Probabilistic Environmental Model Based on Ultrasonic Sensor Networks

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Abstract

A probabilistic grid method algorithm based on wireless sensor network is proposed in order to solve indoor global environmental modeling problem. At first, deploying WSN nodes on the ceiling evenly and processing the discrete data returned by WSN to form a probabilistic grid model within the detection range. In this way, we describe the probability existing obstacles of each grid. When the grids are in overlap detection region, the method of joint probability is used to calculate the probability of obstacles. Finally, a four-dimensional map is built up, that is, three dimensions determine the grid location and the fourth dimension describes the probability of existing obstacles. Simulation result shows that the proposed method can clearly express the obstacles’ existing probability for each grid in indoor environment.

Keywords: Wireless Sensor Network; Ultrasonic Sensor; Probabilistic Grid Method; Environment Modeling; Four-dimensional Probabilistic Figure

1 Introduction

Wireless Sensor Network (WSN) can monitor the global environment with a large number of intelligent nodes. Nowadays, WSN-based indoor environment modeling gains scholars’ high attention [1, 2]. In terms of physical device, the ultrasonic sensors have distant detection range and are harmless to human body [3]. Furthermore, the ultrasonic sensors are less susceptible to adverse environmental impact, such as shadows, light changes, smoke and many other constraints. Therefore ultrasonic sensors are widely equipped on the WSN nodes and become effective means to gain distance, barriers and environmental information.

Based on measurement data of ultrasonic sensor, researchers proposed three environmental models including the center-line model, normal distribution model and uniform distribution model

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Their common weaknesses mainly consist of (1) model is too simple and not accurate, in some cases, there is a huge gap between the model and the real environment; (2) most of the environment models are built based on a single ultrasonic sensor, because ultrasonic distance sensor can only get the distance to obstacles. Thus, they cannot collect adequate information on the environment. Researchers have carried out further explorations to compensate the drawbacks. The method proposed in [5] used line-segment matching to achieve the environmental modeling. In [6], line characterization is used to describe the environment. Then, the extended Kalman filter algorithm is used to estimate the system state in order to establish a more precise map of the environment.

The grid map has the advantage of high accuracy and fast establishment [7]. It is intuitive and easy to fuse information and to integrate statistical data. It is a relatively good choice for the indoor environment [8]. In this article, we will combine probability and spatial grid map to build a new method for indoor environment. Our aim is to establish the global grid map, with four-dimensional probability, of the environment.

2 Characteristics and Model of Ultrasonic Sensors

2.1 Energy distribution of ultrasonic sensors

Ultrasound sensor can obtain the distance between obstacle and itself through signal reflection. Due to the large divergent angle and low resolution, there always exists certain orientation error. Fig. 1 shows the energy distribution of ultrasonic sensor. Here, $\theta$ is the ultrasonic beam angle.

![Energy distribution of ultrasonic sensors](image)

Because of its intrinsic features, ultrasonic sensor requires special model to describe the position between sensors and obstacles. In this paper, cricket nodes are used as ultrasonic sensors, whose beam angle is $60^\circ$ and straight effective detection range is about 3m.

2.2 Ultrasonic sensor model

For ultrasonic sensor, the effective beam angle is an important parameter, which is shown as in this article. $S$ represents the measured distance.
2.2.1 Midline model

Each data returned by ultrasonic sensor is a real number. The midline model provides a visual interpretation of the real numbers, where the obstacles are at the distance $S$ and in the $0^\circ$ launch angle of sensor orientation. When the barrier is closer or ultrasonic beam angle is small, midline model is very simple and effective. However, it can only meet low accuracy requirement because of the ultrasound’s characteristics of wide scattering angle [9].

2.2.2 Normal distribution model

This model considers that obstacles may exist at any point of the arc of divergence angle. The center point is supposed to be at the $0^\circ$ launch angle and $S$ meters away from launch point, while the probability of obstacles existence complies with the normal distribution. Apparently, no obstacles exist within the arc space. Normal distribution model, evolved from the midline model, is more accurate because it takes into account the divergent factor of ultrasound. According to the normal distribution model, it is assumed that the maximal probability of obstacles exists in the middle line [10].

