Exploring Unknown Environment and Map Construction Using Ultrasonic Sensing of Normal Direction of Walls

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Abstract

Ultrasonic sensors are very useful for mobile robots because they have the advantage that the systems are simple and are easy to handle. When a mobile robot is navigated using an ultrasonic sensor, the map of the environment should include information about the reflection characteristics of objects. For this purpose, the map using a vector expression is better than a grid map. In this paper, an environment reconstruction method using a vector map is proposed. In this method, the environment is reconstructed from the data obtained by using our novel ultrasonic sensor which can measure the normal direction of walls, and the next sensing point is determined automatically. The experimental results of a map construction using this algorithm are shown. As a result of the experiments, it is found that the measurement of walls is possible using this method and the effectiveness of the planning algorithm for the sensing point is verified.

1 Introduction

Research into the recognition of environment for a mobile robot is developed around the guidance of path and the exploration of the path. The ultrasonic sensor measures environment quickly. This is useful, because real time processing is required when the robot is navigated. However, it is difficult to recognize the position of objects exactly, because the directivity of an ultrasonic sensor is not sharp sufficiently. Therefore, research into sensor data fusion obtained by using several types of sensor or by sensing from many positions is done for the improvement of accuracy.

Elfes et al.[1] and Borenstein et al.[2] navigated a robot using the position of the unknown obstacles calculated from an occupancy grid. Flynn[3] navigated a robot using the integrated information of ultrasonic sensor data and an infrared sensor. However, the final environment map, in which the position of the object was described, was not reconstructed perfectly in the previous research. This is because the aim of the research was navigation of the robot. Freyberger et al.[4] constructed an environment map around the path using laser range sensor. Iijima et al.[5] proposed an algorithm for exploring the unknown space and for constructing the map in the indoor environment, and performed experiments using a real robot.

As mentioned above, the laser range sensor and the ultrasonic sensor can be used for recognition of the environment. The laser range sensor has weak points since the system is complicated and it is affected by the optical condition of the environment. The ultrasonic sensor has the advantages that its system is simple and it is easy to handle.

In the problem of the map construction using an ultrasonic sensor, only methods for grid map construction have been proposed. The grid map is easy to understand for a human. However, it is difficult for a robot to move referring to this map and using the ultrasonic sensor. In the case that the map is constructed using an ultrasonic sensor, it is necessary to project onto the map the position where the object can be observed. It is particularly important to measure the normal direction of walls for the recognition of position and posture of the robot in the indoor environment in which ultrasound often reflects specularly.

This study aims at describing a map using vectors in order to represent the reflection characteristics of ultrasound, and an algorithm for map construction of the unknown environment is developed. It is difficult to construct a vector map from the information obtained by the conventional ultrasonic sensor. However, it becomes possible to construct a vector map in an uncomplicated environment by using our proposed sensor which can measure the normal direction of walls[6].

2 Problems in exploring unknown environments with ultrasonic sensors

2.1 Information obtained from ultrasonic sensors

When an ultrasonic sensor is used, it is difficult to recognize the shape of the environment because only one dimensional range data can be obtained by this sensor. The most widely used method for measuring the environment is to plot the measured point on the transducer line-of-sight. However, the map of the environment based on this method is quite different from the real environment, because the ultrasonic beam is very wide and it reflects specularly (Fig.1).

2.2 Problems in the use of ultrasonic sensors

It is assumed in this study that the unknown environment satisfies the following conditions.

