Using the Amplitude of Ultrasonic Echoes to Classify Detected Objects in a Scene

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Abstract

This paper presents a study about the amplitude of ultrasonic echoes and a simple model is proposed to predict the shape and amplitude of echoes received from different materials in environments composed of walls and corners. Using this model is possible to distinguish between walls and corners, in a single circular scan of a single ultrasonic transducer pair. The parameters of the model have been derived after exhaustive tests performed on different materials and surfaces. Finally, the experimental results of wall-corner classifications obtained in real tests during the walk of a mobile robot are presented. The results suggest that the proposed method can be of great interest for map building in robotics.

1. Introduction

Ultrasonic sensors are widely used in robotics to avoid collisions and for map building purposes. They have some advantages in comparison with laser or camera: they are low-cost and low-power, they are not light-dependent and, moreover, the ultrasonic signal is low-bandwidth and hence its data processing requirements are reduced. On the other hand there are some disadvantages: medium temperature has influence over the wave absorption; wide beam-width (from 30 to 60 degrees) of the ultrasonic transducer lobe yields imprecise angular measurements, low bandwidth means also low distance resolution, making close objects indistinguishable.

Several characteristics of the ultrasonic received echoes have been used to extract environment features. The more common are based on time elapsed between transmission and reception of a pulse (ToF: “Time of Flight”) [14]. The duration of the echo and its energy is exploited in [11], and the phase differences are used in [4] and [6]. A combination of ToF and amplitude information is used in [10] and in [15], and a combination of frequency, amplitude and ToF is used in [8].

Kleeman and Kuc in [9] stated that “two transmitters and two receivers are necessary and sufficient for discriminating planes, corners, and edges in two dimensions”. This is true if only ToF of echoes are used. Also bibliography we can find several transducer configurations that exploit geometric properties of ultrasonic signal reflection to discriminate between planes and corners with a single scan, as described in [5]. But, if only one transmitter/receiver pair is used, two measurements from different locations will be needed to achieve feature extraction [12]. On the other hand, if more information is added, then one sensor reading at the same location is sufficient to feature extraction [8].

The aim of this paper is to present a new study about the ultrasonic echo amplitude, as this information can be added to ToF in order to obtain more accurate information from environment. This amplitude information could be added to ToF, thus enabling geometric feature differentiation.

The sonar system presented in this paper has only an ultrasonic sensor pair (T/R), taking circular scans from the environment [3]. The amplitude of the received echoes from a single scan is used as the main tool to discriminate between walls and corners.

2. Amplitude of ultrasonic echoes.

The amplitude of the ultrasonic echoes received after scanning the environment depends on several factors: distance, surface characteristics of the reflector, viewing angle and shape of the reflector surface. Below, this dependence is discussed for each of the mentioned factors, introducing the equations that will be used in this paper to
model the ultrasonic signal amplitude.

2.1. Distance.

Ultrasonic signal propagates through air and its intensity decreases with distance due to two main reasons: beam spreading and air absorption. Thus, the signal amplitude obtained in a receiver placed at a distance $x$ from the transmitter will decrease as $x$ increases. In the bibliography, this decay in the amplitude of ultrasonic signal has been modeled using different expressions [2],[13],[15]. In [1], Cracknell indicates that the attenuation of ultrasound in air has two factors: one exponential, due to the medium absorption, and the other, hyperbolic, due to the beam spreading. This can be expressed as

$$A(x) = A_0 \cdot e^{-\alpha x}$$

where:
- $A_0$ is a constant.
- $\alpha$ is the attenuation coefficient of the air, (in dB m$^{-1}$).
- $x$ is distance between emitter and receiver (in metres).

2.2. Surface characteristics of the reflector.

When used in robotic applications, objects are detected when the ultrasonic beam produced in a robot’s transmitter reaches a solid surface, and is back scattered to the receiver transducer, located also in the robot. In the case of Polaroid transducers, the same device can be used both as a receiver and a transmitter. In our case, a piezo-ceramic transmitter-receiver transducer pair is used.

This reflected fraction of incident energy will mainly depend on the physical surface properties. Taking into account these considerations, a simple reflection coefficient $C_r$ is proposed in this paper to model the total intensity reduction of the ultrasonic beam reflected on a surface. Thus, a given object with a uniform surface finish will be modeled as a surface with a quasi-constant reflection coefficient $C_r$, as expressed in the following equation:

$$C_r = \frac{A_{\text{reflected}}}{A_{\text{incident}}}$$

where:
- $C_r$ is the surface reflection coefficient, a numerical value ranging between 0 and 1.
- $A_{\text{reflected}}$ and $A_{\text{incident}}$ are the intensity of the reflected and incident ultrasonic beams, respectively.

