NAVIGATIONAL AIDS TO PREDICT THE POSITION OF AUTOMATED GUIDED VEHICLES WITH ULTRASOUND AND RADIO FREQUENCY SENSING

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Abstract

The conventional method of finding the location of moving Automatic Guided Vehicles (AGV) in pre-defined areas is by Distance Measurement Equipment (DME) based on ultrasound and triangulation technique. In many systems, the ultrasound transmitter needs to be within the line of sight of the receiver to reduce error. To overcome this problem, powerful transmitters are used to ensure omni-directional transmission over large distances, resulting in cone-shaped 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 the AGV. This method requires no line of sight or specific angle to receive the signal from the transmitter. Thus, the vehicle can rotate at 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 the vehicle. The new system shows that the vehicle can be more flexible, and angular restriction does not bind its movement.

Introduction

One pinnacle of development in the manufacturing system was the invention of Automated Guided Vehicles (AGV), a material handling equipment that works in cells without human intervention [1]. The application of the AGV in Flexible Manufacturing Systems (FMS) has placed a 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 method for AGV tracking is the Global Positioning System (GPS). However, due to GPS receivers' large size, limited accuracy, and satellite visibility requirements, this system is not appropriate to use inside an enclosed area [3]. Different methods of AGV 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 AGV's travel is based on the physical track pattern designed into the floor. The AGV cannot deviate from the pre-established route [4].

The flexibility of AGV is greatly limited due to its physical track [5]. If the present track system is eliminated and the AGVs are made trackless, flexibility can be enhanced. Thus, there was a need to develop an AGV system that eliminated the pre-determined tracks.

Developing a trackless AGV needs various modifications to the present system. One new requirement will be finding the location of AGV for navigation. The author of this paper demonstrates a new experimental trackless navigational aid to enhance the flexibility of AGV.

Methods to Find the Position for Navigational Aid

The SENCAR AGV 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]. An ultrasonic positioning system based on the times 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 coordinates [11]. Few research studies have used fuzzy triangulation to identify a robot's position 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 coordinates is installing 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 signal to the receiver directly, or in other words, there should be a line of sight between the transmitter and the receiver. And all the transmitters have to face the receivers 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 coordinates and unknown vehicle rotation. To overcome the problems, powerful transmitters ensure omni-directional transmission over large distances, and this result in cone-shaped propagation [14]. As a result of this cone propagation, the transmitters are not visible in many areas, and resulting triangulation is not possible.

A new system reduces errors by using floating points for triangulation and increasing the flexibility of the system. An acoustic cone made of aluminum and placed above the receiver allows 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 was performed on three-point triangulation algorithms and computer simulations were run 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 lay on, or close to, the same circle.

- The *Newton-Raphson* method fails when the initial guess of the robot's 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.

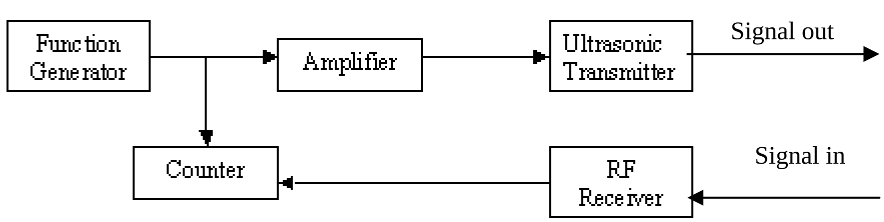
In summary, it appears that none of the above methods alone is always suitable, but an intelligent combination of two or more methods helps overcome the individual weaknesses[14]. There are systems available in the market to overcome some of the above-mentioned problems, but these systems are too large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

Distance Estimation of a Vehicle from the Base Station

The Distance Measuring System (DMS) is used to estimate the distance of the AGV from a known location. The distance measuring system (DMS) consists 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 the 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 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 the other, giving maximum spread of ultrasonic ping. Two base stations operated at 32.5 KHz, and the 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 the counter card and amplified to 20 V p-p by the custom-built inverting amplifier from OPA404KP-ND, as shown in Figure 1. The amplified signal was fed to the 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.