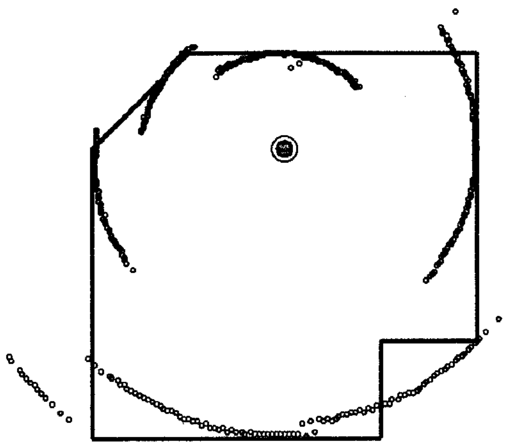

Figure 1: An example of sensing data obtained by the ultrasonic sensor in which the directivity is not so sharp. The solid lines denote the real environment, the small circles are the measured data, and the rather big black circle denotes the sensing point.

- The unknown environment is uncomplicated and it has a flat floor and some flat vertical walls like a indoor corridor.
- The object in the unknown environment is taller than the height of the sensor.
- Every point facing this sensor system and every edge point in the environment can be measured with in the distance of 1m.
- No moving object exists in the environment except the robot.

The following problems must be considered in the recognition of the unknown environment using ultrasound.

2.2.1 Processing range information

In general, the position of the reflecting point of object cannot be specified in terms of direction because the directivity of the ultrasonic sensor is not sharp. In the case that an echo signal is weak such as a reflection from an edge. The direction to the object point cannot be calculated though the distance between the object and the sensor can be measured, (even using our ultrasonic sensor[6]). The range information can specify the position of an object in a certain area, however, it is impossible to determine the exact position. In this case, more information is obtained from multiple sensing points. The problem is how data about the object can be expressed and how the sensing point can be planned in order to understand the exact shape of the object.

2.2.2 Planning sensing points

Since ultrasound has a character of specular reflection, the position from which the wall can be observed is limited to a very narrow area. For example, the area where part of wall A (except the edge) can be measured is rather wide when using a laser range sensor (Fig.2). However, the area is limited to the front of the wall in case of the ultrasonic sensor (Fig.2). Since information obtained one measurement is a small element of the wall, the information must be connected for the estimation of the continuous wall. Consequently, the wall should be measured in small steps.

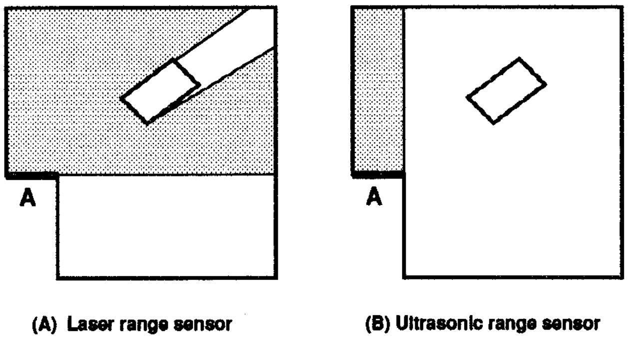

Figure 2: Areas where a part of the wall "A" can be measured.

2.2.3 Determination of free space

For the recognition of an unknown environment, a robot must plan the sensing points and the path for movement. For this purpose, the robot must recognize the free space so that it can move safely. In the case of laser range sensors, the free space is the common region of the width of the laser beam and the field of view in front of the object. On the other hand, since the ultrasonic sensor cannot detect the wall which is not perpendicular to the transducer line-of-sight, the free space cannot be determine even if the object isn't detected by the sensor. If a reflection from an edge can be detected, it is possible to determine the free space when measurements are performed in every direction.

There are many problems which should be solved to reconstruct the map of an environment using an ultrasonic sensor. However, if the necessary normal direction of the wall is obtained by using our ultrasonic sensor[6], the problems in map reconstruction of the environment can be simplified. But, it is still difficult to determine the sensing position automatically.

