Characteristics of Sonar Sensors for Short Range Measurement

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***Abstract*—Sonar, originally used for underwater navigation is widely used in autonomous robotic application for range measurement, obstacle detection, mapping of the environment and navigation. Sonars are widely being used because of they are accurate, easy to handle and low cost. The paper gives fundamental information of sonar operation, physical characteristics and its shortcomings. Some of sonar mathematical models are discussed. These models incorporate the characteristics and short comings of the sonar. The pros and cons of each mathematical sonar sensor model are discussed in detail.**

***Index Terms* — Sonar, Ultrasonic sensor, Angular uncertainty, Specular reflection, Cross talk, Sonar sensor model**

I. INTRODUCTION

Sonar also called Ultrasonic sensor is an acronym for Sound Navigation and Ranging, originally used in under water navigation and detection of objects. It is based on the principle of propagation of sound wave. Sonars are classified as active and passive sonars. Active sonar emits short pulses of sounds and consists of a transmitter and a receiver. The pulse of sound, also called as "ping", and the reflections are called echo of the pulse. The distance to an object, is measured in terms of the time taken by the sound wave from transmission of a pulse to reception which is converted to range by knowing the speed of sound. Sonar sensors are widely used in military applications – anti-submarine warfare, torpedoes, submarine navigation, aircraft, underwater communication and ocean surveillance. Some of the non-military applications of sonars include vehicle location, liquid level detection, automatic doors and autonomous robots.

II. PHYSICAL CHARACTERISTICS OF SONAR

Sonar is possibly the most common sensor on commercial robots operating indoors, and on research robots. They emit a sound waves and measure the time it takes to bounce back. The time-of-flight, i.e., the time taken for the sound to travel to the target and back to the sensor, say T, along with the speed of sound in the environment (even though air changes density with altitude), say V, is sufficient to compute the range of the object based on the following equation:

$$S = V * T/2$$

S is the range. A sonar sensor commonly used in autonomous robots is shown in Fig.1.It consists of a thin metallic membrane, and is like a coin in size and thickness. A very strong electrical signal causes the membrane to vibrate which produces a sound which travels perpendicular to the membrane and a timer is set. After, a short span the membrane becomes stationary. The reflected sound, or echo, vibrates the membrane, and the acquired signal is amplified. If a low energy signal is received, then sonar ignores it, assuming it to be noise. On the contrary, if the energy of the received signal is greater than some apriori determined threshold, the timer is reset, and the time-of-flight obtained. From the above equation, V and T are known. So S, the range between sensor and object in the environment can be calculated [1].

Fig.1 Ultra Sound Sensor (Sonar)

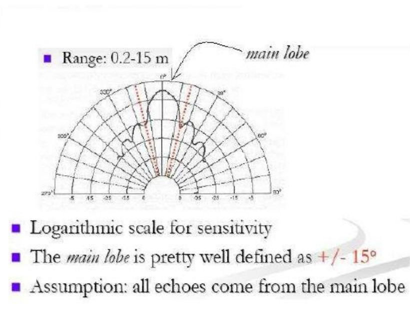


Fig.2 Typical beam pattern of Polaroid Ultrasonic Sensor

In reality, the sonar is not omni-directional. Thus, the radiation energy pattern, on a logarithmic scale, is as shown in Fig.2. The large part of the energy is concentrated in the main lobe, with part of the energy dissipated along the side lobes. Thus, depending on the environment in which the robot is placed, multiple echoes may arise both in the direction of the main lobe as well as side lobes. The output of the sonar is such that only those echoes received along the main lobe are considered. Typical sonar has a main lobe of around 30 degrees. Fig. 3 shows a sonar beam of 30 degrees. The range R is measured at the center of the beam. Typical sonar can measure from 0.2 to 15m [1]. Besides providing direct range measurements, ultrasonic sensors are cheap, fast and have a very good coverage. High range detection accuracy of sonar is another reason for it to be popular. For Polaroid sensor, a typical accuracy is 1% of the reading over the entire range. Ultrasonic sensor is able to provide range information from 0.1524m (6 inches) to 10.668m (35 feet). Though they have numerous advantages, ultrasonic sensors have some shortcomings which are discussed in the next section.

