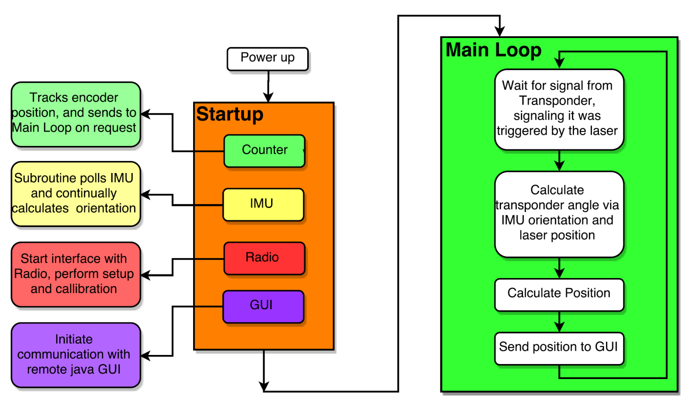

Fig. 3. The location system block diagram.

3) **PaR Location Software**

The PaR system is elegant in its simplicity. The program's flowchart is detailed in Fig. 3. When a transponder broadcasts an ID signal, the PaR location software retrieves four elements of information: the angle of the laser from the encoder, the orientation from the IMU, the ID of the transponder, and the predetermined location of that transponder. That information is used to extrapolate a line. A second transponders angle, ID, and location, allows the software to calculate a second line. The lines intersect at the location of the laser base. Any additional transponders allow for error correction. It is intended to have at least three transponders in range at all times, but can work with two, as shown in Fig. 4.

The software is fast and agile. Because trigonometry takes more clock cycles to process than linear algebra, a dictionary of the motor encoder's 3200 sine and cosine values was created. This way any value returned on the encoder can be referenced for a trigonometric value.

This means in Fig.4 that the positions of the transponders (c_1, d_1) and (c_2, d_2) and the angle of the transponders θ_1 and θ_2 are known values. By using linear algebra, finding the intersection of the lines and the position of the base station can be determined with minimal calculations.

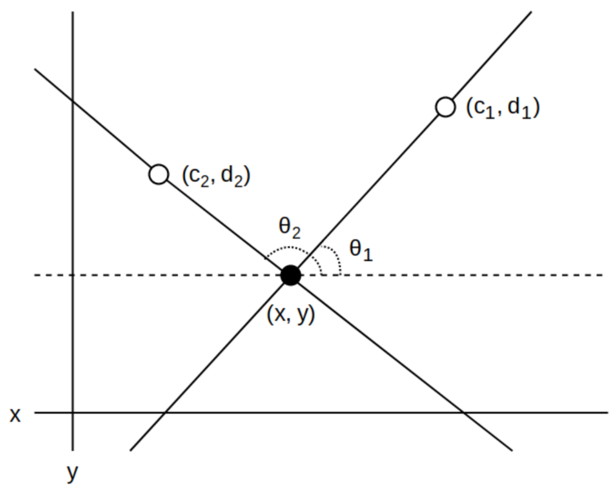

Fig. 4. Triangulation using two transponders.

In equations (1) and (2), a_1 and a_2 are values found in the dictionary, not solved:

$$a_1 = \tan(\theta_1) \tag{1}$$
$$a_2 = \tan(\theta_2) \tag{2}$$

Starting with the equation of a line, we can manipulate a system of equations:

$$y = mx + b, \Rightarrow b = y - mx \tag{3}$$
$$\therefore b_1 = d_1 - a_1 c_1 \tag{4}$$
$$\therefore b_2 = d_2 - a_2 c_2 \tag{5}$$

$$y = a_1 x + b_1 \Rightarrow a_1 x - y = -b_1 \tag{6}$$
$$y = a_2 x + b_2 \Rightarrow a_2 x - y = -b_2 \tag{7}$$

This can be written in matrix form as:

$$\mathbf{A}x = \mathbf{B} \tag{8}$$

where,

$$\mathbf{A} = \begin{bmatrix} a_1 & -1 \\ a_2 & -1 \end{bmatrix}, \ \mathbf{B} = \begin{bmatrix} -b_1 \\ -b_2 \end{bmatrix} \text{ and } \ x = \begin{bmatrix} x \\ y \end{bmatrix} \tag{9}$$

Therefore, x is given as:

$$x = \mathbf{A}^{-1}\mathbf{B} \tag{10}$$

When using this method with three transponders, the Raspberry Pi completes the calculations and returns a location for the GUI to plot in about 2μs.

