Estimating Position and Orientation of an Unmanned Guided Vehicle with Ultrasound and Radio Frequency Sensing

by

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Abstract: Conventional method of finding location of moving an Unmanned Guided Vehicle (UGV) in pre-defined area is by Distance Measurement Equipment (DME) based on Ultrasound and triangulation technique. In many systems the ultrasound transmitter requires to be in line of sight of receiver to reduce the error. In order to overcome this problem powerful transmitters are used to ensure omni directional transmission over large distances resulting in cone shape propagation. In this cone propagation the signal may not be visible in many areas and triangulation is not possible. This paper describes a unique triangulation system based on two different ultrasound signals and Radio Frequency using four transmitters' at different locations and eight receivers fixed on an UGV. This method requires no line of sight or specific angle to receive the signal from transmitter. Thus vehicle can rotate in any angle and move anywhere in a given specific region. At the same time it was possible to estimate the position coordinates and orientation of vehicle. The new system shows that the vehicle can be more flexible and angular restriction does not bind its movement.

I. Introduction

One pinnacle of development in the manufacturing system was the invention of an Unmanned Guided Vehicle (UGV), a material handling equipment that works in cells without human intervention [1]. The application of an UGV in Flexible Manufacturing Systems (FMS) has placed greater demand on automated material handling systems and has become an essential part of FMS due to their flexibility and adaptive behavior [2]. The current methods for an UGV tracking are the Global Positioning System (GPS).

However, due to GPS receiver's large size, limited accuracy, and satellite visibility requirements, this system is not appropriate to use inside an enclosed area [3]. Different methods of UGV navigation as well as their features are: 1) wire guided, 2) inertial guided, 3) laser guided, 4) grid, and 5) chemical path guided. In these navigation systems, the UGVs travel is based on the physical track pattern designed into the floor. An UGV cannot deviate from the pre-established route [4].

The flexibility of an UGV is greatly limited due to their physical track [5]. If the present track system is eliminated and the UGVs are made trackless, flexibility can be enhanced. Thus, there was a need to develop an UGV system, which eliminated the pre-determined tracks. Developing a trackless UGV needs various modifications to the present system. One new requirement will be finding the location of an UGV for navigation. The author in this paper demonstrates a new experimental trackless navigational aid to enhance the flexibility of an UGV.

II. Methods to Find the Position for Navigational Aid

The SENCAR UGV uses infrared beacons mounted on the ceiling to triangulate the position [6]. The AT&T Lab has also developed a low cost infrared location system that uses triangulation to find a position [7]. A low cost ultrasonic 3D position estimate system has been developed that uses the actual time of flight (TOF) from the transmitter to the receiver [8, 9]. Ultrasonic positioning system based on the difference between the time of flight of the sound waves for various sensors has been developed [10].

The matrix based model is an improvement over conventional triangulation technique for co-ordinates [11]. Few researches have used Fuzzy triangulation to identify a robot's positions and orientation [12]. One typical algorithm used for Triangulation Method computation is described in [13]. But most such algorithms are proprietary because the solutions are non-trivial [14].

One of the methods used to find co-ordinates is installing of three or more transmitters at known locations and one receiver on board [14]. If there is one receiver on board it may not be possible to receive signals in any given direction, which limits the accuracy. This means the transmitter has to direct signal to the receiver directly or in other words there should be a line of sight in between the transmitter and the receiver. And all the transmitters have to face the receivers in order to catch the signal or else there can be error.

Another method uses three or more active transmitters mounted on the known location. The sensor rotates and measures the three angles. This system helps in measuring the co-ordinates and unknown vehicle rotation. In order to overcome the problems powerful transmitters to ensure omni directional transmission over large distances and it results in cone shape propagation [14]. As a result of this cone propagation the transmitters are not visible in many areas resulting triangulation not possible.

A new system reduced errors by using floating points for triangulation and increasing the flexibility of their system. An acoustic cone made of aluminum and placed it above the receiver allowing the ultrasonic sound waves to be collected from any direction [15]. One of the disadvantages to this system is the cost and use of many components.

A detailed analysis on three-point triangulation algorithms and ran computer simulations to verify the performance of different algorithms [16]. The results are summarized as follows:

- The geometric triangulation method works consistently only when the robot is within the triangle formed by the three beacons. There are areas outside the beacon triangle where the geometric approach works, but these areas are difficult to determine and are highly dependent on how the angles are defined.
- The *Geometric Circle Intersection* method has large errors when the three beacons and the robot all lie on, or close to, the same circle.
- The *Newton-Raphson* method fails when the initial guess of the robot' position and orientation is beyond a certain bound.
- The heading of at least two of the beacons was required to be greater than 90 degrees. The angular separation between any pair of beacons was required to be greater than 45 degrees.

