IDENTIFICATION OF THE EXPERIMENTAL ULTRASONIC SYSTEM PARAMETERS

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The work has been supported by VEGA grant 1/0690/09. This support is very gratefully acknowledged.

Abstract: Successful navigation of the mobile robot in the environment is impossible without appropriate sensory system. Various mobile robotic systems often use the ultrasonic range finders to sense a working space. The contribution deals with the ultrasonic sensors identification procedure. Novel methodology for determination of the sonar radiation cone width is presented. This procedure allows to specify the parameters of the sonar radiation cone. The identification of the experimental ultrasonic system reveals some new properties of the sonar radiation cone. The ascertained facts allows the mobile robot to move in the environment more safely.

Keywords: ultrasonic range finder, identification of the sonar radiation cone.

1 Introduction

The main goal of recent research in the field of mobile robotics is autonomous performance of mobile robots. Autonomous operation of mobile robots is strongly dependent on the sensor system which often comprises of ultrasonic range finders. Ultrasonic range finders (sonars) are characterized by a number of advantageous features such as ease of use, relatively low cost, safe operation, and thus they are employed in various fields of science and industry for non-contact distance measuring. In mobile robotics, they are used to measure relative distances to the obstacles in the robot neighbourhood to ensure collision-free motion and navigation in the environment. Despite all the advances, the application of ultrasonic sensors is accompanied by a variety of problems such as multiple reflections or extensive wide angle of the ultrasonic beam.

The acquired range readings can be utilised by many ways. One of them is the creation of the environment representation, which is in principle a map of the environment. The occupancy grid is a popular form of the representation of the robot's workspace [3], [5], [7]. Occupancy grids are usually used to express the spatial arrangement of the environment as its two-dimensional projection to the plane of the robot motion. Each cell of the grid represents definite area of space and known information about it. An example of the robotic navigational map in the form of occupancy grid is depicted in Fig. 1.

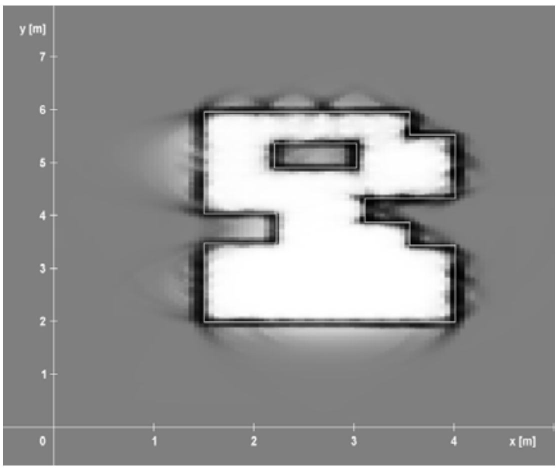

Fig. 1. An example of robot map constructed from ultrasonic measurements.

Main problem in map building algorithms is varied uncertainty of measured sonar data. There are several methods of handling data uncertainty and occupancy grid calculation known [4], [8]. The use of an appropriate and adjusted sensory model is a successful approach to minimize the amount of uncertainty in processing of measured data to a robot navigational map. Such sensory model can be constructed on the basis of the data obtained by identification of essential sonar parameters.

2 Ultrasonic sensor

The problems of sonar usage rise from the physical nature of the operating principle of these systems and resulting data from the sensing process is loaded with a variety of uncertainties. The ultrasonic range finders work according to a simple principle: a packet of ultrasonic waves is generated and the resulting echo is detected. The time elapsed between transmission and reception is assumed to be proportional to the distance of the sensed obstacle. In the air the ultrasonic signal propagates to the space in a beam of the conical form [2].

There are basically three main sources of measurement uncertainty in the process of determination of presence of an object and its relative distance with the ultrasonic sensors. First, the measured distance *r* is affected by an error. The error of measurement is at level of few percent of the measured distance over the entire range. This uncertainty is caused by the characteristics of air such as its temperature, humidity, turbulence and pressure.