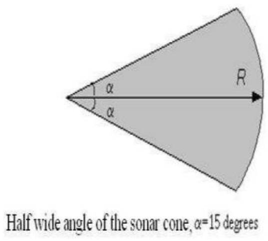


Fig.3 Sonar Beam

II. SHORTCOMINGS OF SONAR

Sonar has heralded as a cheap solution to the mobile robot sensing, because it provides direct range information at low cost. Ultrasonic sensors have several shortcomings. These include poor directionality that limits the accuracy of the measured spatial position of an edge to within 10-50 cm, depending on the distance to the obstacle and the angle between the obstacle surface and the acoustic beam. Frequent misreadings and specular reflections that occur when the angle between the wave front and the normal to a smooth surface is too large and range data are seriously corrupted by reflections and specularities. Some shortcomings discussed here are Angular Uncertainty, Specular Reflection and Cross Talking.

A. Angular Uncertainty

The angular uncertainty is associated with the angular information obtained from the sonar response while detecting any object within a certain range. When an ultrasonic sensor measures a range R meters, it is a representation of a cone with angle 2α within which the object may be present, illustrated in Fig. 4. This cone angle is referred to as the View of Focus (VOF). Evidently, the object can be anywhere in the shaded region, and there is no way to determine the precise position of the object. More specifically, an object that is not perpendicular to the acoustic axis remains undetected. This angular uncertainty is also known as foreshortening. To overcome this problem, probabilities are associated with the highest probability assigned to those echoes occurring along the acoustic axis.

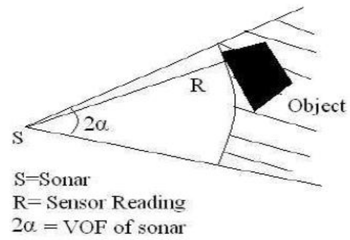


Fig.4 Angular uncertainty of a sonar reading

B. Specular Reflection

Specular reflection is due to different relative positions of the ultrasonic transducer and the reflecting surfaces of the obstacles. When the ultrasound wave emitted from the sonar hits a surface that is sufficiently further away from the acoustic axis of the sonar, and if the object is not perpendicular to the acoustic axis, the echo tends not to be reflected back entirely. This is illustrated in Fig.5. In the two cases depicted here, the obstacle is assumed to lie entirely within the VOF. However, the acoustic axis in Fig.5 is perpendicular to the reflection surface, i.e., incidence angle θ is zero, so that most of the sound energy is reflected directly back to the ultrasonic sensor and only a very small percentage of the energy is scattered in other directions. The shortest range (OB in Fig. 5) is considered as the distance of the obstacle from the sensor. The situation depicted in Fig.6 is quite different in that the reflecting surface is not normal to the acoustic axis of the sonar; i.e., incidence angle θ is no longer zero. Therefore, a good percentage of the energy is not reflected back to the sonar.

For the problem of obstacle avoidance, the shortest range must be considered to be the distance of the obstacle from the sensor. Thus, in this situation OC as shown in Fig.6 must be the range returned in contrast to OB in Fig.5. However, if one maintains the same benchmark as in Fig.6, then the range returned is OB even if the obstacle is in reality closer. Therefore, corrections are to be incorporated to account for this problem. Thus, a factor to be considered is the beam dispersion angle of the selected sonar. Best results for ranging are obtained when the beam centerline is maintained normal to the target surface.

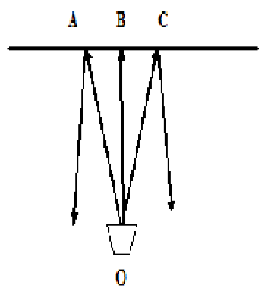


Fig.5 Reflecting surface perpendicular to sonar

However, as Fig.6 shows, if the angle of incidence varies from the perpendicular, the range actually being measured does not always correspond to that associated with the beam centerline. The first beam reflection is from the portion of the target that is closest to the sensor [2].

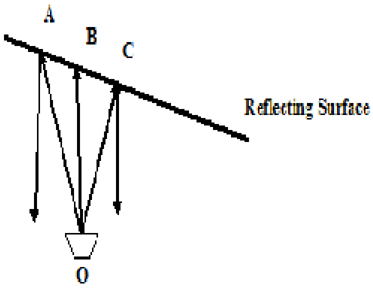


Fig.6 Reflecting surface not perpendicular to sonar

In Fig. 7, the actual line of measurement intersects the target surface at point B as opposed to point A. The width of the beam introduces an uncertainty in the perceived distance to an object from the sensor, but an even greater uncertainty in the angular resolution of the object's position. A very narrow vertical target, such as a long wooden dowel, maintained perpendicular to the floor corresponds to a relatively large region of floor space, which would essentially appear to the sensor to be obstructed. An opening such as a doorway may not be perceptible at all to the robot when only 6 feet away, simply because at that distance, the beam is wider than the door opening. Finally, errors due to the topographical characteristics of the target surface must be taken into account [2].

