NAVIGATING VEHICLES THROUGH AN UNSTRUCTURED ENVIRONMENT WITH SONAR

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ABSTRACT

This paper describes a procedure to navigate a vehicle from a source to a destination through an unstructured environment using only a sonar sensor. The environment to be considered is a two-dimensional floor plan, consisting of line segments of arbitrary size that is extended into the third dimension. To ensure that a sonar-guided vehicle does not collide with an obstacle, it is necessary to consider the obstacles that produce the weakest echoes and determine the conditions under which these obstacles can be detected. In this environment, the smallest echo is produced by the line that defines the boundary between two planes, or the edge. The echo is then a diffracted signal. A problem with detection arises because the amplitude of this diffracted signal, compared to that of specular reflections, is initially smaller and then decreases with distance from the edge. The edge reflection eventually falls below the threshold level of the sensor system when the edge is located beyond some finite range value. Hence, distant edges become invisible. This physical principle then becomes the basis for the navigation strategy, indicating the necessary scanning pattern and maximum step size that guarantee that no collision will occur. The approach is illustrated with results produced by a vehicular robot equipped with a Polaroid sensor.

1. Introduction

Acoustic sensors provide an inexpensive means for determining the proximity of objects and have been useful for implementing sonar systems for robot navigation [1,2]. The most popular are the time-of-flight (TOF) systems, one of which has been implemented by Polaroid [3]. However, problems arise in the straightforward, but naive, interpretation of the TOF reading: Objects that are present are not always detected and range readings produced by the TOF system do not always correspond to objects at that range [4,5,6]. This paper presents a procedure for navigating an autonomous vehicle through an unstructured environment, without collision, aided only with a TOF sonar system.

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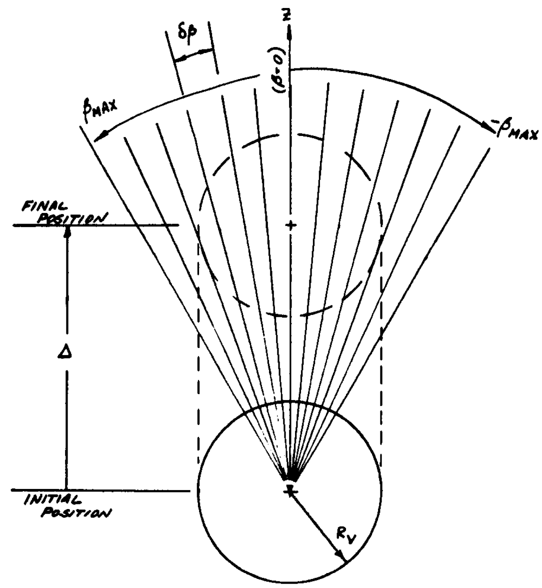

Fig. 1. Definition of scanning density δβ, limit β_{MAX} and radius R_V to accomplish a translation of size Δ without collision.

The basic problem is illustrated in Fig. 1. A vehicle that is contained within a disk of radius R_V is to perform a translation of size Δ without having a collision. The direction of translation defines the line from which the angle β is measured. We will determine the density of the scan, δβ, and the maximum extent of the scan, β_{MAX}, that will detect all obstacles in the path.

In the next section, we summarize the results of a recent paper that describes a spatial sampling criterion for obstacle detection with sonar [7]. A method is developed that determines how to accomplish a translation without a collision. A algorithm is then implemented to navigate the vehicle through an unstructured environment. The approach is illustrated with results produced by a vehicular robot equipped with a Polaroid sensor.

2. The spatial sampling criterion.

Most conventional sonar ranging systems employ a single acoustic transducer that acts as both a transmitter and receiver [3]. After the transmitted pulse encounters an object, an echo may be detected by the same transducer acting as a receiver. A <u>threshold level</u>, denoted by τ, is included in the detector to suppress erroneous readings generated by electronic or acoustic noise. A conventional TOF system produces a range value when the echo amplitude first exceeds the threshold level, say at time t_o. A range measurement z_o is obtained from the time-of-flight by

$$z_o = ct_o/2 \qquad (1)$$

where c is the speed of sound in air (343 m/s at room temperature).