3 Ultrasonic sensor for measuring normal direction of walls

The ultrasonic sensor has several advantages: its hardware is constructed easily and its system is small in size and it's economical to use. For these reasons, this sensor is widely used in the research of mobile robotics. This sensor has relatively high accuracy in a measuring distance, and it is suitable for real time measurement because of its simple calculations. However, because the directivity of the ultrasonic beam generated by this sensor is not sharp. The position of an object can only be estimated in the wide area of the beam width. The position cannot be limited to the transducer line-of-sight when the distance is measured by using this sensor. In order to compensate, plural receivers can be used. Furthermore, the normal direction of the object surface can be measured if the characteristics of the reflective surface of the object are considered. Nakajima et al.[7] controlled a manipulator tracing curved surface using the sensor based on this technique. Such a sensor is constructed by the arrangement shown in Fig.3.

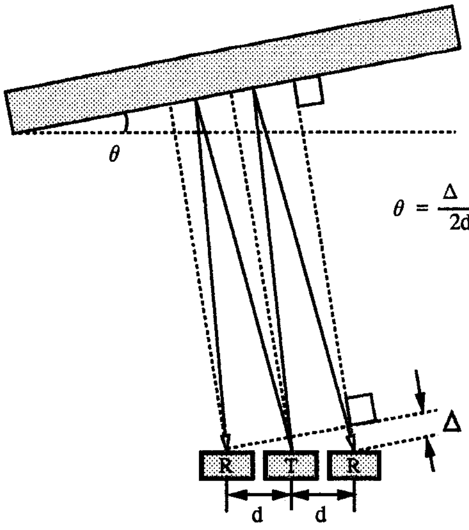

Figure 3: Configuration of the ultrasonic transducers for the measurement of the normal direction of the wall. "T" denotes the transmitter and "R" denotes the receiver.

The inclination of the surface is calculated from the phase difference of the reflected wave using the method of Nakajima et al. In this method, the measurable range of the angle is limited by the wave length of the ultrasound and the geometrical configuration of the receiver. This limited range is insufficient for the sensor of the mobile robot. In our studies the angle is calculated from the difference of the round-trip time-of-flight. With such a method, the problem of missing detection of the leading edge from the received signal must be solved. In order to overcome this problem, a high voltage single pulse is used as the drive signal for the transducer to sharpen the leading edge. The correction of the error uses the inconsistency of the relationship between the propagation times detected by each receiver and the configuration of the receivers. In this study we use two additional receivers. Using

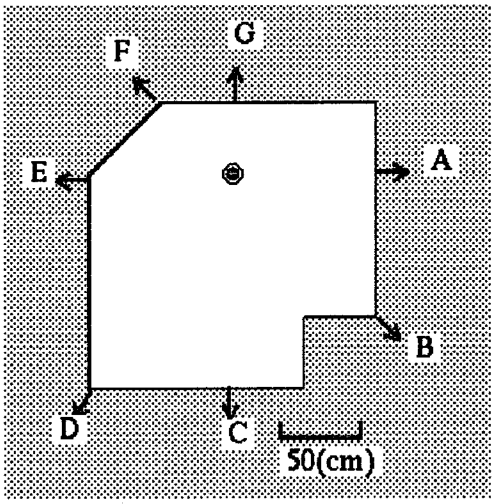

Figure 4: Experimental result for exploring an environment.

such a sensor, the range of the measurable angle depends on the directivity of the ultrasonic transducer. We call this sensor *RADIAN sensor* (Rotary Acoustic DIrection ANgle sensor))[6]. The surface element and its normal direction can be extracted for a flat wall using this sensor. Also, the vertex of a rectangular can be extracted. Fig.4 shows an example of an experimental result for exploring an environment.

In the following sections, a method for exploring unknown environments is examined.

4 Algorithm for map construction in an unknown environment

4.1 Formulation of problem

The ultrasonic sensor proposed by us can measure the distance of the flat wall, when the distance is smaller than 150cm and the angle between the normal direction of the wall and the transducer line-of-sight is in the range of −36deg to +36deg. The accuracy of the inclination of the wall in this sensor is about 2deg when the distance is 50cm and is about 4deg when the distance is 150cm. This performance is the same in case of the rectangular corner as in the flat wall. In case of a weak edge, however, the angle of a wall cannot be measured though the distance to the wall can be measured. This is because the amplitude of the echo signal is weak and the mutual correlation coefficient between the received signals becomes small.

