Map Building for Mobile Robots by High-Resolution Ultrasonic Sensing

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Abstract

This paper presents a novel map building approach for mobile robots. We describe how wide-angled ultrasonic transducers can be used to obtain substantial information of the environment by exploiting the overlapping of detection cones from neighbor sensors. High-resolution ultrasonic sensing incorporates cross echoes between neighbor sensors as well as multiple echoes from different echo paths for each sensor. In this way, a significantly higher number of echoes can be utilized in comparison to conventional ultrasonic sensing methods for mobile robots. In order to benefit from the increased sensor information, algorithms for adequate data post-processing are required. In this context we describe how local environment models can be created, and how they can be spatially integrated to build global environment maps.

1 Introduction

Ultrasonic transducers are preferably used to obtain three-dimensional information of the environment. The most commonly used sonar device for mobile robots is the well known Polaroid ultrasonic ranging system [11] with a detection cone of 30°. Due to the relatively narrow detection range of the Polaroid sensors as well as the angular and spatial displacement of the sensors, cross echoes from neighbor sensors rather arise from multiple reflections than from an object located within the beam-width overlapping of the sensors. The standard Polaroid system is configured to send out a short ultrasonic pulse and to measure the "time of flight" until a first echo from an object can be detected by the same sensor. In order to improve robot perception we decided to use wide-angled ultrasonic transducers and to detect cross echoes from neighbor sensors as well as multiple echoes per sensor. For this purpose, a novel ultrasonic sensing system was designed, and algorithms were developed to post-process the sensor data in order to obtain improved environmental information. Within this paper we describe a circular sensor arrangement for an experimental robot, and we demonstrate the map building approach in a typical indoor environment.

In section 2 we will review related work. A specification of the ultrasonic sensing system will follow in section 3. Creating local environment models will be described in section 4, and building global environment maps will be explained in section 5. A conclusion will be presented in section 6.

2 Related Work

In order to understand the motivation for a novel ultrasonic sensing approach we review related work:

Wilkes et al. [13] present an algorithm that uses multiple peaks in the return signals from several transducers with broad beams of 70° and overlapping fields of view; but they do not exploit cross echoes from neighbor sensors. A grid based representation and a Bayesian update scheme similar to Matthies and Elfes [9] are used to integrate the multiple return signals from multiple transducers and multiple robot positions.

Peremans and Van Campenhout [10] propose a triaural measurement system composed of one transmitting and three receiving ultrasonic sensors in order to distinguish between planes, corners and edges by means of triangulation. They argue that with triaural sensing much less measurements are necessary to recognize these three basic reflector types in comparison to standard time-of-flight sensor systems.

Lawitzky et al. [7] compare monaural (1 transmitter, 1 receiver), binaural (1 transmitter, 2 receivers) and triaural (1 transmitter, 3 receivers) sensor system configurations. They state that binaural or triaural sensing allows to get more information from a single measurement by sensing several features at once. For this reason, they conclude that these principles have a large potential for increasing speed and precision of environment mapping for obstacle avoidance and navigation.

Jörg and Berg [6] present an approach which allows the simultaneous firing of sonar sensors by eliminating misreadings caused by crosstalk or external ultrasound sources. This is achieved by using appropriate pseudo-random sequences together with a matched filter technique. Polaroid series transducers are used and crosstalk can be either eliminated or exploited to perform triangulation.

Wirnitzer et al. [14] use stochastic coding of the transmitted signals and adaptive filtering of the received signals to avoid mutual interference of the sensors and interference with other ultrasonic sensor systems. The target application is an automotive low-range detection system such as a car parking assistant. Wide-angled sensors are employed and cross echoes are explicitly used. An array of several sensors allows, additional to distance measurements, to localize an obstacle inside the operating range of at least two sensors of the array. Additional shape information can be obtained if the sensors operate in the cross echo mode. Based on this ultrasonic sensing system, Schmidt et al. [12] describe a triangulation-based algorithm which allows to distinguish between circular and plane objects and to identify obstacle edges.

Whereas in [14] and [12] only four sensors are intended to be fixed on a car bumper in distances of about 40 or 50 cm, we use a significantly higher number of sensors (e. g. 24 or 32 sensors) and place them close to each other along the periphery of a mobile robot. In this way we obtain high beam-width overlapping with a number of neighbor sensors and thus can efficiently take advantage of multiple cross echoes. Consequently, we can describe our system as a multi-aural measurement system. Since triangulation based algorithms are not very efficient if the sensor distances are short, we developed a grid-based algorithm to obtain increased information of the environment for such sensor configurations on mobile robots.

3 Specification of the Ultrasonic Sensing System

We explain the ultrasonic sensing system based on a circular sensor arrangement for an experimental robot XR4000 from Nomadic Technologies, which serves at FAW to simulate an automatically guided hospital bed (AutoBed) [1]. The XR4000 at FAW has been additionally equipped with 2 antipodal Laser Ranging Systems from SICK Electro-Optics.

