

A Robust Certainty Grid Algorithm for Robotic Vision

Wilfried Elmenreich and Raimund Kirner

Institut für Technische Informatik,
Technische Universität Wien, Vienna, Austria
{wil, raimund}@vmars.tuwien.ac.at

Abstract — *In this paper we describe an algorithm for fault-tolerant sensor mapping for robotic vision. Basically, we use a certainty grid algorithm to map distance measurements into a two-dimensional grid. The well-known certainty grid algorithm can tolerate occasional transient sensor errors and crash failures, but will fail when a sensor provides permanently faulty measurements. Therefore we extended the certainty grid algorithm by a sensor validation method that detects abnormal sensor measurements and adjusts a confidence value for each sensor. This robust certainty grid approach works with at least three sensors with an overlapping sensing range and needs fewer sensor inputs and less memory than other approaches. Our method supports also reintegration of recovered sensors and sensor maintenance by providing a measurement for the operability of a sensor. We also present a case study with an autonomous mobile robot that features the robust certainty grid algorithm in a time-triggered architecture.*

1 Introduction

A mobile robot must be able to notice surrounding objects in order to be able to interact with its environment. Sensors come in a great variety of types and each sensor is able to contribute to the task of environmental perception.

However, given multiple sensory inputs, the task of modelling these data into a simple, comprehensible image of the environment can be arduous when problems of temporal accuracy [1], imprecise and faulty measurements, and sensor deprivation are considered.

This paper describes an algorithm for mapping sensor information to a unified view of the environment based on the certainty grid approach. The first certainty grid method has been developed at Carnegie-Mellon University in the 1980ies [2]. However, the certainty grid suffers from faulty sensor measurements when they are not detected at the sensor level.

It is the objective of this paper to propose an extension of the certainty grid algorithm by a sensor validation method at the sensor integration level.

Comparing sensor measurements directly is difficult when their measurements are made at different time instants. As a result we used an approval method for calculating confi-

dence values for each sensor. Our algorithm is able to implicitly detect sensors with malfunctions followed by a reduction of the sensor’s input contribution to the certainty grid. Our approach supports inherently automatic integration of recovered sensors. Furthermore our approach facilitates sensor maintenance by assigning each sensor dynamically a confidence value which can be a measure for the reliability of the sensor.

The robust certainty grid algorithm has been tested with simulated sensor faults. We have also implemented a demonstrator with an autonomous mobile robot that features the robust certainty grid algorithm.

The remainder of the paper is organized as follows: Section 2 gives an overview on the original certainty grid algorithm. The following section discusses the influence of sensor faults on the certainty grid. Section 4 describes the robust certainty grid algorithm. Section 6 describes the functionality of our demonstrator. The paper is concluded in Section 7.

2 Certainty Grid Algorithm

This section provides a brief overview of existing certainty grid algorithms.

A *certainty* or *occupancy grid* is a multidimensional (typically 2D or 3D) representation of the robot’s environment. The observed space is subdivided into cells, where each cell stores information about the corresponding environment and an estimated probability for the correctness of this information. Typically, a cell state can be “free”, if the place appears to be void, or “occupied” if an object has been detected for that cell. Cells not reached by sensors reflect an “uncertain” state. The cell state and the probabilistic estimate of its correctness can be mapped into a single number reflecting the confidence of a cell to be free.

Basically, it is assumed, that the application using the certainty grid has no a priori knowledge of the geometry of its environment and the objects in this environment are mostly static. The effect of occasional sensor errors can be neglected, because according to [3], they will have little effect on the grid.

The calculation of new grid values is usually done by Bayesian inference. The English clergyman Thomas Bayes stated in a paper (published after his death in the Philosophical Transactions of the Royal Society of London [4]) the rule known today as Bayes’ theorem:

$$P(H|E) = \frac{P(E|H)P(H)}{P(E)} \quad (1)$$

Bayes’ theorem quantifies the probability of hypothesis H , given that event E has occurred. $P(H)$ is the *a priori* probability of hypothesis H , $P(H|E)$ states the *a posteriori* probability of hypothesis H . $P(E|H)$ is the probability that event E is observed given that H is true. If multiple events have to be considered using Bayes’ rule, the order of processing does not influence the result.