2.2.3 Average distribution model

Average distribution model is somewhat similar with the normal distribution model. It also regards that obstacles may exist at any point of the arc whose radius is $S$ and central angle is $\alpha$ [11]. However, the average distribution model considers that existence probability of obstacles is same for any point of arc. This is different from the normal distribution model.

2.2.4 Probabilistic space grid model

Uniform distribution of ultrasonic models in that the barrier distribution center is the center line of the arc in the ultrasonic probe within the arc and the sonar posed that the three-dimensional region is conical. As shown in Fig.2:

![Fig. 2: Single ultrasonic sensor detection range(left)](image)

However, within the scope of the ultrasonic probe cone area, the probability of the existence of obstacles is different. In this paper, the probabilistic space grid model is used for obstacles modeling which in the cone area of the ultrasonic detection.

As shown in Fig.3, cone can also be seen as an isosceles triangle spins half turn around its bottom edge of the high. To extract this isosceles triangle, the basic vision is determined by the $\beta$ and $R$,
\( \beta \) is the cone width half-angle, \( R \) is the maximum detection distance, vision can be projected onto regular grids, each grid cell is recorded with the corresponding spatial location of idle or occupied state, called the occupied grid. In the figure, \( \gamma \) represents the considered geometric center of the grid and the length of the sensors connection, \( \alpha \) represents the angle between the centerline of ultrasound beam and the line of the sensors connection, \( S \) is the measured distance value [12].

Fig. 3: Grid model of ultrasonic sensor

Vision can be divided into three areas: Area I: this area is the region within \( S \) returned by sensor. Area II: Beginning from the arc whose radius is returned value \( S \), there is an area whose region is regarded as the prescribed degree of fault tolerance (error range). Area III: This area is outside of the area whose radius is the returned value of the sensor and should belong to "the part blocked by some obstacle". The situation of the grids in it is unknown. In the occupied grids, each element (grid) grid \([i][j]\) of the coverage area which is scanned by sensors must calculate the probability \( P_{occupied/s} \). The returned data is converted into the probability:

For every grid within Area II:

\[
P(occupied) = \frac{(R - r) + (\beta - \partial)/\beta}{2} \times Max_{occupied} \quad (1)
\]

\[
P(idle) = 1 - P(occupied) \quad (2)
\]

\( Max_{occupied} \) is corresponding with the maximum probability of occupation in the formula.

For every grid within Area I:

\[
P(occupied) = \frac{(R - r) + (\beta - \partial)/\beta}{2} \quad (3)
\]

\[
P(occupied) = 1 - P(idle) \quad (4)
\]

In the formula, \( P_{(s/occupied)} \) and \( P_{(s/idle)} \) is obtained by the sensor model, called the priori probability. Here, \( P_{(s/occupied)} = P_{(s/idle)} \), and thus the value calculated by sensor model can be directly regarded as the occupation probability.

Since the establishment of three-dimensional map in polar coordinates is very inconvenient and difficult to express, therefore, we convert three-dimensional polar coordinates into Cartesian coordinate space. The known data of Cricket is \( R=3m \), \( \beta=30 \).

\[
r \times \sin \alpha = \sqrt{x^2 + y^2} \quad (5)
\]
\[ r \cos \alpha = 3 - z \quad (6) \]
\[ \tan \alpha = \frac{\sqrt{x^2 + y^2}}{3 - z} \quad (7) \]

Formula (8)(9) can be concluded from formula (5)(6)(7):

\[ \alpha = \arctan \frac{\sqrt{x^2 + y^2}}{3 - z} \quad (8) \]
\[ r = \frac{3 - z}{\cos(\arctan \frac{\sqrt{x^2 + y^2}}{3 - z})} \quad (9) \]

When calculating \( P \), the formula (8)(9), \( R=3 \text{m}, \beta=30\) should be plug into Eq. (1)(3).

3 Probability Grid Map

3.1 The probability grid map established by single three-dimensional ultrasonic sensor

To create space Cartesian coordinate system in the interior space firstly, then the interior space of the \( XY \) plane is divided into \( M\times N \) grids, and each grid is a square with sides of length \( L \). By the use of calculus ideas, three-dimensional space accumulated by numerous \( XY \) plane in the \( Z \)-direction. Namely: to make the three-dimensional into slice processing in the \( Z \)-direction, as shown in Fig.4:

![Fig. 4: Schematic diagram of the divided grid space](image)

The spatial coordinates of each grid is represented by the grid center \((X, Y, Z)\) coordinates, and each color means that the probability of the existence of obstacles in the grid, as shown in Fig.4 right. Since each point has four values, it is called the probability of the obstacle existence of four-dimensional map.