Thus, using the eq. (1), and eq. (2), the amplitude of an ultrasonic echo received after reflection in a normal plane of a surface with reflection coefficient $C_r$, placed at distance $x$ will be expressed as

$$A(x) = A_0 \cdot C_r \cdot e^{-2\alpha x}$$

(Note that $2x$ is the total path length travelled by the ultrasonic signal in this case).

2.3. Shape of reflecting surfaces.

Some differences between edges, walls and corners scanned shapes were modeled in [14]. However other authors have reported that amplitudes of echoes reflected from walls and the ones reflected from right-corners, for same type of material, distance and incidence angle, have almost the same shape [15]. In fact, the numerous samples taken from real environments have showed us that there are not effective differences between the angular responses of a corner and those coming from a wall. This makes a corner indistinguishable from their angular shape from a wall located at the same distance and normal to the transducers.
be seen in Fig. 1, the echo reflection from a wall and the echo reflection from a right corner are different in a substantial aspect: the echoes reflected from a wall only touch the surface once, whereas echoes from the corner are reflected twice during the flight towards the receiver. Thus, signal absorption will not be the same, and some additional dispersion will be added to the reflected beam. This suggests an interesting conclusion, exploited in this paper: ‘a corner always will produce smaller amplitude echoes than a wall of the same characteristics placed at the same distance’.

3. Description of the model’s parameters.

As indicated in previous section 2, the amplitude of received ultrasonic echoes depends on several parameters. This amplitude behavior can be easily modeled using a simplified equation, as follows:

$$A = A_0 \cdot C_r N \cdot e^{\frac{-2\pi}{2x}} \cdot e^{\left(-\frac{4\pi^2}{\alpha^2 x^2}\right)}$$  \hspace{1cm} (4)

where:

- \(A\) is the peak amplitude of the echo obtained in the ultrasonic receiver, measured in Volts.
- \(A_0\) is a constant for the transducers, independent of the material or shape of reflecting surfaces.
- \(\alpha\) is the attenuation coefficient of the air, (in dB m\(^{-1}\)). (In this article, a value of 0.275 dB m\(^{-1}\) will be used, as later explained).
- \(x\) is the distance between the transducers pair and the target (in metres).
- \(C_r\) is the reflection coefficient of the reflector’s surface. It is a number between 0 and 1, and represents the ratio between the intensity returned back to the transducer and the incident intensity of the acoustic beam. This single parameter includes both the absorption and the additional dispersion effects. This is an evident simplification of the complex phenomena occurred in the reflection of the ultrasonic beam. Nevertheless, this simplification will provide good results and agrees well with the experimental data obtained.
- \(N\) can take two values, depending on the reflector’s shape: a value of 1 in the case of a wall, and a value of 2 in the case of a right corner. This means the number of reflections suffered by the ultrasonic beam on the target’s surface before reaching the receiver. (In acute corners, \(N\) can take values higher than 2, but in this paper, these type of targets are not considered).
- \(\theta\) is the angle of sight under which the target is viewed by the transducer.

The eq. (4) will be used in the following sections to predict the peak amplitude of the echo obtained from an object placed at a distance \(x\) from the transducers, viewed by an angle \(\theta\) and with a known reflection coefficient \(C_r\).

4. Application of the model.

In this paper, only two types of targets are assumed as representatives of the main part of the scene: walls and corners. In fact, the target points detected in scanned scenes are mainly coming from targets with a single reflection (flat surfaces) or targets with two reflections (right corners). The flat surface amount needed to produce an echo is small enough to represent almost any form of room outline as if were formed by small flat pieces. Acute corners produce more than 3 reflections, and thus, the final intensity received is considerably reduced. Also, edges are targets that produce small amplitude echoes. In our approach, only echoes with amplitude enough to be considered as walls or corners are taken into account, disregarding echoes with more reduced amplitude, which are considered as noise for map building purposes.

In the Fig. 2 the peak amplitude values of the received echoes from walls and corners have been plotted. Theoretical amplitude values predicted by the eq. (4) have also been plotted for walls and corners. As it can be observed, the experimental data are grouped around the predicted values. However, due to the noise there is an appreciable spreading of some data points that will difficult their classification for distances above 2 meters.