Hoover and Olsen present an application of a certainty grid where a set of video cameras is used to detect free space in the vicinity of a robot [5]. They use the multiple views from different angles to overcome the problem of occlusion and to increase performance, however they do not discuss the subject of sensors delivering faulty measurements.

Sensor information usually is imperfect with respect to restricted temporal and spatial coverage, limited precision, and possible sensor malfunctions or ambiguous measure-

ments. To maximize the capabilities and performance it is often necessary to use a variety of sensor devices that complement each other. Modelling such sensor measurements into the grid is an estimation problem [6].

Matthies and Elfes [7] propose a uniform method for integration of various sensor types. Each sensor is assigned a spatial interpretation model, developed for each kind of sensor, that maps the sensor measurement into corresponding cells. When sensor uncertainties are taken into account, we arrive at a probabilistic sensor model.

Figure 1 depicts the data flow of a certainty grid implementation with three sensors. The sensor in the right position delivers faulty measurements which results in a deviation of the certainty grid from the real object positions.

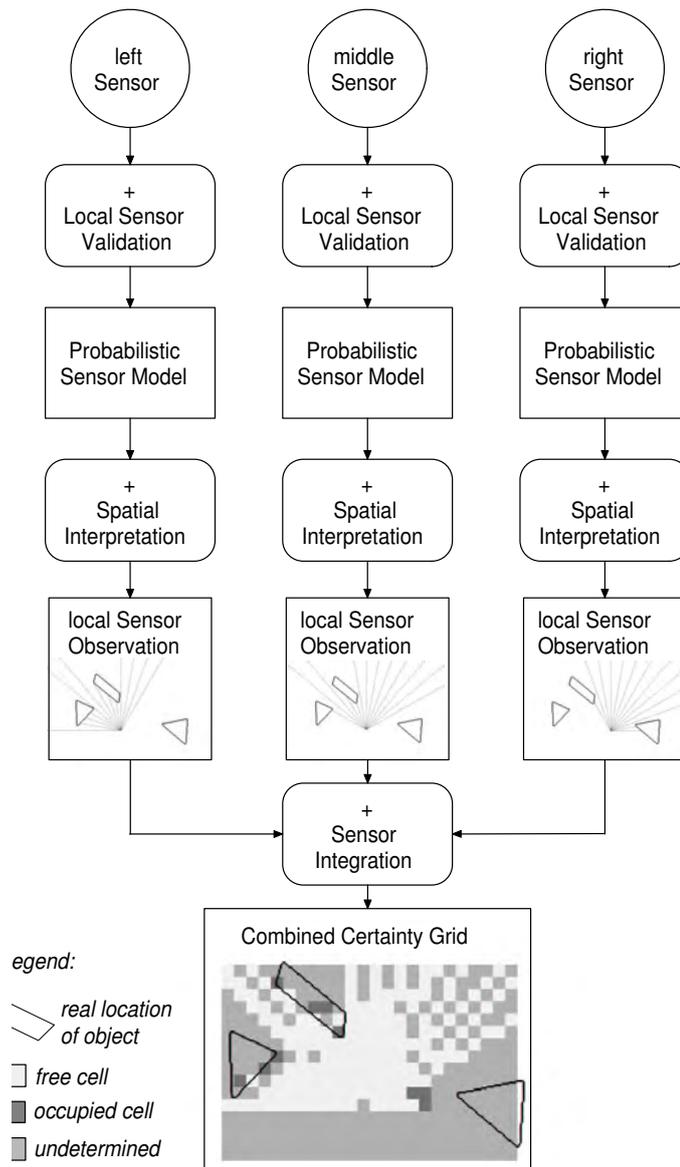


Figure 1: Certainty Grid Data Flow

3 Dealing With Sensor Faults

Martin and Moravec [3] concluded that the effects of occasional sensor faults on the grid can be neglected.

Furthermore, if a sensor input has crash failure semantics, i. e., it provides either a correct value or no value at all, the existing methods are sufficient to handle this situation if each important grid cell is served by more than one sensor.