The new ultrasonic sensing system consists of a ring of 24 sensors, spaced with an angular displacement of 15° and mounted on top of the robot (Figure 1). In contrast to other research work ([4], [5], [8]), which widely used ultrasonic range finders from Polaroid Corporation with a detection cone of 30°, we employ wide-angled sensors from Robert Bosch GmbH with an elliptical detection cone of 120° in one axis and 60° in the other axis. The latter sensors were primarily manufactured for automotive use, e. g. for parking pilots [14].

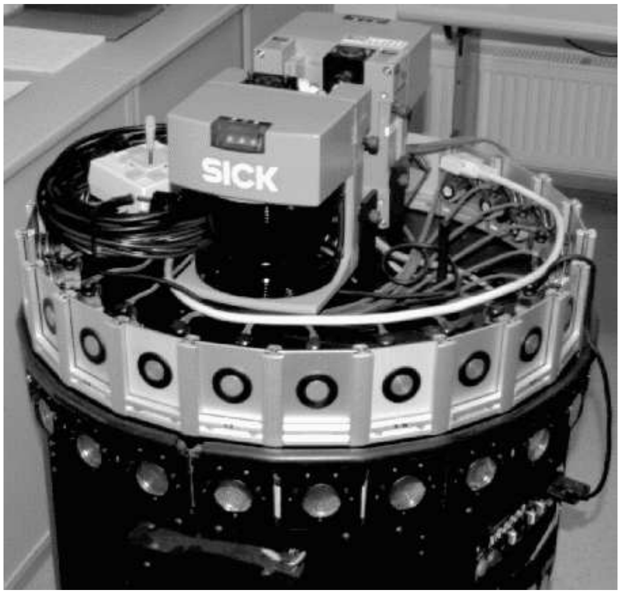

Figure 1: *Sensor arrangement for a circular robot*

On the one hand, wide-angled ultrasonic transducers can detect objects within a broader range, but on the other hand, they make it more difficult to estimate within this broader range the actual location of the object causing the echo. In order to gain a substantial advantage of the broader detection range, we propose to exploit the overlapping of the detection cones from neighbor sensors if they are placed close enough to each other and the angular displacement is not larger than the detection range.

In the case of the new sonar sensing system for the XR4000 we arranged the 24 Bosch sensors exactly above the upper ring of 24 Polaroid sensors this robot is originally equipped with. This facilitates comparison of the two sonar sensing systems. The 2 laser range finders are also mounted on top of the robot in order to scan just above the sonar rings, which allows comparison between sonar readings and laser readings.

We orientate the ultrasonic sensors with the 60° detection range to a horizontal position and we use the 120° range for vertical object detection. With this kind of sensor arrangement we obtain beam-width overlapping up to the third neighbor sensor on each side. We could also orientate the sensors with the 120° detection range to a horizontal position and would then obtain beam-width overlapping with even more neighbor sensors.

If beam-width overlaps up to the third neighbor sensor on each side, every eighth sensor in the ring can be fired simultaneously without mutual interference. The other sensors are in a listening mode during this time. The sensor in the middle of seven passive sensors between two firing sensors will normally not receive any echoes, though this might occur due to multiple reflections.

As a basis for further explanations we define direct and cross echoes as well as their detection ranges. We speak about direct echoes when the transmitting sensor also receives the signal, and we speak about cross echoes when one of the neighbor sensors receives it. With the chosen sensor orientation, the horizontal detection range for direct echoes is 60° and for cross echoes approximately 45°, 30° or 15°, depending whether the first, second or third neighbor sensor is involved, since the angular displacement of the sensors is 15°. Consequently we obtain 24 direct echo paths and 144 (= 6 * 24) cross echo paths. Isometric lines of direct echo paths can be depicted as circular arcs with 60° and isometric lines of cross echo paths as elliptic arcs with about 45°, 30° or 15°.

4 Creating Local Environment Models

As a reference to systematically compare sonar readings with laser readings, a polygonal environment model was extracted from laser range finder data [2]. Regarding the polygonal environment model we distinguish between line segments which describe existent features of the environment and pseudo line segments which arise from the visibility angle of the laser range finders. Figure 2 shows the obtained polygonal environment model, including all line segments, pseudo line segments and their intersections, which are illustrated as solid lines, dashed lines and points respectively.