The objective is to construct the vector map of an environment using the *RADIAN sensor*. It is easy to construct the map represented as lines in the 2 dimensional field, because the general indoor environment consists of flat walls. It is necessary to describe the shape of the object surface in order to express the reflection characteristics. In the exploration of the unknown environment, the accuracy of the movement of the robot is not considered.

```
program mapping
begin
  do
    get-sensor-data
    vector-map-construction
    grid-map-construction
    sensing-point-planning (next-point)
    path-planning
    move-to-next-point
  until (next-point = NULL)
end
```

Figure 5: Algorithm for map construction.

4.2 Map construction

The algorithm for autonomous map construction is shown in Fig.5. The detail of each part of the algorithm is as follows.

4.2.1 Construction of vector map

The information of environment obtained by our sensor system is different from the shape data of the object obtained by a laser range sensor. The ultrasonic data is a set of the small surface elements existing discretely. Since a structured environment such as indoor corridors is only considered. It can be assumed that a wall exists between two surface elements, if the surface elements exist next to each other. The continuous wall is reconstructed by jointing the discrete surface elements (Fig.6).

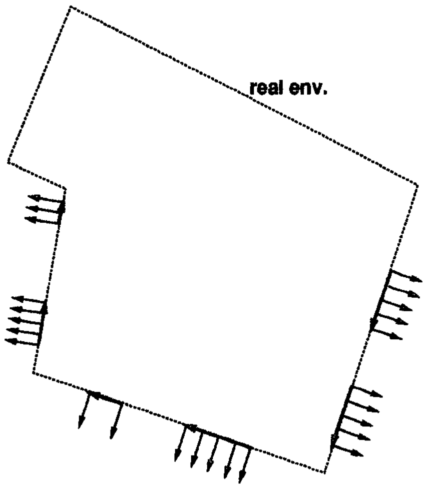

Figure 6: Method for the wall reconstruction. The arrows which are perpendicular to the walls are the detected surface elements. The arrows which are parallel to the walls are the connected continuous walls, and the dotted lines are the walls of the real environment.

4.2.2 Construction of grid map

To recognize the environment autonomously, the robot must be able to determine the next sensing point. For this purpose, the free space, i.e. the area where the robot can move safely must be detected. If it is assumed that the reflection from the nearest position of the object which exists in a certain distance from the sensor is correctly detected when the ultrasonic sensor is rotated in 360deg, then the inside of the circle whose radius is equal to the the detected nearest distance and whose center is the sensor position can be considered as the free area. The nearest position of the object is the surface or the edge of the object. As ultrasound is diffracted at an edge, the echo from edge can be detected theoretically. However, all edges cannot be observed because of the low signal to noise ratio.

The nearest distance is available in the range of the direction of ±90 degree. This is because the nearest distance is measured to the center and the only objects existing in the environment are mostly flat walls (Fig.7).

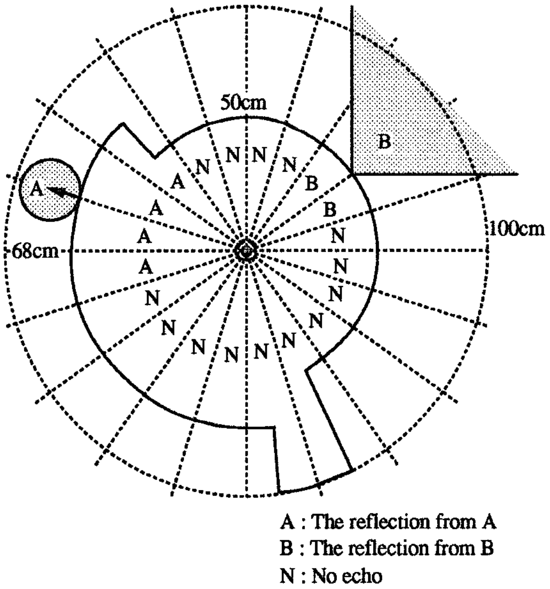

Figure 7: Method for determination of the free area.