The second uncertainty is a phenomenon of multiple reflections, which may occur in the case that the incidence angle of signal to the obstacle is larger than a so-called *critical angle* which is strongly dependent on the surface characteristics. In this case the reflection of the signal is mainly specular and the sensor may receive the ultrasonic beam after multiple reflections, which is called a *long reading*, or it may even disappear. Therefore, in order to return a significant range reading, the angle of incidence on the object surface has to be smaller than the critical angle.

The third source of uncertainty results from the propagation of the ultrasonic signal to the space in the form of a cone with an apex in the centre of the sensor active element and an axis in the scanning direction. The angle of radiation cone can be in fact fairly wide. So the exact angular position of the object reflecting the echo might not be determined. An example of such situation is depicted in the Fig. 2.

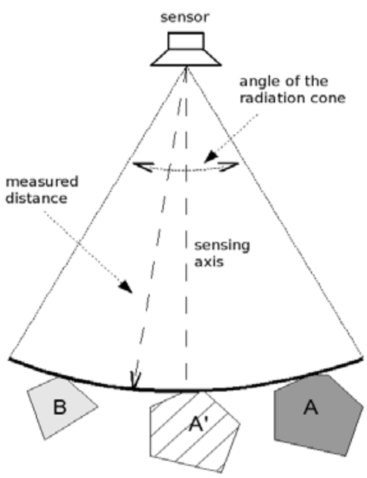

Fig. 2. Position uncertainty of the object echoing the ultrasonic signal.

When the relevant distance measurement in the given direction is performed it is not possible to determine the exact position of the object. The signal reflecting object **A** can be situated somewhere along the arc with the radius of the measured distance and arc angle equal to the radiation cone angle, for example in the position **A'**. Also it is not possible to detect, if the ultrasound signal was reflected by another object **B**. When the distance measurement is obtained, the object position uncertainty is consequently solved by considering the placement of obstacles along the whole length of the circular arc. Therefore, in robot environment representation, there are updated all grid cells corresponding to radiation cone arc in the measured distance.

For modelling of the uncertainty given by the wide radiation cone of the sonar sensor in angular resolution, an angular radiation function fa is introduced [4], [7]. Since the intensity of the ultrasonic waves decreases to zero at the borders of the radiation cone, the degree of certainty of some area to be occupied by obstacle or to be empty, is assumed to be higher for points close to the radiation cone axis. This is realised by the angular modulation function

$$f_a(\theta) = \begin{cases} P(\theta) & ,0 \le |\theta| \le \theta_k \\ 0, & |\theta| > \theta_k \end{cases}, \qquad (1)$$

where $P(\theta)$ is the radiation directivity function [2], [4], θ is angular distance measured with respect to the radiation cone axis and θ_k is limiting angle of the radiation cone of given sensor. The important value of the sonar so-called *limiting angle* can be computed from certain intrinsic parameters of the sonar. In general the limiting angles of the radiation cone are dependent on the ultrasound wavelength and the radius of active element of the sensor [2].

Mathematical model of angular uncertainty of measurement requires a knowledge of the angular range in which the sensor is able to detect an obstacle. Although the theoretical value of limiting angle for the sensor can be calculated, if the sensor parameters are unknown or a more precise value is needed for sensory model, the identification of the limiting angle is the only way of determining its real value.