The eq. (4) models the theoretical behavior of the peak amplitude of the received echoes from the targets. So, it can
be used to predict the readings to be obtained from a given scene or, the more important, to identify the type of the target which produces a given echo. In the first case, it is necessary to know the parameters of each target: its distance $x$, its reflection coefficient $C_r$, the exponent $N$ (1 for walls, 2 for corners), and the angle $\theta$ under which the target point is being observed by the transducer. From these parameters, and using eq. (4), the predicted value of the peak amplitude of an echo from the target can be obtained.

In the second case - the classification problem after a reading $A$ has been taken - only one of the above-mentioned parameters is needed: the reflection coefficient $C_r$. This is true because the distance $x$ is a datum obtained from the ToF of the echo, and the angle $\theta$ is not needed anymore if the reading $A$ corresponds with a sight angle of $\theta = 0$ degrees. (This later is possible when a complete scan has been taken, given that the peaks of the scanned ‘mountains’ will always correspond with a zero sight angle with the target point, as already discussed). Under these conditions, the value of $N$ can be derived from eq. (4), as shows the next equation:

$$
N = \frac{\ln \left( \frac{2 \cdot A \cdot x}{d_0} + 2 \cdot \alpha \cdot x \right)}{\ln C_r} \tag{5}
$$

As already indicated, a result of 1 for $N$ will mean that the target point is a wall (or a flat surface) whereas a value of 2 will indicate a corner, or a surface with two reflections of the ultrasonic beam. Of course, the measured data will have added noise, some due to the measurement process, and the main part due to the non-uniform value of $C_r$ throughout all the surfaces; and in practice, $N$ values obtained from eq. (5) will have some noise added.

By grouping the experimental results obtained from real walls and those obtained from real corners, each target category will have a statistical distribution grouped around the values 1 and 2, respectively. In Fig. 3, the density of probability of the experimental values of $N$ obtained for walls and corners, using the eq. (5) have been plotted. As it can be seen in this figure, the data are grouped around the $N$ value of 1 for walls, and around 2 in the case of corners, being the shape of the distributions similar to Gaussian distribution.

Each distribution -which is supposed in this paper to be Gaussian-, will have its mean and its standard deviation. If the assumptions made about the model are valid, the mean of the values of $N$ obtained from walls must be close to 1, and the one obtained from corners must be in close proximity to 2. The standard deviations obtained in the distributions of the results will be strongly dependent of the uniformity of the walls and the corners in the scene, and this fact must be taken into account for the classification of the targets.

Thus, let us define $m_1$ as the mean of the experimental distributions of the values of $N$ obtained for the walls in a scene, and $m_2$ as the corresponding to the corners (as explained, $m_1$ will be close to 1 and $m_2$ will be close to 2). Also, $\sigma_1$ and $\sigma_2$ will be their corresponding standard deviations.

![Fig. 3. Density of probability of the experimental values of N obtained using eq. (5) for walls and corners. The material of surfaces was concrete ($C_r=0.59$) in this experiment. Solid lines: adjusted Gaussian distribution. Dashed lines: experimental data).](image)

![Fig. 4. Theoretical plot of two normal distributions corresponding to values of N for walls (mean $m_1=1$) and corners (mean $m_2=2$); (arbitrary standard deviations $\sigma_1=0.3$ and $\sigma_2=0.32$ have been chosen). The intersecting point ($N_0=1.49$ in this example) will be the limit value to classify targets between walls and corners.](image)
point of intersection between the two distributions. Let us call $N_0$ to the abscissa of this point. A target with a calculated value of $N=N_0$, will have the same probability of being a wall than a corner. Thus, targets with a value of $N$ above $N_0$ will be a corner more probably than a wall and values of $N$ below this limit will indicate more probably a wall.

5. Experimental Results.

The procedure to obtain an estimate of $C_r$ from a given material is simple, and can be undertaken offline. Previous knowledge of $A_0$ is assumed at sensor's calibration time. In our case, the value obtained has been $A_0 = 3.948$ V m, after exhaustive tests carried out in laboratory. Also, the value of air attenuation $\alpha$ has been measured in the conducted experiments, obtaining $\alpha = 0.275$ dB m$^{-1}$.