The free space is stored using a grid map with a resolution of 5cm. When the intensity of the echo signal is sufficiently large, the surface element can be measured because each receiver can detect the leading edge of the echo accurately. On the contrary, when the intensity of the echo signal is rather small, the position of the reflection point cannot be localized within an area which is narrower than the beam width of the ultrasound. The distance to objects can only be measured and the position of the object cannot be determined in such cases. This information is also added in the grid map. Fig.8 shows the grid map for Fig.7.

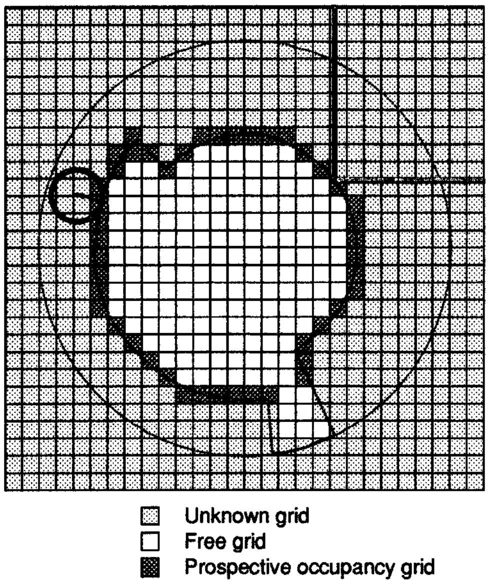

Figure 8: Construction of the grid map.

The attributes of the grid are unknown, free occupied, and possibly occupied. A possibly occupied area means information based on distance only (the orientation cannot be measured). The existence of a near object is recognized from the data of the possibly occupied area and it is utilized in the planning of the sensing point. The order of the priority in overwriting the grid is [occupied > free > possibly occupied > unknown].

4.3 Sensing point planning

The problem of environment recognition, depends on the type of environment that needs to be mapped. Also the method for planning of the sensing point is determined by the type of environment. Indoor environments are only considered in this study, so the environment can be expressed as a vector map. The basic concept of the exploration is to recognize the position of the walls which form the environment. Consequently, as the world is closed by walls, the end condition of map construction is that the boundary of the environment is recognized perfectly. All the attributes of the grid in the inside area of the boundary must be known. The attributes cannot be known in the region near the corner because the directivity of the ultrasonic beam is not sufficiently sharp. The existence of unknown areas is allowed near corners.

At the next sensing point, a surface element can be correctly detected if:

1. The sensing point is on the extended line of the known wall.
2. The sensing point is near a possible occupied area.
3. The sensing point is near the boundary between an unknown area and the free space.

The algorithm for the determining the sensing point is as follows.

4.3.1 Determining the sensing point for wall extension

The first condition for the determining the sensing point is to explore along the extended line of a known wall. Our method uses the evaluating function $ptl(x, y)$, which becomes maximum on the line when a point extended 30cm from the known wall can be observed.

$$ptl(x, y) = \frac{1}{n}\sum_{i=1}^{n} dist(i), \qquad (1)$$

$$dist(i) = \begin{cases} d/30 & \text{for} \quad d \leq 30, \\ 1 - (d - 30)/90 & \text{for} \quad 30 < d < 120, \end{cases} \qquad (2)$$

where d is the distance between the edge of a line segment and the foot of the perpendicular drawn from the point of (x, y) to the line i. A visualization of this evaluating function is shown in Fig.9.