2.1 Experimental ultrasonic measuring system

The ultrasonic measuring system is designed as a part of the sensor system of the mobile robot. The system was proposed to satisfy several requirements such as low demand on power supply and overall low weight. Moreover the technical design of the system emphasizes, simplicity, reliability and accuracy. The system achieved satisfactory experimental results with acceptable price level. It consists of the sonar and rotary platform which enables the sonar to set at an angle of desired direction during measurement. The rotary platform is driven by a stepper motor in the range of 360° with the step size of 0.9°. The technical solution of the ultrasonic system is based on the transmitter T40-16 and the receiver R40-16 by Nippon Ceramic Company [6]. The measuring range varies from about 10-15 cm to 3-4 meters and it is sufficient for navigation of the robot in a working environment. The ultrasonic measuring system is hierarchically divided into two parts. The sensing unit contains sensor and circuits of the transmitter and the receiver. The ultrasonic sensor consists of the separate transmitter (T40-16) and receiver (R40-16). The sensors have cylindrical shape with diameter of 16 mm and height of 12 mm. The resonance frequency of the sensor is 40 kHz. The sensing unit is linked to control unit based on the flexibly controllable RISC processor PIC16F873 clocked at 4 MHz. The control unit manages emission of ultrasound pulses and it also digitally processes the received signal. The essential parts of the experimental ultrasonic system are depicted in the Fig. 3.

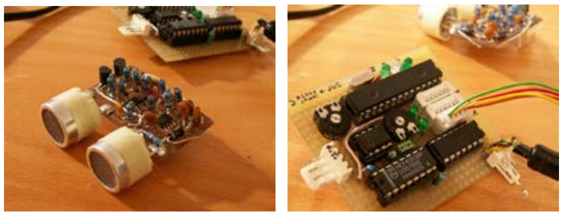

Fig. 3. Sensing and control unit of the experimental ultrasonic range finder.

3 Sonar identification method

Mathematical modelling of ultrasound sensor uncertainties requires accurate values of certain parameters of the used sensor. It is required to know the angular range in which the sensor can detect the obstacle. This value can be roughly determined from the sensor parameters given by the manufacturer or by its identification which is obviously more accurate. Any other methods for determination of the exact radiation cone angle of ultrasonic sensors were not found in available sources. Perhaps the only attempt to obtain this value by the measurements is published in [1]. Above facts lead to development of a method for determination of the size of the radiation cone angle. Identified value can be consequently used to create a precise mathematical model of the used sensor.

The aim was to determine the sensor parameter which is called the *effective angle of the radiation cone* (EARC). This parameter means the width of the radiation cone, which actually applies at the measuring distance to obstacles. After this manner the defined sensor parameter reflects practically usable ultrasonic signal cone angle. Identification of the EARC size is based on the conditions close to real situations of the ultrasonic sensor utilization. Thus measured beam angle is essentially identical to angle which applies in the mapping of an unknown area occupied with a number of obstacles of various quality and character. The determined value of radiation cone angle is the one maximally possible, which in view of scanning obstacles is the worst case of the horizontal angle uncertainty. In real environments, the reflecting conditions are worse in the vast majority of cases, as compared with those in identification measurement and smaller width of the radiation cone is applied in the reflection. Yet such cases can occur, hence the determined cone width is the searched sensor parameter. EARC identification principle is as follows and is shown in Fig. 4.

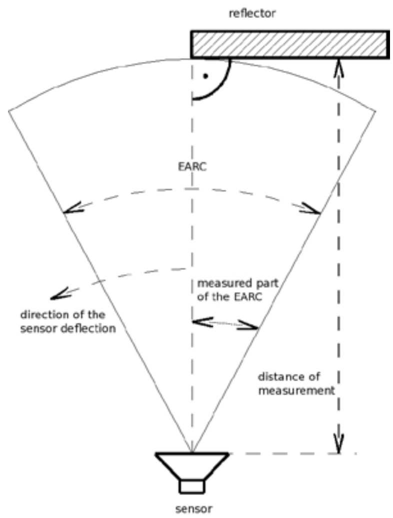

Fig. 4. Scheme for identification of effective radiation cone angle.