However, one problem of the certainty grid algorithm as found in the literature [2, 3, 6, 7] arrives when a sensor permanently provides faulty measurements. For example a distance sensor could refuse to detect any object and always report “no object nearby”. Such a fault would result in a significant deviation of the representation of the environment in the grid from the actual environment.

There are two possible solutions to this problem:

Replicated sensors: Making the sensors fault-tolerant by replication results in costs for extra sensors and voting nodes. For example each sensor could be extended to triple-modular redundant sensors, the basic idea of such fault-tolerant units has already been presented in [8]. However these extra sensors would not contribute to the grid resolution or improve the update frequency. In applications where weight, power consumption, and cost is an issue, this approach is not economical.

Replicated certainty grids: The generation of multiple grids and the application of standard fault-tolerant algorithms among these grids does not need extra sensors. Each single certainty grid would represent a fault isolation area, e. g. supported by a single sensor. The final view will then be generated by majority voting among the separate grids. This approach, however, has the disadvantage of increased memory resource requirements. A system with n sensors would need the $(n + 1)$ -fold amount of memory to represent the grids.

While the replicated sensors approach deals with the problems at sensor level, the second approach takes effect at the grid level. Because of hardware and wiring costs we decided for a grid level solution as described in the second approach. Since RAM memory is a critical resource in embedded systems like a mobile robot we aimed at sophisticated algorithm with low memory requirements, which is described in the following section.

4 Robust Certainty Grid Algorithm

We assume, that a sensor node may have a failure mode where it permanently submits measurements with incorrect values. It is our goal to extend the existing certainty grid to tolerate such sensor faults.

This goal will be achieved by analyzing the redundant parts of the certainty grid. Furthermore, we assume that we have no a priori knowledge about the redundant and non-redundant parts, thus we head for an automatic sensor validation.

It is difficult to validate sensors directly by comparing their inputs, because measurements from different sensors for the certainty grid are often made from different angles and at different time instants - a deviation in sensor measurements may be caused by a sensor fault as well as by a change in the environment.

Therefore, we use an approval method for maintaining a confidence measurement for each sensor. The confidence value will be a measurement for the correctness of a sensor. This confidence measurement $conf$ may be a real value ranging from 0 to 1:

$$conf = \begin{cases} 0 & \text{sensor appears to be wrong} \\ \dots & \\ 1 & \text{sensor appears to be correct} \end{cases}$$

If we have a priori knowledge about the sensor reliabilities, an initial confidence value that reflects the respective reliability can be chosen at startup. If we have no knowledge about the reliability of sensors the respective confidence values are initialized with 1.

As in the known certainty grid algorithms, each grid cell contains a probabilistic value occ ranging from 0 to 1 corresponding to the believe, that this cell is occupied by an object:

$$cell.occ = \begin{cases} 0 & \text{free} \\ \dots & \\ 0.5 & \text{uncertain} \\ \dots & \\ 1 & \text{occupied} \end{cases}$$

Additionally we store the main contributor (e. g., the sensor that updated this cell most recently) of the occ value with the cell. This property of each cell will be named the *current owner* of the cell:

$$cell.owner = \begin{cases} 0 & \text{unknown} \\ 1 & \text{sensor 1} \\ \dots & \\ n & \text{sensor n} \end{cases}$$

All grid cells are initialized with $cell.occ = 0.5$ and $cell.owner = unknown$.

When a new measurement has to be added to the grid, the following *AddToGrid* algorithm is executed: (Fig. 2 lists the algorithm in pseudocode)

If the particular grid cell has no contributor listed in its owner field, the measurement of the sensor is taken as is and the cell stores the index of the sensor as new owner.

If there was a contributor, the measurement is first compared to the cell value $cell.occ$. A value named *comparison* is calculated that means a *confirmation* of old cell value and new measurement, if the value is above a certain threshold, and means a *contradiction* of old cell value and new measurement, if the value is below a certain different threshold. In Figure 2 comparison is normalized to represent a value within $[-1, +1]$.