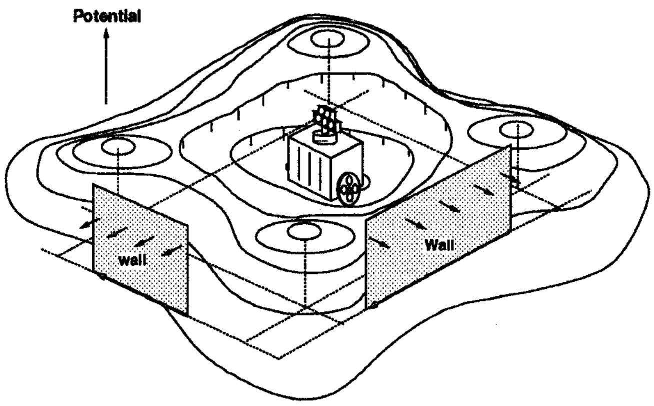

Figure 9: A visualization of the evaluating function in case it is assumed that the wall can be extended.

Moreover, the evaluating function is multiplied by the distance from the robot in order to reduce the amount of the movement by the robot.

$$ptl(x, y) = ptl(x, y) \times (1 - dist/500), \qquad (3)$$

where $dist$ is the distance between the coordinates of the robot and the point (x, y). The robot moves to the grid in whose evaluating function has the highest value.

4.3.2 Determining the sensing point for wall finding

When no extendable wall exists or sensing the extended line of detected wall is impossible, the sensing point is determined near possible occupied area and unknown area boundary. This is far from occupied areas, so we can find the surface element of an unknown wall. The evaluating function is given by the following equation.

$$\begin{aligned} ptl(x,y) &= Number(\text{Prospective}, 8) \\ &+ \frac{1}{2} \times Number(\text{Unknown} \cap \text{Boundary}, 8) \\ &- Number(\text{Occupied}, 12), \end{aligned} \tag{4}$$

where $Number(\text{Xgrid}, num)$ is the function which returns the number of grids whose attributes are Xgrid which exist within the distance *num*.

4.4 Path planning

When a robot moves toward next sensing point, the safest and shortest path from the present position to the goal must be selected. In this algorithm, we use a modified distance transform method reported by Zelinsky[8] to find a path which considers both robot safety and minimum distance to the goal.

5 Experiment for map construction in unknown environment

5.1 Experiment

Experiments for the exploration of an indoor environment and the map construction were performed using our sensor system. The sensing of the environment is carried out by using *RADIAN sensor* which is mounted on the autonomous mobile robot "YAMABICO"[6]. At each sensing point, the stepping motor is stopped every 18 degrees and surface element data is collected in 20 directions. After the measurements are taken, the obtained data is forward to a workstation. The map is constructed and the next sensing point and the path is planned on the workstation according to the algorithm mentioned above. The planned path is sent to the robot, and it moves to the next sensing point. The map is constructed by repeating these processes.

Fig.10 shows the process of map construction in an unknown environment. In each figure, the grid map appears in the upper left corner. The information about surface elements and the vector map obtained at the sensing point (denoted "o") appears in the upper right corner. The history of the sensing point appears in the lower left corner, respectively. The lower right part of the figure shows the circle which represents the reliably measurable area whose radius is 1m. The lower right figure also shows the distance information which is plotted on the transducer line-of-sight obtained at each sensing point, and the information of the normal direction of the wall. The small circle shown in the grid map represents the next sensing point. The arrow shown in the vector map represents the path of the movement to the next sensing point.

Fig.11 shows the comparison between the vector map obtained by the robot and the vector map of the real environment.

5.2 Discussion

The map was constructed with few errors as shown in Fig.11. The difference between the map of the real environment and the map constructed by the experiment might be caused by the initial error and the accumulating error of the robot position obtained by the dead reckoning system. In this figure, the lower side wall is originally constructed by 2 lines, but this wall has only 1 line in the reconstructed map. This difference arises from the process where the data of the normal direction of the wall is fitted to a line calculated by a Hough transform rather than measurement error.