The ultrasonic sensor is placed pointing to the free space. Essential aim of the identification procedure is to measure the size EARC at different distances. Obtained values enable to determine whether the size of the radiation cone angle varies with distance. Therefore the reflector echoing sent ultrasonic signal is placed at chosen distances. Real obstacles in robot's working environment have different sizes and shapes. Moreover, the obstacles are formed from miscellaneous materials. The reflection of the signal by obstacle is strongly associated with the properties of its surface and it also depends on the angle at which signal hit the reflecting surface of the obstacle. The signal is reflected towards the transmitter if it hits the surface at an angle which is smaller than critical angle. Otherwise the signal is bounced away from the transmitter. It is important to consider these facts. The relative position of the sensor and the reflecting surface is chosen with the signal vertically impinging on the surface throughout the whole measurement. This selection effectively eliminates the surface properties of the reflecting object related to the critical angle. Such configuration is also ideal for a signal reflection and the maximum possible amount of energy transmitted into that direction returns back to the sensor. However, the surface properties play role even in such measuring configuration. If the surface has some absorption properties in relation to the ultrasonic signal, or if the surface has ability to distract the signal, only portion of the impinged signal returns back to the sensor. Therefore, in order to bounce maximum energy, a hard and smooth material is chosen as the reflective surface. The size of the reflector has also influence on signal reflection and it must be sufficiently large to simulate the ideal case of reflection, in which the maximum amount of acoustic energy is reflected to the receiver. The key element of the identification method is a mutual position of the sensor and reflector. The reflector is placed with its reflection surface plane being perpendicular to the axis connecting the sensor and the side edge of the reflector as shown in Fig. 4.

The ultrasonic signal beam spreads into the space in the form of radiation cone with spherical front part. The amount of acoustic energy gradually decreases from the cone axis to its boundaries. Determination of the radiation cone borders consists of gradually reducing amount of energy emitted towards the reflector. The requirement of vertical impingement on the reflector of gradually reduced ultrasonic signal is achieved by gradual deflection of the sensor. It is conveniently accomplished by horizontal rotation of the sensor with sufficiently small steps. The rotation begins from the base position with radiation cone axis directed perpendicularly to the reflecting plane and proceeds to one side as shown in the Fig. 4. At every step of the measurement the reflecting surface is vertically hit by diminished part of the signal and rest of the signal spread further into free space. Such gradual decrease in strength of the acoustic signal reaches the point, where the reflected signal is incapable to activate the receiver and the signal loss occurs. Thus the receiver is able to capture the echo to the particular measurement step. This sensor deflection threshold step determines a boundary of the radiation cone. This deflection step also defines limiting angle of the radiation cone at a given distance and within that angle the sensor is able to detect the presence of obstacles. Achieving the limiting angle is indicated by the absence of echoes in successive deflection steps or by measuring distances considerably greater than the distance to the reflecting surface. This case occurs if the signal is reflected from an object situated behind the reflecting surface. Therefore the measurement should be performed in an environment large enough to safely identify the source of reflection. After this manner only the limiting angle of the radiation cone at one side of the cone axis is obtained. The second limiting angle is analogously determined with placement of the reflector on the opposite side of the axis connecting the sensor with the edge of the reflector and by deflection of the sensor to the opposite side. In this way it is possible to determine the effective angle of the radiation cone for any ultrasonic sensor with sufficient accuracy.

4 Experimental results

The experiment was performed in a relatively large open room. The necessary tools were arranged as it is shown in the Fig. 4. As the reflecting surface was chosen a smooth board with dimensions 1.5 × 0.6 m. The experimental ultrasonic measuring system was placed at height of 1 m to exclude theoretical possibility to capture the reflection from uneven floor. Reflecting surface was placed at regular distance intervals with a step 0.25 m in the range from 0.5 to 3 m. The sensor was deflected from the zero position when the cone axis is perpendicular to the reflecting surface plane (Fig. 4), to maximal deflection of 90° with increments by 0.9°. Distances obtained by turning the sensor from the zero position to a maximum deflection of 90°, and accordingly backward to the zero position, were recorded in one measurement. This procedure was repeated 10 times for each measuring. By this manner 20 distance values for each sensor deflection step were obtained. In the evaluation process of measurements, the angle of the sensor deflection presenting a loss of reflected signal was considered as the angular limit of the EARC. Irregular receipt of the reflected signal was observed for deflections in the vicinity of EARC edge. It was manifested as various number of distance values corresponding to reflection as well as loss of signal. The value which appropriately represents the collected measurements for each sensor deflection angle allow to identify the boundaries of EARC. The median of the data set is such suitable representational value, because it determines the predominant number of measured distances. To verify the symmetry of EARC, the experiment was carried out also for the second side of the radiation cone. Subsequently two EARC limit values for given distance from the sensor were obtained, corresponding to the left and to the right side of the cone. The sensor limiting angles are listed in Table 1 and the medians of the measured data sets are shown in Fig. 5.