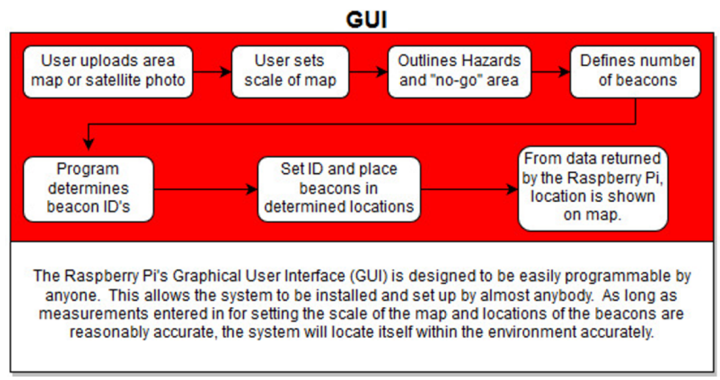

Fig. 5. GUI flowchart.

4) **Graphical User Interface**

In order to make the system user friendly, a simple but secure interface was implemented. The GUI illustrated in Fig. 5 allows the user to upload a satellite map, aerial photography, architectural drawings, or any other scaled replica of the area. The user sets the scale of the map and determines how many transponders are to be placed. Then the user can drag and drop the transponders onto the map, corresponding with the actual placement, as shown in Fig.6. The transponder locations are converted into Cartesian coordinates and saved in a dictionary file on the Raspberry Pi. The Pi uses this to quickly access the predetermined locations for each beacon used.

III. Testing, Results, Problems, and Solutions

The positional information sent back during testing is accurate within approximately 3% ($\pm$ 1.5%) relative to the distance to the transponders. Fig.7 shows the Cartesian coordinates found, while simultaneously Fig. 8 shows the angles being reported by encoder to the PaR software.

Occasionally, errors will jump to nearly 10%. These errors are sporadic, and the cause is unclear, but evidence suggests that the IMU is the cause, since they happen uniformly across

Fig. 6. A screenshot of the GUI

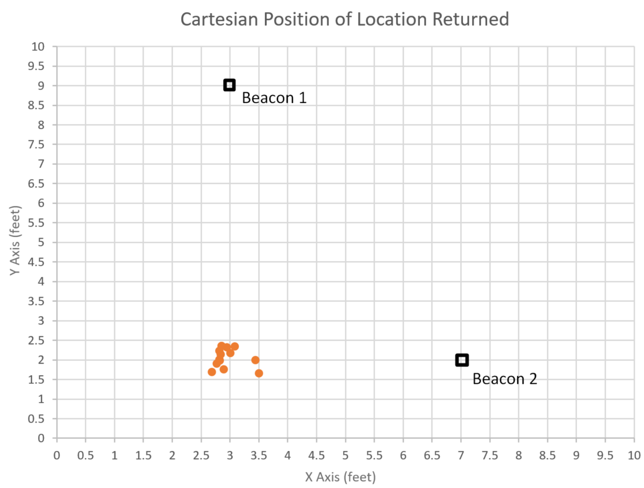

Fig. 7. A plot of the locations found over time.

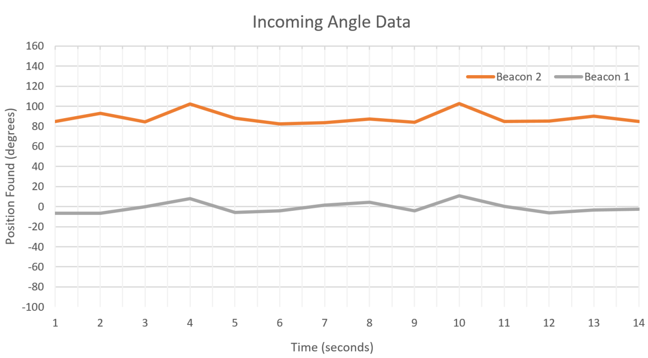

Fig. 8. The angles of beacons found over time.

all transponders. Since this was intended to be merely a proof of concept, the limitations of the system and variance shown in the resultant data were considered acceptable, but the addition of a more robust IMU and an absolute encoder would reduce the errors dramatically.