6 Conclusion

The map of environment was conventionally constructed using a grid map. However, the method for the representation of the map considering the characteristics of the specular reflection of ultrasound is necessary. In this paper, a map construction method using vector map was presented. In the recognition of the environment using ultrasound, it is generally possible to find long walls, but it is difficult to find small walls which can only be measured from a small area because of reflected specularly. However, the position of the object can be limited by using the sensor data in which the directivity is not sharp and by sensing from many points.

The method for reconstruction of the environment from the data obtained by using our ultrasonic sensor, and the algorithm for determination of the next sensing point were presented in this paper. The experimental results of map construction using this algorithm were also shown. As the result of the experiments, it was found that the measurement of the walls is possible using this method and the effectiveness of the planning algorithm of the sensing point which is proposed in this paper was verified. In our experiments, the errors in position and posture of the robot were ignored and they must be considered in the future.

In conclusion, it was found that walls in the environment can be detected using our ultrasonic sensor, and the problem of finding undiscovered walls can be solved. In order to reconstruct the map perfectly using the ultrasonic sensor, it may be necessary to estimate the position of the wall from the reflection characteristics of the ultrasound in corners.

Acknowledgement

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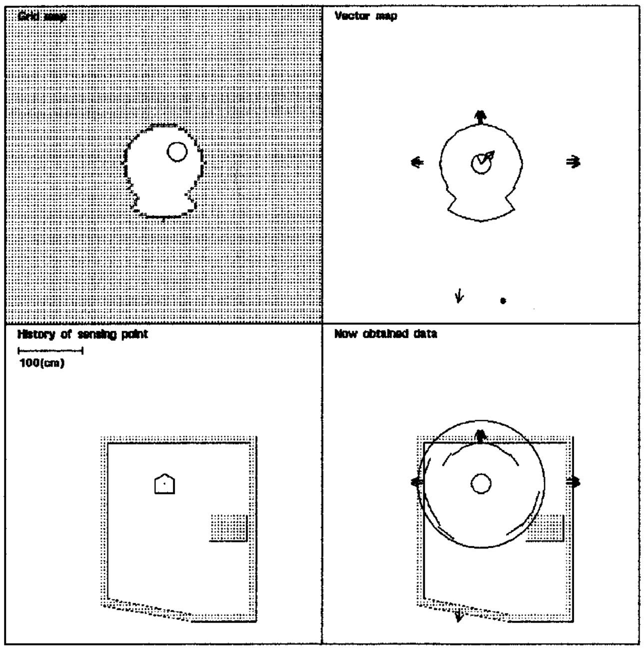
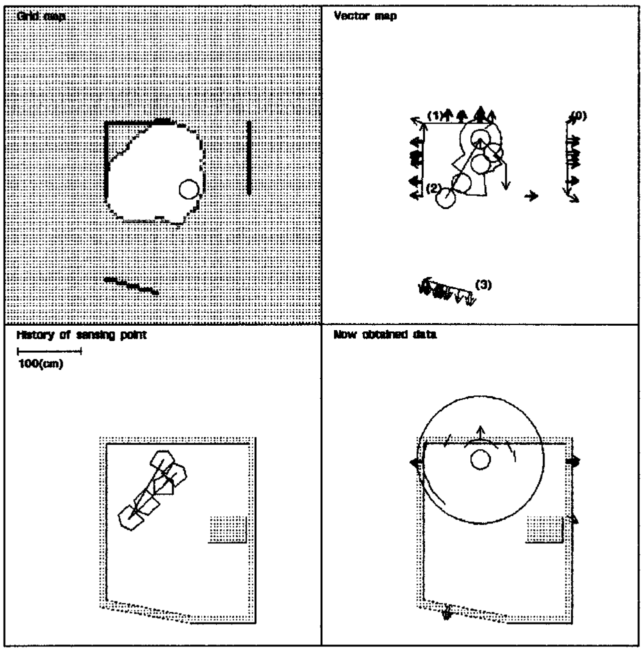
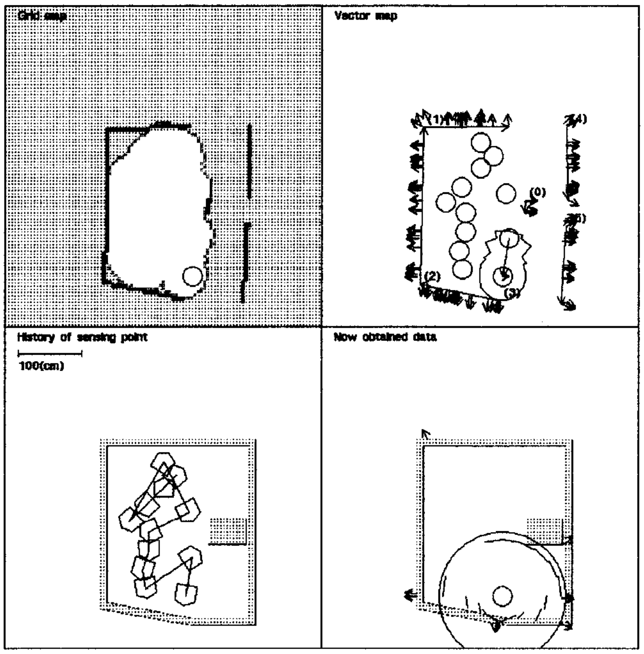