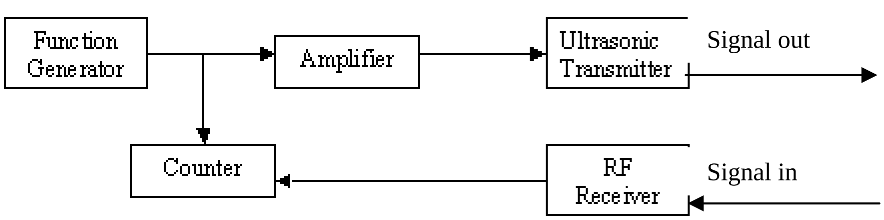
In summary, it appears that none of the above methods alone is always suitable, but an intelligent combination of two or more methods helps overcome the individual weaknesses [14]. There are systems available in the market to overcome some of the above-mentioned problems. But, these systems are too large and expensive for operation [14, 15]. To overcome above-mentioned problems a need of smaller and inexpensive system exists.

III. Distance Estimation of a UGV from the Base Station

Distance Measuring System (DMS) is used to estimate the distance of the UGV from a known location. The distance measuring system (DMS) consisted of three parts – the base stations, mobile unit, and a time counter program. The four identical base stations transmit the ultrasound signal to the mobile unit. Also, the base station receives the radio frequency signal emitted by the mobile unit in response to the ultrasound signal. The position coordinates of a mobile unit vary continuously and the base stations are fixed. The DMS measures the distance between the base station and the mobile unit by measuring the time of flight of the ultrasonic pulse to the mobile unit. The base station recognizes the response and calculates the time of flight, which is the time, elapsed between the ultrasonic signal sent and the radio signal received. The features and the functions of the various parts constituting the DMS are as follows:

Base Stations:

A base station consists of five parts, ultrasonic transmitters, amplifiers, counters, function generators, and a radio frequency receiver, as shown in the Flowchart 1.



Flowchart 1: Block Diagram for a Base Station

There were four identical base stations at four different locations and each station contained one pair of transmitters. Only one pair was active at a particular time. Each transmitter in a pair formed an angle of 120° with one another giving maximum spread of ultrasonic ping. Two base stations operated at 32.5 KHz and other two operated at 40 KHz. A National Instruments 32-bit Counter/Timers card, NI 6602 programmed using C++ was used as a function generator to produce TTL signals. The TTL signals were fed to counter card and amplified to 20V p-p by the custom-built inverting amplifier from OPA404KP-ND, as shown in Figure 1. The amplified signal was fed to ultrasonic transmitter. The TTL signals latched the counter to zero and started counting the time. The counter card was set at 20 MHz clock speed. The counting process continued until a signal from the RF receiver to unlatch the counter, was received.

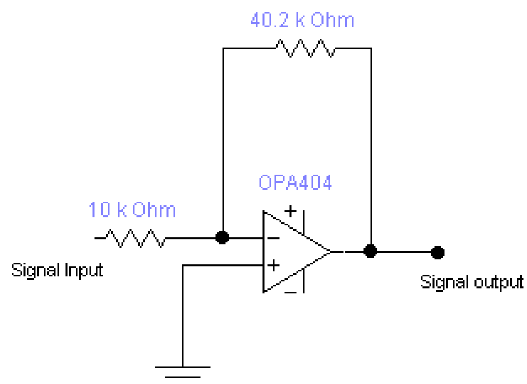
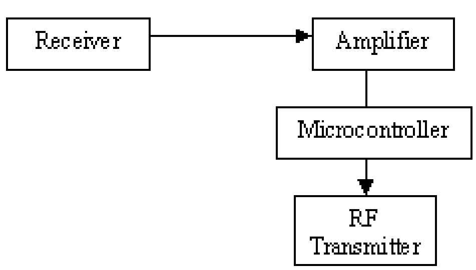


Figure 1: Custom-Built Amplifiers from OPA404KP-ND for Base Station

Mobile Unit:

The mobile unit was mounted on an UGV. The mobile unit received the ultrasound signal from the base station and transmitted the radio signal in response. The mobile units consisted of an ultrasonic receivers, RF transmitter, amplifier, and micro controller, as shown in the Flowchart 2. There were eight ultrasonic receivers, four sensing signals at 32.5 KHz and other four at 40 KHz. The ultrasonic receivers of same frequency were placed on each side of rectangle shaped project box, which aided in receiving the signal irrespective of vehicle orientation. The project boxes were installed at the head and tail positions respectively.