In case of a confirmation, the confidence values of the new sensor and the owner are both increased up to a maximal bound of confidence. In case of a contradiction, the confidence values of the new sensor and the owner are both decreased down to a lower bound of confidence. Since sensor faults are usually a rare event, we use a higher value for the degradation of the confidence value than for the increase.

If *comparison* is not significant, it does neither yield a confirmation nor a contradiction.

The new occupancy value of the cell is calculated as a weighted average between old value and measurement. The weights are derived from the respective confidence values

```

procedure AddToGrid( sensor, cell )
begin
  if (cell.owner = unknown) or (cell.owner = sensor) then
    cell.occ := sensor.measurement;
    cell.owner := sensor;
  else
    comparison := 4*(cell.occ-0.5)*(sensor.measurement-0.5);
    weight1 := abs(cell.occ-0.5)*cell.owner.conf;
    weight2 := abs(sensor.measurement-0.5)*sensor.conf;
    cell.occ := (cell.occ*weight1+sensor.measurement*weight2)
               / (weight1 + weight2);
    if comparison > THRESHOLD then
      inc(cell.owner.conf);
      inc(sensor.conf);
    if comparison < -THRESHOLD then
      dec(cell.owner.conf);
      dec(sensor.conf);
    contribution := 4*(cell.occ-0.5)*(sensor.measurement-0.5);
    if contribution > THRESHOLD then
      cell.owner := sensor;
    else
      cell.owner := unknown;
end

```

Figure 2: Pseudocode of the AddToGrid algorithm

and the significance of the measurement. A measurement is more significant if it has a greater absolute distance to the *uncertain* state (0.5).

Thereafter, a new owner has to be selected. Therefore, a value *contribution* is derived. *contribution* is calculated the same way as the comparison value, but it uses the new *cell.occ* value.

The *contribution* is a measurement of the consistency of the sensor measurement with the new *cell.occ* value. If the *contribution* is above a certain threshold, the contributing sensor becomes the new owner of the cell. Otherwise the *cell.owner* value will be reset to *unknown*.

Table 1 gives examples for updating grid cell values by sensor measurements. The value for THRESHOLD had been chosen with 0.5. In the first case, the sensor measurement and the grid cell value confirm each other. The result is an increased confidence for the sensor that originally contributed to this cell (the *owner*) and the sensor that produced the new measurement. In this example the sensor becomes also the new *owner* of the entry. In the second case, the sensor's measurement does contradict the grid value – the sensor reports free space while the grid cell value is sure about an object. Thus, the confidences of the involved sensors are decreased. Case 3 shows a less severe contradiction, because the grid cell is not quite certain about its content. Hence mainly the new measurement influences the updated grid value. Case 4 shows again a measurement that confirms the grid value and leads to a rise of the sensors' confidences. Thus, the sensors' confidence

Before update				Intermediate results and state after update				
cell.occ	cell.owner.conf	sensor.measurement	sensor.conf	comparison	new cell.occ	confidences	contribution	cell.owner
0.8	1	1	1	0.6	0.925	increased	0.85	<i>sensor_i</i>
0.925	1	0	1	-0.85	0.425	decreased	0.15	<i>unknown</i>
0.425	1	1	0.8	-0.15	0.909	unchanged	0.818	<i>sensor_i</i>
0.909	0.8	1	0.8	0.818	0.959	increased	0.918	<i>sensor_i</i>

Table 1: Examples for grid cell updates

values are dynamically updated according to the comparison of their measurements to the grid. A bad performing sensor will subsequently loose confidence and eventually drop out of the set of contributing sensors. However if the sensor recovers, it will gain confidence again by repeated confirming measurements.

The approach works with at least three sensors whereof one sensor might be faulty at one time. In comparison to the node level approach discussed in Section 3, the proposed method gains extra sensor space, because the sensor views must overlap only partially. There must be at least one grid cell, which is served by all three sensors.