The transmitting transducer forms a beam in which the acoustic energy is concentrated. The half-width of this beam is the angle Θ_o given by

$$\Theta_o = \sin^{-1}(0.61\lambda/a) \qquad (2)$$

where λ is the <u>wavelength</u> of the acoustic signal (computed as $\lambda = c/f$, where f is usually taken as the resonant frequency of the transducer) and a is the radius of the transducer aperture.

The amplitude of the radiated pressure, denoted by $A(\Theta)$, is a function of angular deviation from the transducer orientation Θ. A time-controlled gain amplifier is usually included to normalize the maximum amplitude to unity and to compensate for the loss of the signal with range [3]. The amplitude of the radiated pressure can then be approximated by a Gaussian curve independent of range:

$$A(\Theta) = e^{-2\Theta^2/\Theta_o^{\,2}}, \text{ for } |\Theta| \le \Theta_o \qquad (3)$$
$$= 0, \qquad \text{for } |\Theta| > \Theta_o.$$

The environment in which the sonar operates is modeled as a two-dimensional floor plan and the sonar scans are to be performed in the horizontal plane. A line size $> \lambda/5$ precludes problems associated with zero-thickness walls, while an angle between walls $> 60^o$ precludes sharp wedges. This model is general enough to approximate most real-world environments. For this environment, two categories of structures that produce echoes can be considered, as shown in Fig. 2: <u>reflecting surfaces</u>, whose dimensions are larger than the wavelength, and <u>diffracting edges</u> whose dimensions are smaller than the wavelength.

<u>Detection of surfaces.</u> The value of β_{MAX} is determined by the worst case orientation of an oblique surface that can cause a collision during the translation. The worst case occurs when a surface is located at the edge of the vehicular disk after the translation. Before the translation, the distance from the sensor measured along the normal to the surface is equal to $Z_{SURFACE}$ and at angle β. Since a surface can be oriented by choosing $Z_{SURFACE}$ and β to cause a collision to occur after translation for any value of Δ, it is necessary to scan almost the full $\pm 90^o$ relative to the translation direction [8]. Hence,

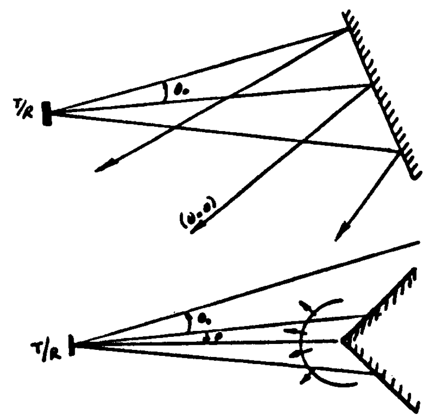

Fig. 2. Reflections from surfaces and edges.

$$\beta_{MAX} \sim 90^o \qquad (4)$$

Having chosen β_{MAX}, we must now determine the criterion for the range reading as a function of the scan direction, denoted by $Z_{TOF}(\beta)$. Otherwise, a surface that is parallel to our desired translation direction located at a range less than Δ may prevent us from moving. Obviously, if a range reading taken in the desired direction of movement ($\beta=0$) is observed to be less than the translation distance, or $Z_{TOF}(0) < \Delta$, then we would not make the move. The analysis is simplified by shrinking the radius of the vehicle R_V to zero and growing the surface range to compensate. We then note that

$$Z_{SURFACE} = \Delta \cos(\beta) \qquad (5)$$

Restoring the radius of the disk, we find that we can make a collision-free move if

$$Z_{TOF}(\beta) > \Delta\cos(\beta) + R_V \qquad (6)$$

as shown in Fig. 3.