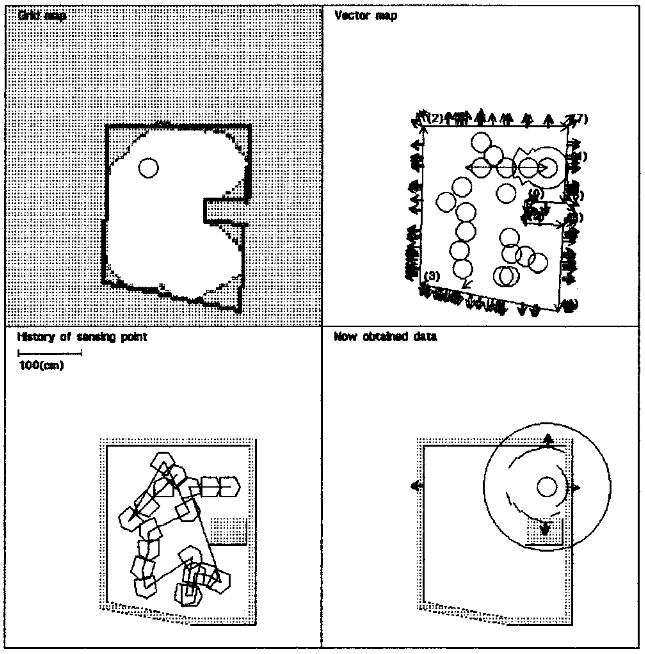
(A) Maps after 1 time measurement



(B) Maps after 5 times measurements



(C) Maps after 12 times measurements



(D) Final maps after 19 times measurements

Figure 10: Experimental results for map construction of unknown environment.

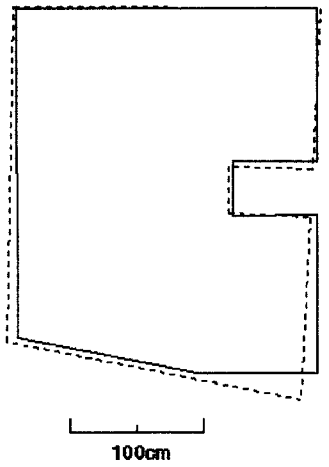


Figure 11: Comparison between the map of the real environment (solid line) and the map constructed from experimental sensor data (dotted line).

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