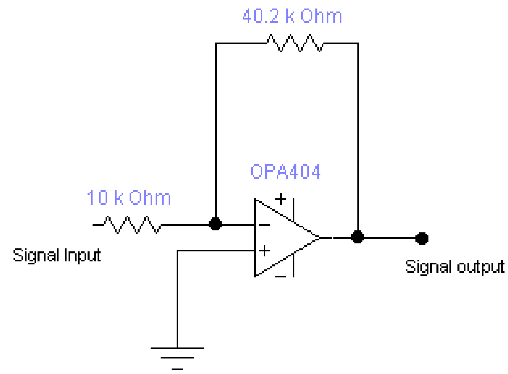
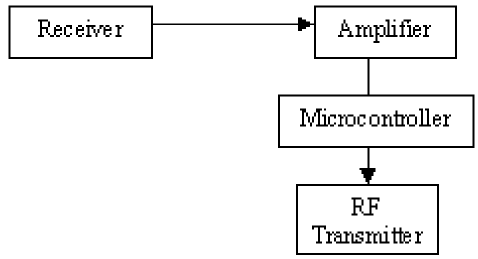


Figure 1: Custom-built Amplifiers from OPA404KP-ND for Base Station

Mobile Unit:
The mobile unit was mounted on the AGV. 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 receiver, RF transmitter, amplifier, and micro controller, as shown in Flowchart 2. There were eight ultrasonic receivers—four sensing signals at 32.5 KHz and the other four at 40 KHz. The ultrasonic receivers of the same frequency were placed on each side of a 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.

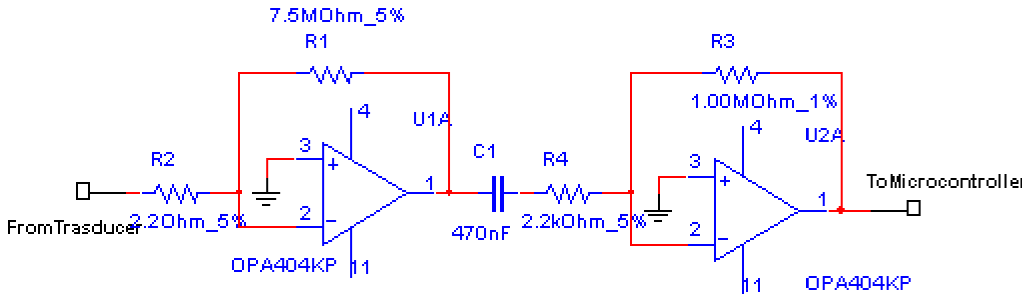


Figure 2: Custom-built Amplifiers from OPA404KP-ND for Mobile Station

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, the micro controller triggered the RF transmitter to send the signal to the base station.

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 caused the counter to estimate the time of flight of the 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),
$= C\ (0.000000005)$

where C = number of counts, and 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, and d_0 = Distance traveled in inches.

$d = [V (T_a\text{-}t)]$ …………..……………………….. (Equation 4),

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

$d = [331(T_a\text{-}t)]$ ………………..……...……….… (Equation 5)

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

Estimation of the Position and Orientation of the Vehicle

After the distance computation of the vehicle from the four different base stations, the position estimation process began. 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 AGV, while the tail was one of the vertexes of the second triangle of an AGV. 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 AGV. The triangulation algorithm was used to determine this unknown position of the vertex and hence the position of an AGV.

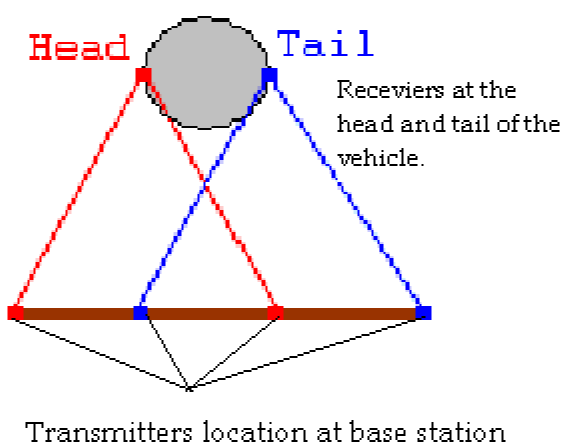


Figure 3: Triangles Formed by the Base Station and Mobile Unit

Estimating the Head and Tail Coordinates of an AGV:

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 AGV, respectively.

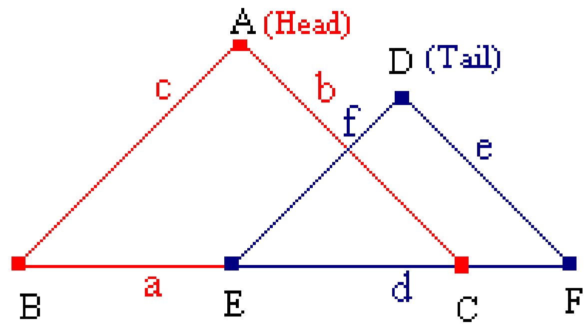


Figure 4: Triangles Formed by Connecting the Sensors and Transmitter

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

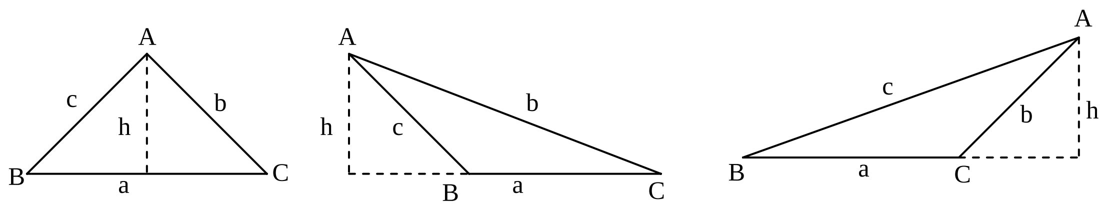


Figure 5: Possible Orientations of the Triangle

The following, 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→ $s = \frac{a+b+c}{2}$.