Flowchart 2: Block Diagram for the Mobile Unit

When the ultrasonic pulse reached the ultrasonic receiver, the signal was processed through a custom-built inverting amplifier from OPA404KP-ND, Figure 2.

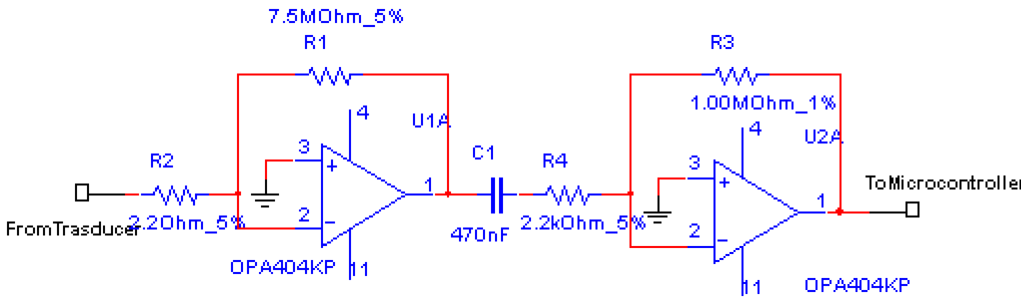


Figure 2: Custom-Built Amplifiers from OPA404KP-ND for Mobile Station

The amplified signal was then fed to a Basic Stamp 2sx micro controller. The micro controller programmed using P-Basic, measured the pulse width of the signal. After sensing an appropriate pulse micro controller triggered the RF transmitter to send signal to the base station.

IV. Counter Program to Estimate Time

This C++ program was used to write the counter value in text format. It measured the number of counts between the latch and unlatch period. The number of counts was then multiplied by the average time period between any two adjacent counts. This process made the counter to estimate the time of flight of ultrasound signal to travel from base stations to the mobile unit.
The resulting time of flight is found from:

$T = C\ (1/20MHz)$……………………….……… (Equation.1)
$\quad = C\ (0.000000005)$

Where C = number of counts, T = time of flight in seconds. To minimize the error of recorded time, the average of four consecutive time values was used as the time of flight.

$T_a = (T_1+T_2+T_3+T_4)/4$…………………….……… (Equation.2)
Where T_a = average time of flight in seconds.

The numeric value of the average time of flight was saved in a text file. Once the average time of flight (T_a) was known, the distance could be found by using the following equations:

Distance traveled by the ultrasound wave is given by:

$d_0 = V\ T_a$ ………………………….…………… (Equation.3)

Where V= velocity of propagation, d_0 = Distance traveled in inches.

d = [V (T_a-t)] ……………………………………….. (Equation.4)

Where d= estimated distance in inches, t = time elapse across the electronic circuit.

d = [331(T_a-t)] ………………..……...…………… (Equation.5)

Velocity (V) is speed of sound and travels at 331m/s.

V. Estimation of the Position and Orientation of an UGV

After the distance computation of the vehicle from the four different base stations, the position estimation process was begun. This process is a combination of two separate, independent algorithms:

1. For estimating the position, i.e., the coordinates (x, y) for the vehicle's head and tail
2. For determining the orientation of the vehicle.

To determine the position and orientation of the vehicle, a triangulation approach was adopted where the receivers and transmitters formed a triangle, as shown in Figure 3. One of the vertexes of one of the triangles was the head position of an UGV, while the tail was one of the vertexes of the second triangle of an UGV. As the positions of the transmitters on the base station were known, the only unknown vertex in the triangle was either the head or the tail of an UGV. The triangulation algorithm was used to determine this unknown position of the vertex and hence the position of an UGV.