<u>Diffracted echo detection.</u> The diffracted echo is a cylindrical wave that appears to be emanating from the line defining the edge. Since a cylindrical wave diverges in only one radial direction

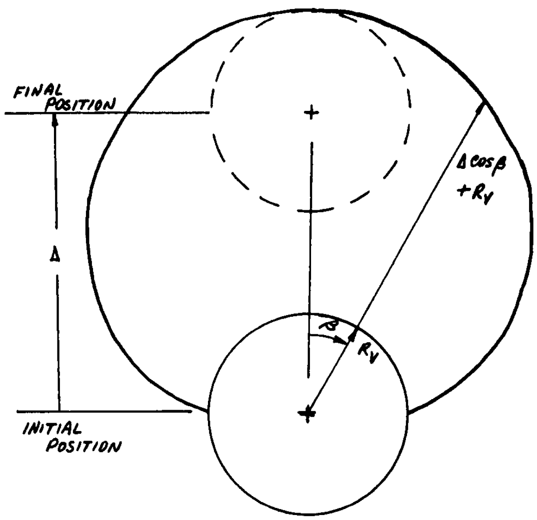

Fig. 3. The surface-free region.

(as opposed to a spherical wave, which diverges in two radial directions), the amplitude decreases as the inverse square root of the distance travelled [4]. The amplitude of the echo diffracted from an edge also has a smaller amplitude than the signal reflected from a surface. We have experimentally observed the diffracted signal amplitude from a 90^o edge to be 5% of the amplitude reflected from a surface when measured at 10 cm from the edge. This small echo is the main reason that edges are not typically observed with conventional sonar systems.

Incorporating these observations for diffracted echoes, the amplitude of the detected echo diffracted from an edge located at angle θ with respect to the sensor orientation and at range z, denoted by $A_E(\theta,z)$, is equal to

$$A_E(\theta,z) = 0.16\ z^{-1/2}\ e^{-4\theta^2/\theta_o^2},\ \text{for } |\theta| \le \theta_o \quad (7)$$
$$= 0,\ \text{for } |\theta| > \theta_o$$

where z is measured in cm. The reciprocity principle [9] was employed to obtain the factor of 4 in the exponent. Eq. (7) holds for the common 90^o edge, but as sharper wedge-like edges are encountered, the amplitude of the diffracted signal is decreased and the 0.16 coefficient must be reduced. For example, 60^o wedges have been observed to reduce this coefficient to 0.08.

This spreading loss of the diffracted echo has important consequences in terms of its

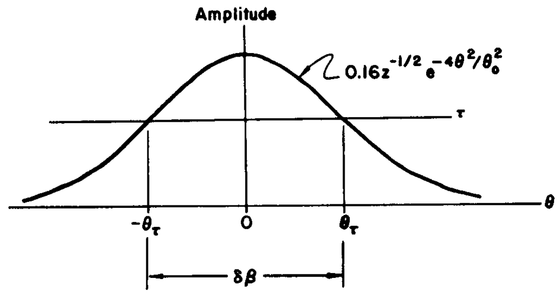

Fig. 4. Echo amplitude as a function of angular deviation from transducer orientation.

detection. For a given value of threshold τ, there exists a range beyond which an edge will not be detected. The condition on the scanning density δβ for edge detection is shown in Fig. 4. The amplitude of the diffracted signal given by (7) is shown as a function of θ to indicate the echo amplitude as the transducer scans across the edge in a continuous angle. In practice, this curve is sampled at a discrete set of angles separated by δβ. To detect the edge, δβ must be small enough so that at least one such echo amplitude exceeds the threshold.

For a desired edge-free range, Z_{SAFE}, we can determine the scanning density δβ. If θ_τ is the angle for which the echo is equal to the threshold, we have

$$A_E(\theta_\tau, Z_{SAFE}) = 0.16\ Z_{SAFE}^{-1/2}\ e^{-4\theta_\tau^2/\theta_o^2} = \tau \quad (8)$$

Solving for θ_τ, we get

$$\theta_\tau = 0.5\ \theta_o\ [\ -\ln(6.25\ \tau\ Z_{SAFE}^{1/2})\ ]^{1/2} \quad (9)$$

To have at least one sample whose echo amplitude exceeds the threshold, we need $\delta\beta < 2\theta_\tau$. Inserting this condition, we have the desired result

$$\delta\beta < \theta_o\ [\ -\ln(6.25\ \tau\ Z_{SAFE}^{1/2})\ ]^{1/2} \quad (10)$$

With this scanning density, we can detect an edge that lies within $z < Z_{SAFE}$ of the transducer system. We now apply this result to determining the maximum safe step size Δ in the next section.