The extra amount of memory for the grid representation is the storage for the owner values, thus

$$\frac{\lceil \log_2(n_{sensors} + 1) \rceil}{8} \cdot gridheight \cdot gridwidth, \tag{2}$$

more bytes of memory, where $n_{sensors}$ is the number of sensor contributing to the grid. The memory requirements for the confidence values can usually be neglected, if the number of sensors is remarkably lower than the total number of cells in the grid. Thus, the memory requirements of the robust certainty grid algorithm are considerable less than the memory consumption of the fault-tolerant approach at grid level discussed in Section 3

In contrast to Bayes' formula, the *AddToGrid* procedure is not commutative. Thus, when a grid cell is updated by subsequent measurements, the order of updates makes a difference in the result. This can be explained because we change the a priori probabilities for the sensors with each update. We overcome the disadvantage of sensitivity to message ordering by applying a time-triggered schedule. By avoiding race conditions, time-triggered communication and computation ensures a predictable order of message tasks.

5 Recovery of Sensor Confidence

According to [9, 10], the probability of transient faults is much higher than the probability of permanent faults. The robust certainty grid algorithm cares for a decrease of the confidence value for a failing sensor. However, as soon as the failure has passed the sensor's confidence rises again due to subsequent positive comparisons. This self-healing behavior is related to the concept of self-stabilization as introduced by Dijkstra in [11].

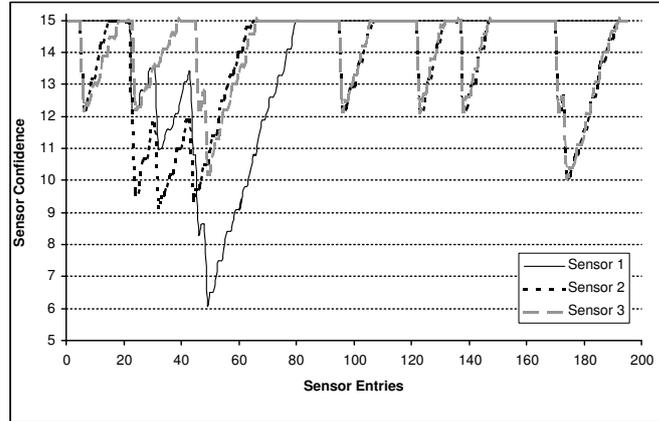


Figure 3: Recovery of sensor confidence after a transient failure

Figure 3 depicts the confidence values of a set of three sensors from a simulation of about 200 sensor readings using the robust certainty grid algorithm. All sensors had been initialized with the highest confidence, but sensor 1 suffered from a transient failure during its first 50 readings. The simulated failure added a noise signal of 20% of the sensor's range to the output signal. While that failure persisted, the confidence of sensor 1 decreased. The confidence values of sensor 2 and 3 were also fluctuating due to inconsistencies in their readings and contradictions with sensor 1. As shown in the figure, the confidence value of sensor 1 recovered within about 30 sensor readings after removal of the transient failure.

6 Case Study

We implemented the robust certainty grid in a mobile robot for demonstration purposes. The mobile robot comprises a model car (“smart car”) equipped with a suit of pivoted distance sensors, two ultrasonic sensors pointing straight forward, an electric drive, and a steering unit (see Figure 4).

In [12] we showed that time-triggered communication networks are apt to implement real-time sensor fusing applications. Therefore, we used a time-triggered sensor fusion model [13] where all communication instants and computation tasks are a priori planned in a time-triggered schedule.

We used a TTP/A network to interconnect distance sensors, servo motors for sensor pivoting, driving, and steering units. Each unit is a separate TTP/A node implemented on a low-cost microcontroller and equipped with a smart transducer interface [14].