Non-line of sight (N-LoS), when something gets in between the transmitter and receiver, degrades the navigation performance. The reason the GPS loses resolution is the N-LoS with some of it's satellites. In addition, since the constellation of GPS sattelites is in constant change, the error varies constantly [9]. ToF and TDoA need a clear path, without it, multipath propagation adds time to the signal's flight, and causes error. If solutions to these problems are known, the expense to correct it is prohibitive.

The same N-LoS issue affects the PaR system, but the cost of an additional transponder is currently under \$15 (prototype cost is significantly higher than production cost will be), therefore putting more transponders in the system is an effective solution to the N-LoS issue. The system can have up to 65,536 unique transponders, which would blanket a very large area. Slight modifications allow over one million transponders, and exponentially greater coverage.

The physical system shown in Fig. 9 has a small footprint. The transponders being 90 x 70 x 40 mm and weigh less than 250g with the battery. The base is 200 x 75 x 120 mm and weighs less than 1kg. These small sizes make them unobtrusive, and adaptable to many sizes of AV. It connects via Wi-Fi to the computer running the GUI, making monitoring from a distance a feasible option.

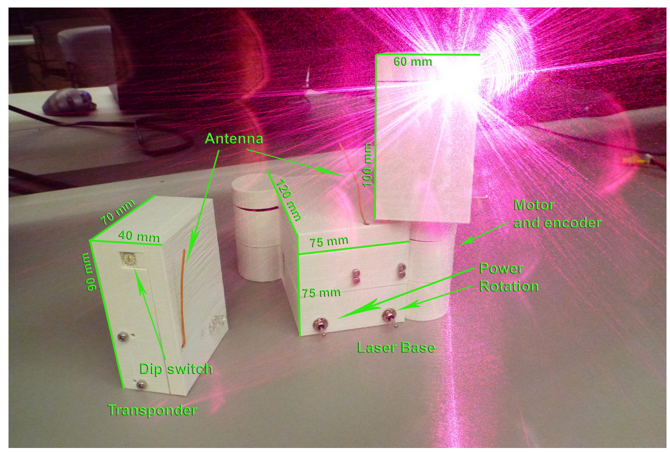

Fig. 9. Transponder and base station.

IV. Conclusion and Future Work

The proof of concept detailed in this paper shows a new localized positioning technique, and a system implemented to run it. Preliminary testing shows it to be more accurate than GPS, especially indoors or outside in urban environments. Using a laser and a network of transponders, a new method of triangulation has been developed with an accuracy of approximately 3% relative to the distance to the transponders. It is designed to overcome the inaccuracy of GPS; but with a low cost of production and implementation, and can be used either indoors or outdoors. Furthermore, very little (if any) infrastructure change is needed to implement this system.

The low cost and versatility of this system makes it a system worth fine tuning. We have plans to add more functionality to the software and upgrade the hardware in the next phase of our research.

TABLE I
LIST OF COMPONENTS

Placement	Item	Cost
Base Station		
	Laser Diode	$47.40
	16mm Glass Rod	$8.70
	9 DOF IMU	$15.95
	Raspberry Pi	$39.99
	Buck Converter	$6.99
	2000mAh Battery	$12.99
	50:1 Gearmotor	$39.95
	Radio Transceiver	9.95
Transponders	**3 units**	
	(x3) PIC microcontrollers	5.40
	(x3) Op Amps	$8.64
	(x3) Radio Transceivers	$29.85
	(x3) Photodiodes	$3.95
	(x3) Rotary Dip Switch	$6.69
Total		$243.39

*some things not listed (wire, resistors, capacitors, 3D printing filament, perf board, solder, etc.) would add a minimal cost, and were not accounted for in the budget.

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