3. Choice of step size Δ.

The value of Δ is limited by the maximum range for which an edge can be detected. If the sensor is located at the center of the vehicular disk of radius R_V, the step size that can be made without collision is given by

$$\Delta \leq Z_{SAFE} - R_V \qquad (11)$$

In many practical systems, $\delta\beta$ is dictated to be some value, i.e., 0.9^o by a 400 step/revolution stepper motor used for the scanning or 15^o by a 24 element Denning ring. For a given value of $\delta\beta$, the value of Z_{SAFE} is determined by inverting (10) to give

$$Z_{SAFE} = \frac{e^{-\delta\beta^2/\theta_o^2}}{39\tau^2} \qquad (12)$$

Thus, we have reached our desired result: When the sonar system has a consistent set of values for parameters $\delta\beta$, β_{MAX} and Δ, the autonomous vehicle can move a distance Δ without experiencing a collision. We now apply this result to develop a strategy to navigate through an unstructured environment in the next section.

4. Navigating through an unstructured environment.

Since we have devised a scheme that allows us to move through an unstructured environment with step size Δ, our approach is to discretize the floor plan into a square grid pattern having a dimension $\Delta/\sqrt{2}$ on a side, thus defining a Cartesian coordinate system. The grid pattern is represented as a 2-D array in computer memory. Let the vehicle be located initially at an arbitrary point on the grid and the location of the desired destination (x_d, y_d) be given. The task is to find a path from the initial location to the destination without a collision. With the size of the grid given above, a translation to any one of the eight adjacent grid points can be made without danger of a collision, since the diagonal translation has size Δ. A path is found by choosing the adjacent grid point that minimizes the distance to the destination.

The environment is assumed to contain at least one path that has a minimum width of dimension D_{MIN}. To guarantee that a trajectory can be found for the vehicle under arbitrary grid placement, the diagonal of the grid (equal to the step size Δ) must be less than the minimum path width minus the vehicle diameter, or

$$0 < \Delta < D_{MIN} - 2R_V \leq Z_{SAFE} - R_V \qquad (13)$$

In the example presented below, R_V=192 mm, D_{MIN}=533 mm, Δ=141 mm and Z_{SAFE}=296 mm. Different values were used for a larger vehicle [8], although the value for Z_{SAFE} is not a function of vehicle size, but only sensor parameters τ and $\delta\beta$.

To keep track of the progress, the points of occupancy are coded in computer memory as 1) current location, 2) destination, 3) previously unvisited, 4) previously visited, and 5) blocked by an obstacle. The algorithm performs a translation to take the vehicle to the previously unvisited grid point that minimizes the distance to the destination.

The motion of the vehicle is an alternating sequence of rotations, for performing the scans, followed by translations. Since the environment is discretized, at each point, there is a choice of one of eight directions. However, directions that lead to previously visited points or to points blocked by obstructions are not considered. The vehicle moves to the previously unvisited point which is closest to the destination. A 180^o scan centered about the direction of translation is performed to detect obstacles. If no obstacle is detected, the vehicle makes a translation. Otherwise, the grid point in that direction is marked as blocked by obstacle and the next available direction is chosen.

Since there are eight possible directions and a 180^o scan is performed about each direction, as many as four complete revolutions may be required before a translation is performed. One method to increase the speed of this algorithm is to exploit the redundancy in the scanning information. If an obstacle is detected in one scan, then it can be 'seen' at most in the three other scans that include the direction of the obstacle within their 180^o scans. Hence, a check is made to see if the range to the obstacle also blocks the translation in the other three directions as well. We observed that this method reduces the time of translation from source to destination in a cluttered environment by as much as 60%.

One interesting type of environmental structure is a blind alley. At the end of a blind alley, the vehicle is surrounded only by obstacles and previously visited points. In this case, a path through the previously visited points is taken to the nearest unvisited point. Afterwards, all grid point within the blind alley are coded as obstacles. This eliminates the futile re-visiting of blind alleys when searching for alternate paths.