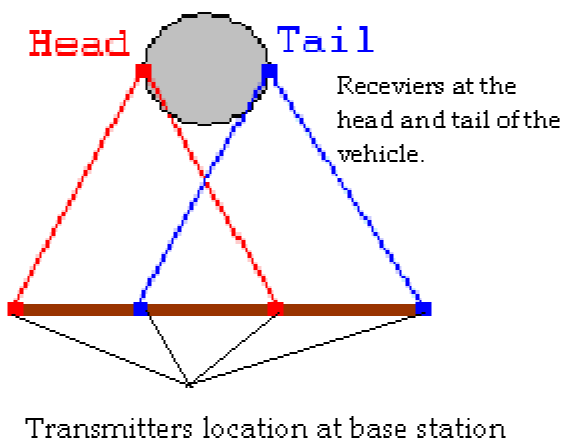


Figure 3: Triangles Formed by the Base Station and Mobile Unit

Estimating the Head and Tail Coordinates of an UGV:

Figure 4 below shows the triangle formed during the execution for the program. The vertices B, E, C, and F were at the base of the triangle. The vertices A and D were the head and the tail of an UGV, respectively.

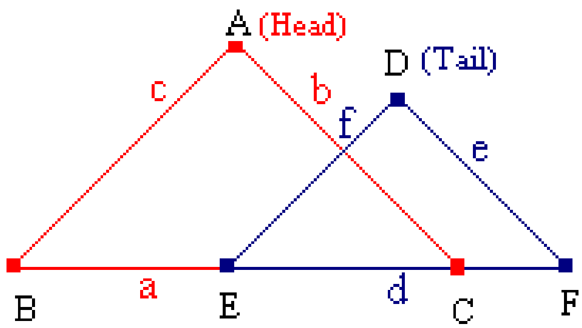


Figure 4: Triangles Formed by Connecting the Sensors and Transmitter

The triangulation algorithm was used for determining the head and tail position, i.e., coordinates for the vertex A and D. The Figure 5 also illustrates the different possible positions of the head/tail of the vehicle during the travel of an UGV.

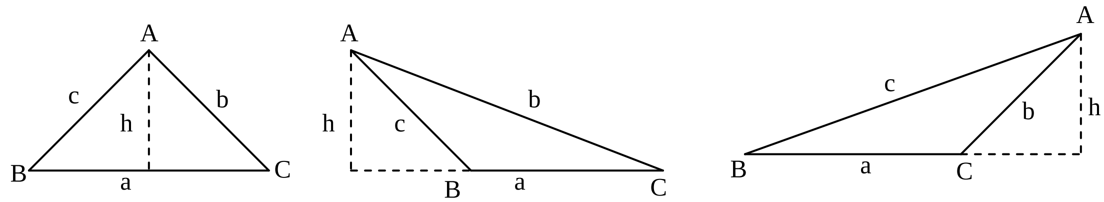


Figure 5: Possible Orientations of the Triangle

Here, in detail, is the algorithm used to estimate the unknown vertices:

Step 1: Obtain the distances of the sides of the triangle (i.e., a, b, and c).

Step 2: The area of the triangle was calculated using the formula:

$$Area = \sqrt{s*(s-a)*(s-b)*(s-c)}$$

Where 's' was the semi-perimeter of the triangle→ $s = \dfrac{a+b+c}{2}$.

Step 3: In the next step, the height of the triangle was calculated using the formula –

$$height\,(h) = \frac{2*Area}{base\,length}$$

Step 4: Also the angle at the vertices B and C were obtained using the arc sine formulas.

a. $$Angle\,C = \sin^{-1}\left(\frac{height}{b}\right)$$

b. $Angle\,B = \sin^{-1}\left(\frac{height}{c}\right)$

Step 5: As only interior angles were used in the algorithm, it had to be determined if these angles were the exterior ones or the interior ones. If side (‘c’) was greater than sides, (‘a’) and, (‘b’) then the angle obtained (i.e., Angle C) was the exterior angle. The supplementary angle was used instead. Similar calculation was performed for the angle B, opposite to the other side (‘b’).

Step 6: For the algorithm to work in a desired manner, the base of the triangle had to be parallel to the x-axis. The angle the base made with the x-axis was calculated by taking the arc cosine of the dot product of the unit vector of the base and the unit vector of the x-axis.

a) The dot product of any two vectors V1 and V2 was obtained by the expression 1x*V2x + V1y*V2y + V1z*V2z where (‘x’), (‘y’), and (‘z’) are the components of the vector representing the different coordinate’s axis.

b) The angle the base vector made with the x-axis was obtained by taking the arc cosine of the dot product, i.e., $\theta = \cos^{-1}(\mathrm{V1x} * \mathrm{V2x} + \mathrm{V1y} * \mathrm{V2y} + \mathrm{V1z} * \mathrm{V2z})$.

c) If the (‘y’) coordinate of the vertex C was greater than the (‘y’) coordinate of the vertex B, then the angle was multiplied by –1 to obtain the negative of the angle.