The network also contains a master node and a data processing node. The distance

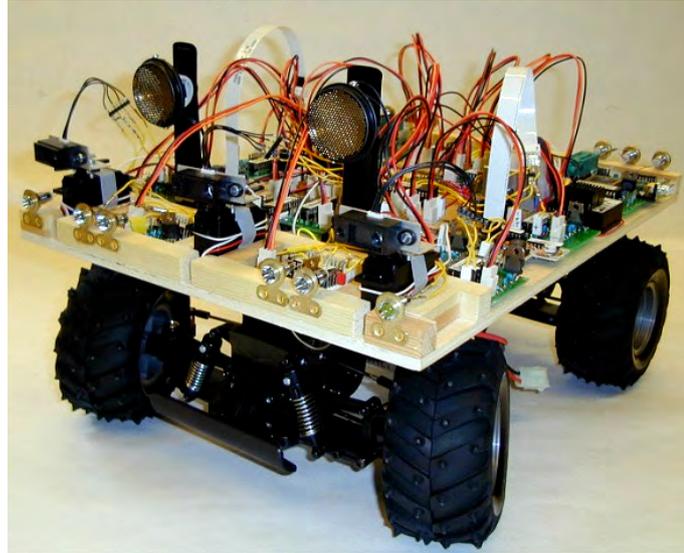


Figure 4: Smart Car: Autonomous mobile robot with pivoting sensors

sensors are swivelled around by servo motors enabling them to scan the area in front of the robot. The sensors generate a value that corresponds to the distance of the object they are aimed at.

The data stream provided by the distance sensors is taken over by the data processing node that fuses the perceptions from the distance sensors with a model of the robot's environment, using the robust certainty algorithm described in the previous section. Thus, the shapes of obstacles are stored and assigned with a probability value. We added a function that moves all values up to the *uncertain* state with the progression of time. So, an object has to be re-scanned periodically.

We used 8-bit values to express the probability values between 0 and 1. Thus 0x00 corresponds to the *free* state, 0x80 means the *uncertain* state while 0xFF is used to express the *occupied* state of a grid cell. Fig. 5 depicts an example of a grid allocation.

Movement decisions about direction and speed are made based on a vector field histogram derived from the certainty grid [15]. The vector field histogram is a method to

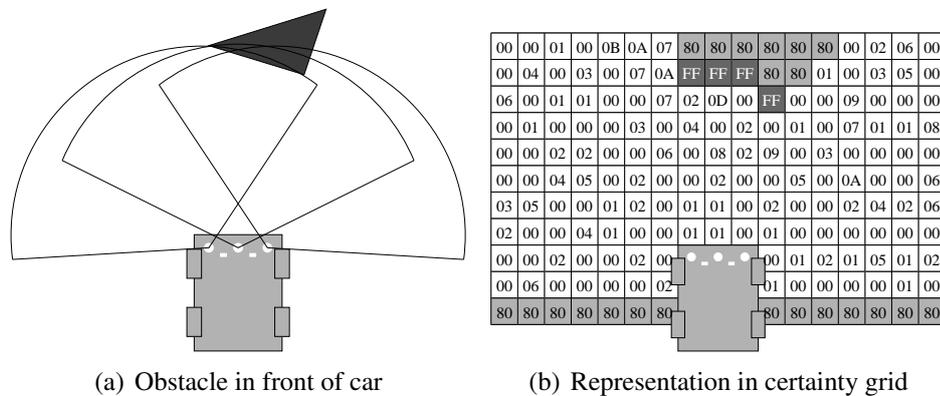


Figure 5: Fusion of measurements into the certainty grid

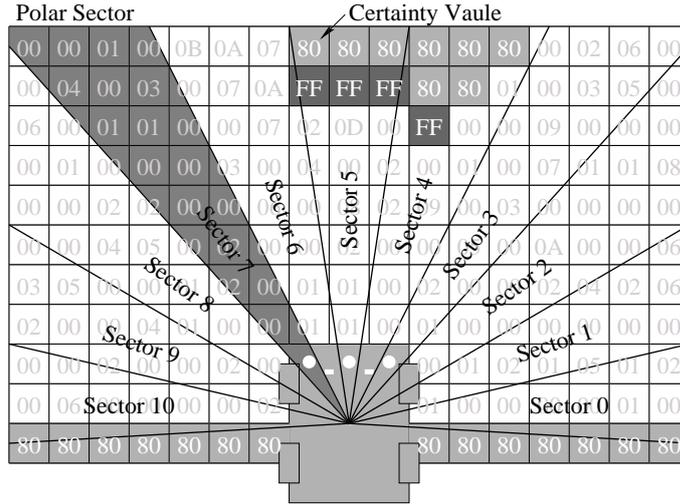


Figure 6: Dividing the certainty grid into polar sectors.

determine the direction with the lowest obstacle density. The algorithm uses the grid representation of the environment which is provided at the cluster level.