In this paper, for the sensor model shown in Fig.3, Bayesian method is adopted to establish the environmental grid map, but what it builds is a three-dimensional grid map. In the Bayesian approach, sensor model produces \( P(s/H) \) in the form of conditional probability, that when the corresponding grid is indeed occupied, the returned value is the sensor actual measurements’ probability, but what we actually concern is the probability of the occupied grid which represented
by \( P_{(H/s)} \), when the returned value is the actual measured value. By the probability we can see that the two are not the same, but meet the Bayes rule, namely:

\[
P(H|s) = \frac{P(s|H)P(H)}{P(s|H)P(H) + P(s|-H)P(-H)}
\]  

(10)

If “occupation” instead of \( H \), the above equation becomes:

\[
P(\text{occupied}|s) = \frac{P(s|\text{occupied})P(\text{occupied})}{P(s|\text{occupied})P(\text{occupied}) + P(s|idle)P(idle)}
\]  

(11)

Fig. 5: Schematic diagram of the single sensor grid probability model

As shown in Fig.5, when the returned value is 1.5m, the ultrasonic sensor uses a single spatial probability grid sensor model to figure out the three-dimensional grid map which represents the obstacles’ existence probability of each grid within the cone detection range of the sensor.

### 3.2 A three-dimensional probability grid map established by ultrasonic sensor network

To create the Cartesian coordinate system in Interior space, then the \( XY \) plane of the interior space is divided into \( M \times N \) grids, each grid is a square with side length \( L \). Each sensor’s coverage is the cone shown in fig.2. The circumference of the bottom cone is the square of the circumference formed by the numerous grids, as shown in Fig.6.

![Schematic diagram of multiple sensors covering](image)

This grid’s probability of the existence obstacles can be solved by the following formula:

\[
P = 1 - (1 - P1) \times (1 - P2)
\]  

(12)
4 Simulation and Data Analysis

In the 5m long, 5m wide, 2.6m high indoor environment, as shown in Fig.7, since the maximum effective detection distance of the ultrasonic sensors-in-use is 3m, the ultrasonic sensor evenly deployed in the ceiling which is height of 2.6m from the ground. Thus, in the conical detection range, the generatrix length of the cone is 3m, the circle radius of the conical bottom is 1.5m. Taking the accuracy of the hardware and multiple environmental modeling results into account, each grid’s side is set to 0.25m. To arrange a number of regular shape obstacles, \( H \) stands for the height of each obstacle.

![Fig. 7: Layout of the indoor environment](image1)

25 ultrasonic sensors evenly deployed on the ceiling in accordance with the 5×5 ways which are formed into a wireless sensor network. Then the values returned by WSN are combined with the probability grid model to build a global environmental four-dimensional probability grid map. As noted above, the calculation method of the probability of existence obstacle is decided by whether the grid is in the overlap detection area. So first we determine whether the grid is in the overlap detection area. If the target point and the cone vertex’s coordinates are known, the slope between the two can be derived.

In sum, through the slope from target point to the apex of the cone and the slope from the bottom to the cone vertex, we can determine the location of the point is outside the detection area, a single sensor detection area, or in the overlap detection area. Fig.8 shows the result of the calculation.

![Fig. 8: Four-dimensional space grid probability map](image2)

\((X, Y, Z)\) coordinates determine the grid position in space, different colors indicate the probability value of the existence obstacles, the color of the right side of Fig.8 from light blue to
light yellow is the probability value from 0 to 1, and what all other values mean is the grid not within the scope of the cone detected by the WSN. We can see the probability shown in Fig.8 is consistent with the distribution of obstacles shown in Fig.7.

5 Conclusion

This paper begins and analyzes by describing the characteristics and model of ultrasonic sensors, and then proposes a model of spatial probability grid. After that, we judge the location of the grid in space and establish algorithms to calculate the probability of existence obstacles. Finally, we carry out the simulation in the indoor environment, build the spatial probability grid maps, and well expressed the probability of existence obstacles with the four-dimensional map.

References