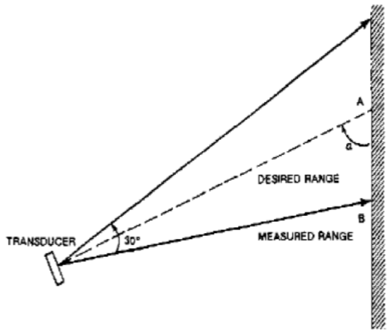
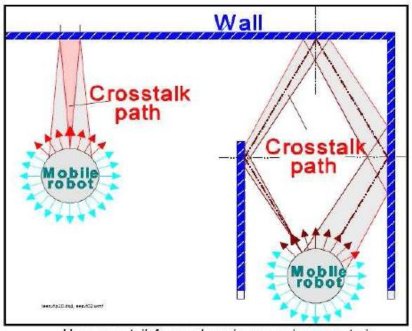


Fig.7

C. Cross Talking

Cross Talking is shortcoming seen when more than one sensor or sonar ring is used. If one sensor receives the sound emitted by another sensor leads to cross-talking. This is an undesirable phenomenon. This can be overcome by proper spacing and firing of sensors. Therefore, the group of sensors is selected in such way that spacing between the individual sensors is optimal and the refresh rate is improved in comparison to firing the sonar systems one-by-one [1].



How *crosstalk* from onboard sensors is generated:
a. *Direct* critical path.; b. *Indirect* critical path.

Fig.8 Cross Talking

III. Response of Sonar to Wall and Corner Feature of an Obstacle

To have a better understanding of ultrasonic sensors, the sonar responses from two typical geometrical shapes, a wall and a corner are shown in Fig.9. Here, the central feature of the response is an arc of circle, centered with respect to the normal of the wall surface. This pattern is caused by the main lobe where the energy is the highest. When the normal to the surface leaves the main lobe, the energy is reflected away from the source. Similar case happens to the secondary lobe: if the normal to the surface is within the secondary lobe, the sound gets reflected. As the secondary lobe has lower energy than the main one, there is a range error. For the case shown in Fig.8, the central pattern is an arc of circle centered about the corner. It comes from a double specular reflection at the corner. The neighboring arcs can be attributed to the secondary lobes. The left-most and right-most arcs come from specular reflections on the sides of the corners.

When the sonar is close to the corner, it is difficult to predict where the returned echo is actually coming from. The multi-sonar responses in Fig.9 appear rather noisy. There are some responses that show range values far beyond the physical boundaries of the wall and the corner.

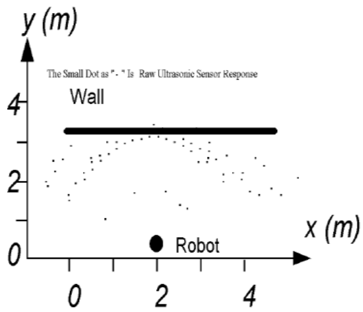


Fig.8 Typical sonar responses from a wall.

The data is collected for wall and corner responses by firing the sonar ring of 16 ultrasonic sensors. The noisy patterns of sonar responses are due to physical characteristics of Polaroid ultrasonic sensor, and also due to the interaction between sensors and the operating environment.

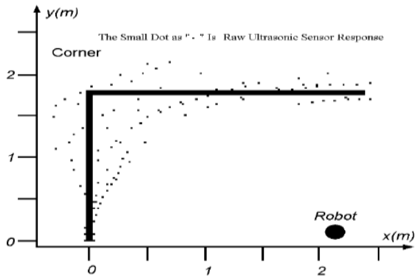


Fig.9 Typical sonar responses to a corner.