The journey terminates if the destination is reached or if the region occupied by the vehicle is surrounded by obstacles and no more unvisited points exist. If the unsuccessful termination occurs, then no path from the initial point to destination exists.

A representative floor plan and the automatically determined path are shown in Fig. 5. A variety of materials were used for the obstacles: the rectangular objects were cardboard cases for computer manuals, the triangle was constructed of typing paper and the cylinders were metal pipes. A blind alley was included to observe the behavior of the algorithm. A 0.53 meter wide path from source to destination was verified by moving a stick of that length through the environment. The scanning operations were

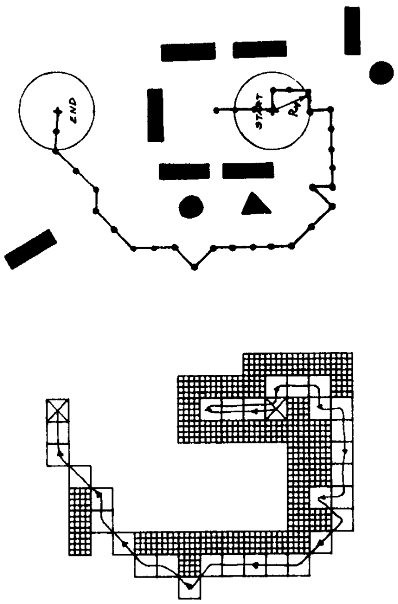

Fig. 5. Example of collision-free path through an unstructured environment. The dimension of the vehicle radius R_V = 192 mm.

performed at the locations represented by dots. The automatically generated path taken by the vehicle that avoided all the obstacles is shown in the figure.

The bottom figure shows the representation of the environment in memory. The source and destination are indicated by X's. Shaded areas indicate grid points that are blocked by obstacles and the open squares show the visited points. Note that the shaded areas could be viewed as a sonar map having a resolution on the order of $\Delta+R_V$, which is much coarser than the resolution capabilities of the sonar system itself.

5. Summary and Discussion.

By considering the physical principles of the transducer pattern and reflection processes from surfaces and edges, we are able to determine the scanning density $\delta\beta$ and scanning width β_{MAX} that allows a vehicle to make a translation of size Δ without experiencing a collision with any obstacle. In practice, the value of Δ is limited to small values that allow the diffracted signal from an edge to be detected. By eqs. (11) and (12), this step size is determined by the scanning density $\delta\beta$ and threshold τ. Even with the highest scanning density possible ($\delta\beta$=0),

$$Z_{SAFE} \leq 1/(39\tau^2). \quad (14)$$

The stop-and-scan motion that we employed with our vehicle could have been made continuous if a transducer array replaced the single rotating transducer. But in all cases, the environment must still be sampled every time a translation of Z_{SAFE} is accomplished.

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REFERENCES

1. Moravec H.P. and Elfes, A. High resolution maps from wide angle sonar. IEEE International Conference Robotics Automation, 116-121, 1985.

2. Crowley, J.L. Dynamic world modeling for an intelligent mobile robot using rotating ultrasonic ranging device. IEEE International Conference Robotics Automation, 128-135, 1985.

3. Polaroid. Ultrasonic Range Finders, Cambridge, MA, 1982.

4. Kuc, R. and Siegel, M.W. Physically-based simulation model for acoustic sensor robot navigation. IEEE Trans. Pattern Analysis and Machine Intelligence, PAMI-9, pp. 766-778, 1987.

5. Borenstein, J. and Koren, Y. Obstacle avoidance with ultrasonic sensors. IEEE J. Robotics Automation, Vol. 4, 213-218, 1988.

6. Elfes, A. Sonar based real-world mapping and navigation. IEEE J. Robotics and Automation, Vol. 3, 249-265.

7. Kuc, R. A spatial sampling criterion for sonar obstacle detection. Submitted to IEEE Trans. Pattern Analysis and Machine Intelligence.

8. Kuc, R. and Viard, B.V. A physically-based navigation strategy for sonar-guided vehicles. Submitted to International J. Robotics Research.

9. Smith, M.S. Introduction to Antennas, New York: Springer-Verlag, 1988.