Table 1. Measured values of the left and right limiting angle of the Nippon sensor.

Measuring distance [m]	Left limiting angle [°]	Right limiting angle [°]
0.50	46.8	39.6
0.75	42.3	38.7
1.00	39.6	34.2
1.25	36.9	31.5
1.50	33.3	35.1
1.75	34.2	31.5
2.00	32.4	27.9
2.25	31.5	24.3
2.50	28.8	26.1
2.75	27.0	22.5
3.00	27.0	25.2

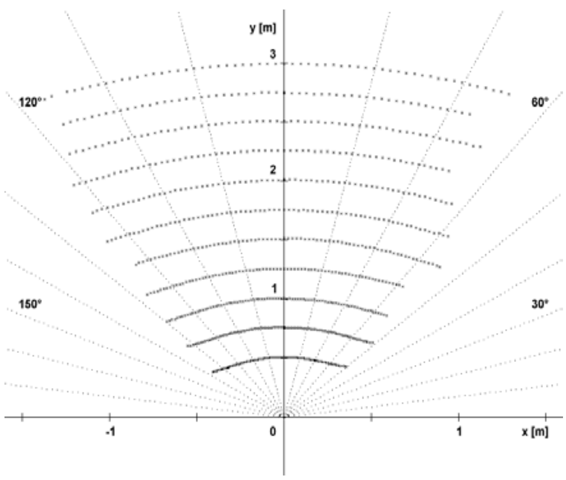

Fig. 5. Results of the EARC identification of the Nippon sensor.

The measurement results show the properties of the used sonar. The Nippon sensor has significantly wide cone angle. Founded values of its width gradually decrease with increasing distance and they move in the range of about 40° to 25°, which is well documented in the Table 1 and Fig. 5. It can be concluded that a significant portion of the transmitted acoustic signal is absorbed in the environment along the edges of the cone with increasing distance to the obstacle. Thus the sensor shows a considerable decrease of the EARC parameter with the change of the measured distance and therefore it is suitable for measuring shorter distances. However a maximal distance of 3 m is sufficient for practical navigation of smaller mobile robot. The observed data suggest that the cone beam is only slightly asymmetric in respect to the radiation cone axis.

5. Conclusion

Motion of the mobile robot in the environment is dependent on information acquired by its sensory system. The sensory system of common mobile robot is usually equipped with ultrasonic range finders. These are used to measure a distance from the robot to a nearby obstacle in a given direction. The main disadvantage of the ultrasonic sensor is considerable amount of uncertainties of various type embedded in the sensed data. Processing of the uncertain data results in inaccurate information about the environment. Therefore minimisation of this uncertainty leads to the more accurate environment models and to improved robot motion in the working environment. The sensor model is a key element in the processing of gathered distance data into the environment representation. The mathematical models of the ultrasonic sensors used in mobile robotics are based on the angular width of the sensor radiation cone. The most accurate value of this parameter is obtained by identification of the sensor really used. Therefore development of reliable sonar identification procedure was necessary. The identified parameter is the sonar effective angle of the radiation cone as the function of the measuring distance. Determination of this functional relation is accomplished by a proposed identification method. The procedure was successfully applied to identify the cone width of the experimental ultrasonic sensor. Acquired data revealed constriction of the radiation cone with increased measuring distance and its asymmetric shape. The knowledge of these facts consequently simplifies the robot navigation tasks and makes them safer.

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