IV. Types of Ultrasonic Sensor Model

Different approaches are possible in obtaining a mathematical model of sonar. Sonar models may vary greatly in their complexity, their ability to take into account various experimentally observed effects, and the amount of information about the environment that they require. In the simplest model for sonar sensors proposed by Moravae and Elfes, the range measurement is interpreted as the distance to the nearest obstacle in the direction of the beam centerline. This model presents several problems. Firstly it fails for specular surfaces, which reflect sonar beam like a mirror. Furthermore a direct return is only produced from specular surfaces if the sonar beam is incident close to 90°. Secondly, for oblique incidence angles, return is produced, or a multiple specular reflection occurs, giving rise to wrong measurements. Finally another problem with this model is that it ignores the width of the sonar beam not taking into consideration that the objects in the beam periphery may cause the reflections that come back to the sensor [3].

Elfes build a navigation map based on occupancy grid where each region was classified as empty, occupied and unknown. Each range measurement is interpreted as providing information about empty and occupied volumes in the space, subtended by the beam sonar (a 30° opening angle in this case). The occupancy information is modeled as probability profiles. It produces good sonar maps in non-specular environments, but it can fail completely when the environment is specular [4-7].

Kuo and Siegel made a model for the ultrasonic sensors based on the principles of acoustics and the knowledge of the detection circuitry of the Polaroid Range Finder. They focused on reflections from corners, edges and walls. The main conclusion obtained from this model is that, for small incidence angles (<6°), the wave reflected from a specular wall will always measure normal distance to the wall, independent of incidence angle. The model does not deal with the effects caused by the irregular angular radiation pattern of the sonar transducer, and does not attempt to model non-specular surfaces [8].

Leonard and Durrant-Whyte made a good description of the effects caused by the angular irregularity. Several sets of range readings from specular surfaces are collected and plotted, starting with a small increment in the incidence angle (0.588°) until a maximum angle of 30°. For small incidence angles, where the beam intensity is strong, sequences of adjacent readings define a horizontal segment line. These sequences are called "regions of constant depth – RCD", which correspond to arcs in Cartesian coordinates. The extraction of these regions is based on the difference between the minimum and maximum values of a sequence of readings; inferior to a present limit $(|V_{max} - V_{min}| < \partial_r)$. The width β of a RCD is the difference between the minimum and maximum values of a sequence of readings. It is set a minimum value for β, usually between 5°-10°. This value allows the distinction between strong echo and weak echo. If $\beta < \beta_{min}$ it is considered a weak return. Leonard and Durrant-Whyte stated that weak returns are caused by low intensity radiation in the beam's side-lobes, and give a theoretical explanation for the overestimates, based on the properties of the Polaroid detection system. They proposed that the best way to deal with weak signals is to ignore them. A method was proposed, based on the searching for regions of constant depth, to distinguish weak from strong returns, and only to process the strong returns in mapping system [9].

Harris and Recce describe a model for ultrasonic sensors based on analysis of data obtained with Polaroid sonar. The collection of data is acquired starting from a fixed position with an angular spacing of 1.8°. Two models were defined: one for rough surfaces and one for smooth surfaces. In the first case, the model allows to obtain the average μ and deviation σ of the readings acquired, as a function of the normal distance δ and the incidence angle θ. In the second case the model is based on a group of controlled values, with one input – the incidence angle – and three outputs: the direction probability of the return wave, the estimate of the average of the direct returns (average of the direct returns less the distance in the direction of the normal) and the deviation of the direct returns. Among the sonar models discussed above, the model considered in this dissertation is the model proposed by Moravae & Elfes. As it helps define the physical characteristics of sonar precisely [10].

Edouard Ivanjko et al have modeled the sonar assumes the axial and radial component of a sonar reading to be independent of each other. They then modeled the axial component with a Gaussian distribution around the returned range reading $\bar{r} \sim N(\bar{r},\ 0.01\bar{r}$ + 0.01m) and the radial component with a uniform distribution within the main lobe angle: $\theta \sim U(-12.5°, 12.5°)$. This model gives a fairly accurate qualitative description of sonar range readings and an advantage is it requires no modeling of the environment. It can successfully be used for modeling uncertainty when building occupancy grid maps [11].

V. Conclusion

The paper discusses the working and physical characteristics of sonar sensor are discussed in detail. The brief discussion on the shortcomings of sonar – angular uncertainty, specular reflection and crosstalk is included. In particular, the response of sonar for walls and corners were shown. The various mathematical models are for sonar sensors are brought out. It should be noted the each of these models incorporate the physical characteristics and short comings effectively to improve the accuracy of range measurement.

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