In principle, $C_r$ can be obtained from only one ultrasonic reading from a wall oriented normal to the transducer, at a given distance $x$ (calculated from the reading, using the ToF method). Given that $N$ for a wall is 1 and that $\theta=0^\circ$, we can use the eq. 5 to obtain $C_r$ from the value of peak amplitude $A$ obtained from the echo, as follows:

$$C_r = \frac{A}{A_0} \cdot 2x \cdot e^{2\alpha x}$$  \hspace{1cm} (6)

In fact, this method is applicable in all the cases where the found target point is known to be a wall, enabling the on-line estimation of $C_r$. However, as $C_r$ shows significant variability around its mean value, it is highly recommendable to take sufficient number of readings before making an estimate for $C_r$.

Using the above method, several materials encountered in diverse rooms, offices and corridors of our university have been measured and the results obtained for $C_r$(mean) are showed in Table 1, together with their standard deviation

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean $C_r$</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railite®</td>
<td>0.76</td>
<td>0.03</td>
</tr>
<tr>
<td>Glass</td>
<td>0.71</td>
<td>0.10</td>
</tr>
<tr>
<td>Polished Plastic</td>
<td>0.64</td>
<td>0.06</td>
</tr>
<tr>
<td>Pladur® wall</td>
<td>0.62</td>
<td>0.07</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.59</td>
<td>0.09</td>
</tr>
<tr>
<td>Cork</td>
<td>0.57</td>
<td>0.07</td>
</tr>
<tr>
<td>Natural Wood</td>
<td>0.51</td>
<td>0.04</td>
</tr>
<tr>
<td>Matt Plastic</td>
<td>0.47</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The model has been tested in a series of experiments, conducted in several rooms of our department. In these experiments, the robot has been guided in different trajectories, and numerous scans have been taken to recognise walls and corners of these environments, which are mainly of the same material. The obtained results are very satisfactory, as it can be seen in Fig. 5. A set of measurements taken into a room made of concrete has been selected as an example. Amplitude and ToF are collected from 25 different poses of the sensor, (marked as 'o' in Fig. 5). A circular scan has been taken from each location, and the eq. (4) has been applied in order to classify reflectors between walls and corners. The results obtained in the classification of the echoes detected in the 25 poses of the robot during its walk, are represented graphically. As previously indicated, all the echoes located above 2 m are rejected in order to achieve better results.

The percentages of classification results for this room are also given in Table 2. Also, in the Table 3, the results of a global test performed in several different rooms of the same material (concrete) are presented. About 600 echoes from walls and 300 echoes from corners have been processed in this test.

<table>
<thead>
<tr>
<th>Obstacle type</th>
<th>Classified as: Wall</th>
<th>Classified as: Corner</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALL</td>
<td>98%</td>
<td>2%</td>
</tr>
<tr>
<td>CORNER</td>
<td>9%</td>
<td>91%</td>
</tr>
</tbody>
</table>

Table 1. Experimental values of $C_r$ for some materials and their corresponding standard deviation.
Table 3 Global classification results from different rooms made of same material of Table 2.

<table>
<thead>
<tr>
<th>Obstacle type</th>
<th>Classified as: Wall</th>
<th>Classified as: Corner</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALL</td>
<td>97%</td>
<td>3%</td>
</tr>
<tr>
<td>CORNER</td>
<td>7%</td>
<td>93%</td>
</tr>
</tbody>
</table>

6. Summary and Conclusions

In this paper, a study about the amplitude of ultrasonic echoes have been presented, and a simple model to predict the shape and amplitude of echoes received from different materials in environments composed of walls and corners has been proposed. Using this model is possible to distinguish between walls and corners in a single circular scan of a single ultrasonic transducer pair. The parameters of the model have been derived after exhaustive tests performed on different materials and surfaces. Finally, the experimental results of wall-corner classifications obtained in real tests during the walk of a mobile robot have been presented. The results suggest that the proposed method can be of great interest for map building in robotics.

The proposed model application requires previous knowledge of the reflection coefficient $C_r$, and the assumption of that all the walls and corners of the environment are made of the same material. Also, uniformity in all the surfaces is required. If a scene fails to meet these restrictions, the expected results in the classification will be poor. These restrictions are somewhat strong, but applying optimal estimation procedures, the parameter $C_r$ can be dynamically estimated, enhancing the classification results. In the cases where different materials are found in the same scene, a mean value of different materials can be assumed for $C_r$. The experiments conducted show us that the variability of $C_r$ from one material to another is about the same order of the variability of $C_r$ for the same material in most cases (see Table 1). Thus, the use of mean values will produce the lesser errors in the resulting final map.

References