Step 7: All the vertices were rotated by this angle to obtain their rotated points. The equation for rotation is as shown below:

$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$ where ‘θ’ is the angle of rotation.

Before rotating all the points around vertex B, the points were translated by the distance equal to the distance of the vertex B from the origin. After rotation, all the points were translated back by the same distance to make it look as if the points were rotated about vertex B. The translation equations are:

$$T_e = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

Step 8: The above steps were simplified to give the equation for vertex C in two dimensions:

$$C_x = \text{Cos}\theta(C_x – B_x) – \text{Sin}\ \theta(C_y – B_y) + B_x$$
$$C_y = \text{Sin}\ \theta(C_x – B_x) + \text{Cos}\ \theta(C_y – B_y) + B_y$$

where 'C_x' is the x-coordinate of vertex C
'C_y' is y-coordinate of the vertex C
'θ' is the angle of rotation

Step 9: Then it was checked if the angle at vertex C was acute or obtuse.

a. If the angle was acute, then the position of vertex A was given by:

i. A.x = C.x - b*cos(angle at vertex C)
ii. A.y = C.y + b*sin(angle at vertex C)

b. If the angle was obtuse, then the position of the vertex A was given by

i. A.x = B.x + c*cos(angle at vertex B)
ii. A.y = B.y + c*sin(angle at vertex B)

Step 10: In the final step, all the points were rotated back by the negative of the angle ('θ'), as used in step 7, to obtain the final position of the vertex A, i.e., the position for the head position of the UGV. The steps 1 to 10 were repeated to estimate the coordinates of the vertex B, i.e., the tail.

VI. Determining the Orientation of an UGV

The following steps served to determine the orientation of an UGV:

Step 1: The vector connecting the head and tail was determined.

Vector.x = tail.x – head.x
Vector.y = tail.y – head.y
Magnitude = $\sqrt{Vector.x^2 + Vector.y^2}$

Step 2: The unit vector components were calculated by:

$$Unit\,Vector.x = \frac{Vector.x}{Magnitude}$$

$$Unit\,Vector.y = \frac{Vector.y}{Magnitude}$$

Step 3: To obtain the angle the vector made with the y-axis, the dot product of this unit vector with the unit vector representing the y-axis was calculated.

a. Unit Vector for y-Axis (axis) = {0.0, 1.0}
b. Dot product = $Unit\,Vector.x * axis.x + Unit\,Vector.y * axis.y$

Step 4: The arc cosine of the dot product was taken, which gave the orientation angle of the head with respect to the y-axis – $\theta = \cos^{-1}(dot\ product)$

Step 5: The following methods were used to determine if the angle calculated using the dot product was in the clockwise or counter clockwise direction from the vertical axis.

a. The cross product of the Unit Vector and the axis Vector was obtained which became known as Cross Vector.
   i. Cross Product $= \begin{vmatrix} i & j & k \\ a & b & c \\ d & e & f \end{vmatrix}$ where a, b, c, d, e, and f were the components of the vectors and i, j, k were the direction vectors.
b. The magnitude of the cross vector was determined as shown in step 3.
c. Then, it was converted into a unit vector as shown in step 4.
d. Since the calculations were in 2 dimensions, the vector to pointing down was the vector representing the Z-Axis. The unit vector along the Z-Axis was {-1.0, 0.0}.
e. The dot product of the two vectors was then determined.
f. If the dot product was equal to +1, then the direction of the angle, between the two passed vectors, was clockwise; else counter clockwise.

Step 6: If the angle calculated was in the counter clockwise direction, then θ was subtracted from 360°. This gave the orientation of the head from the Y-Axis.

Step 7: To get the orientation of the tail with respect to the y-axis, θ was subtracted from180°. If θ was less than 0°, then 360° was added to θ to give the final orientation of the tail with respect to the Y-Axis.

VII. Conclusion and Recommendations

This paper gives a detailed explanation on construction of navigational aid for an UGV by combining ultrasound and radio frequency signals. By incorporating ultrasound receiver's 90 degrees apart this system requires no line of sight or specific angle to receive the signal from transmitter. Adding second ultrasound signal made prediction of vehicle orientation possible. This shows that new navigational aid can be more flexible and angular restriction does not bind vehicle movement enhancing the flexibility of vehicle in a given specific region. This system has provided precise position and orientation which may vary with the distance. A statistical study based on relationship between distance of vehicle from the transmitter and position error can be conducted to elaborate performance as well as reliability of the navigational aid.

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Biography

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