The vector field histogram approach divides the certainty grid into disjoint polar sectors S_k (see Figure 6).

For each cell C_{ij} in a given sector an obstacle vector m_{ij} is calculated. The magnitude of m_{ij} depends on the certainty value occ_{ij} of the cell and also on the distance d_{ij} between the vehicle and the respective cell:

$$m_{ij} = (occ_{ij})^2(a - b \cdot d_{ij}) \quad (3)$$

with $a - b \cdot d_{max} = 0$. a and b are positive constants that define the sensitivity of the algorithm to the object distance. d_{max} is the distance between the farthest cell and the vehicle.

Hence, the sum over all obstacle vectors m_{ij} in sector S_k forms an obstacle density entity h_k :

$$h_k = \sum_{C_{ij} \in S_k} m_{ij}, \quad k = 1, \dots, n. \quad (4)$$

At this point the entities h_1, h_2, \dots, h_n are used to form a histogram (see Figure 7), which can be used for obstacle avoidance.

High magnitudes in the histogram indicates regions with high obstacle density, while areas with low magnitudes indicate regions with low obstacle density. By applying a threshold to the histogram it is possible to localize regions with low obstacle density, which can be used for obstacle avoidance. The car will then be moved towards the most promising direction. Moving or turning of the car affords a correction of the grid values. Since the grid contains only 17×11 values the shift and rotate operations can be applied to the grid in real-time.

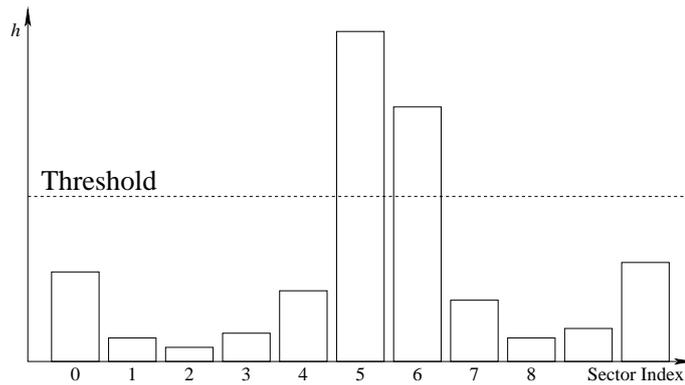


Figure 7: Histogram of the obstacle density.

The smart car is able to move autonomously through its environment. Additionally, it has an interface to a service point for monitoring and configuration access. Via this monitoring interface it is possible to watch snapshots of the certainty grid or the sensor confidence values. The non time-critical service communication is routed concurrently to the real-time system that receives the sensor values and maintains the grid and confidence values. It is possible to route the service access over different networks, e. g. over a wireless link and CORBA to a service station somewhere connected to the internet.

7 Conclusion

The class of certainty grid algorithms are qualified for mapping sensor information of mobile robots into a concise description of the environment.

The previously published certainty grid algorithms can tolerate occasional transient sensor errors and crash failures but will fail for permanent sensor faults.

We developed a method for sensor validation that detects abnormal sensor measurements and adjusts a weight value of the corresponding sensor. Recovered sensors are reintegrated automatically. This robust certainty grid approach supports also sensor maintenance, because it provides a measurement for the operability of a sensor.

The robust certainty grid will be implemented in a mobile autonomous robot with a time-triggered communication architecture.

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About the Authors

Wilfried Elmenreich was born in 1973. Before going to the Vienna University of Technology, he studied at the Engineering School for Electrotechnics and Control in Weiz, Styria. In 1998, he received a Master’s degree in computer science and in 2002 a doctoral degree in technical sciences both from the Vienna University of Technology in Austria. His research interests include real-time and embedded systems, smart transducer networks, fieldbus communication, and sensor fusion.

Raimund Kirner is a research assistant at the Institut für Technische Informatik, Real-Time Systems Group at the Vienna University of Technology. He has studied Computer Science at TU Vienna and received the Dipl.-Ing. (Master’s) degree in 2000. In June 2003, Raimund Kirner has finished his doctoral studies in Computer Science with Prof. Peter Puschner at the Vienna University of Technology as research advisor.