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: Because only interior angles were used in the algorithm, it had to be determined whether these angles were 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. A similar calculation was performed for Angle B, opposite to the other side (*b*).

Step 6: For the algorithm to work in the 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, and
θ is the angle of rotation.

Step 9: Then, check 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 vertex A, i.e., the position for the head position of the AGV. Steps 1 to 10 were repeated to estimate the coordinates of vertex B, i.e., the tail.

Determining the Orientation of the Vehicle

The following steps served to determine the orientation of the AGV.

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:

$$UnitVector.x = \frac{Vector.x}{Magnitude}$$

$$UnitVector.y = \frac{Vector.y}{Magnitude}$$

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 = $UnitVector.x * axis.x + UnitVector.y * axis.y$

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 two dimensions, the vector 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; otherwise it was 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 from 180°. 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

Conclusion and Recommendations

This paper gives a detailed explanation of the construction of a navigational aid for AGVs by combining ultrasound and radio frequency signals. By incorporating ultrasound receivers 90 degrees apart, this system requires no line of sight or specific angle to receive the signal from a transmitter. Adding a second ultrasound signal made prediction of vehicle orientation possible. This shows that a new navigational aid can be more flexible, and angular restriction does not bind vehicle movement, thus enhancing the flexibility of a 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 the 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.

Reference

[1] Black, J.T. (1991). The design of factory with a future. New York: McGraw-Hill.

[2] Yu, W. and Egbelu, P.J. (2001). Design of a variable path tandem layout for automated guided vehicle system. *Journal of Manufacturing Systems*, 20.

[3] Getting, I.A. (1993). The global positioning systems. *IEEE Spectrum*, December, 33–47.

[4] Siemens, http://www.Agvsystems.Com/Faqs/Q6.Htm. Accessed on May 20, 2007.

[5] Dixon, J. and Henlich, O. (2008). Mobile robot navigation. http://www.Doc.Ic.Ac.Uk/~Nd/Surprise_97/Journal/Vol4/Jmd/. Imperial College, London. Accessed May 8, 2004.

[6] Rathbone, R. R., Valley, R.A. and Kindlmann, P.J. (2000). Beacon-referenced dead reckoning: a versatile guidance system. *Robotics Engineers*, 8, 11–16.

[7] Miller, G.L., Wagner, E.R. and AT&T Bell Laboratories (1988). An optical rangefinder for autonomous robot cart navigation. *Society of Photo-Optical Instrumentation Engineers*, Vol. 852.

[8] When, H.W. and Belanger, P.R. (1997). Ultrasonic-based robot position estimation. *IEEE Transactions on Robotics and Automation*, 13, 682–692.

[9] Mahajan, A. and Figueroa, F. (1999). An automatic self installation and calibration method for 3d position sensing using ultrasonic. *Robotics and Autonomous Systems*, 28, 281–294.

[10] Ray, P.K., Unnikrishanan, N. and Mahajan, A. (2002). Accuracy consideration in 3d ultrasonic positioning system based on the difference in time of flight. Department of Mechanical Engineering and Energy Process, Southern Illinois University, Carbondale, IL.

[11] Kuang, W.T. and Morris, A.S. (1999). Algorithm for robot position tracking using ultrasonic. *Electronics Letters*, 35.

[12] Demirli, K. and Turksen, I.B. (2000). Sonar based mobile robot localization by using fuzzy logic. *Robotics and Autonomous Systems*, 33, 109–123.

[13] Shoval, S., Benchetrit, U., and Lenz, E., 1995, Control and positioning of an AGV for material handling in an industrial environment. *Manufacturing Systems*, Vol. 25, No. 4, 1996, pp. 405–40

[14] Borenstein, J., Everett, H.R., and Feng, L. (1996). Navigating mobile robots: sensors and techniques. A.K. Peters, Ltd.

[15] Navrro-Serment, A.E., Paredis, J.J. and Khosal, P.K. (2000). A beacon system for the localization of distributed robotic teams. The Institute for Complex Engineered Systems. Carnegie Mellon University. Pittsburgh, PA.

[16] Cohen, C. and Koss, F., 1992, “A comprehensive study of three object triangulation.” Proceedings of the 1993 SPIE Conference on Mobile Robots, Boston, MA, Nov. 18–20, 95–106.

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