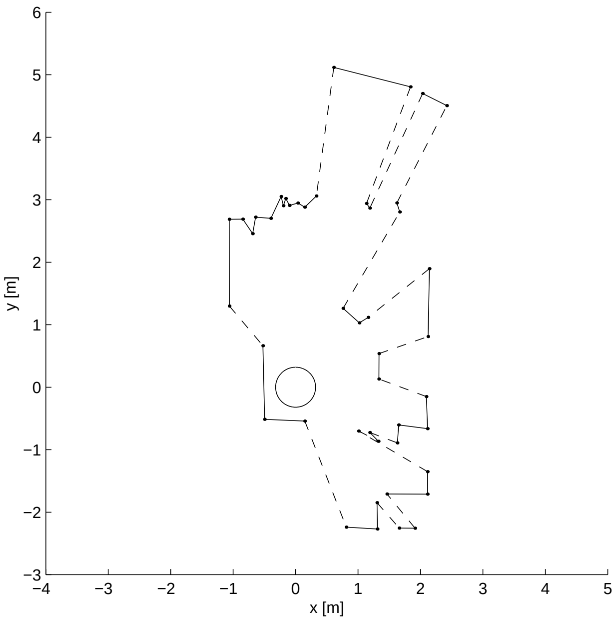

Figure 2: *Polygonal environment model created from laser range finder data*

Figure 3 presents the distance readings from the ultrasonic sensing system together with the polygonal environment model created from laser range finder data. The distance readings for all direct and cross echo paths are depicted as circular and elliptic arcs. Echo paths with no detectable echo within the operating range of the sensors are represented by arcs corresponding to the maximum distance detection range ($d_{max} \approx 2m$).

We now create local environment models from ultrasonic sensor data by extracting straight line elements as follows [3]:

We first represent all circular and elliptic echo arcs within the attainable distance detection range by a predefined number of equidistant points on the arc. Then we assume that an echo could originate from the surface of an object located at each discrete point on the arc and having a perpendicular reflection line to the sensor. We assume the potential reflecting surfaces to be vertical and we represent them by horizontal lines on the level of the sensor, thus implying horizontal echo paths between the sensors and the objects. By using Hesse's normal form of the equation of a line (with the distance ρ from the point of origin in the coordinate system and the angle θ between the normal of the line and the x-axis), the lines can be Hough transformed into parameter space and can be illustrated as points in a ρ/θ-diagram.

We now deploy a 100 × 100 occupancy grid in parameter space with a cell size of $0.04m$ in ρ-dimension and a cell size of $0.0628rad$ in θ-dimension. We accumulate the number of points in each cell and thereafter we apply a 2-dimensional low pass filter to the occupancy grid in order to balance between neighbor cells. Then we search for highly occupied cells in the filtered grid by comparing the occupancy values with a predefined occupancy threshold. According to this, all points belonging to cells with an occupancy value beneath the threshold are discarded and all points belonging to cells with an occupancy value beyond the threshold are used for building clusters. The clusters consist of points belonging to regions of cohesive highly occupied cells that can be determined by a connected components analysis. Finally, we calculate the centers of gravity for the clusters, which represent extracted straight line elements in parameter space. Figure 4 shows the extracted straight line elements in workspace.

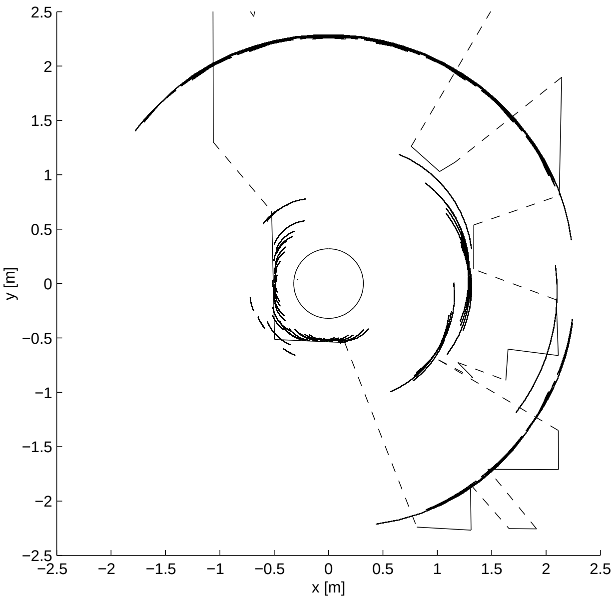

Figure 3: *Distance readings from the ultrasonic sensing system*

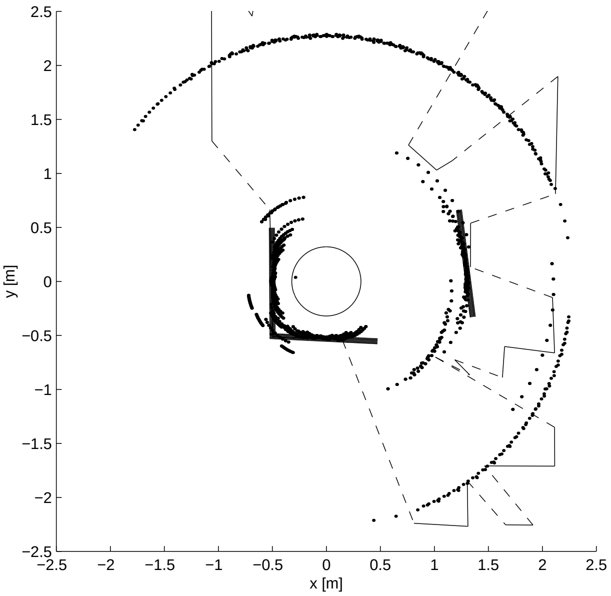

Figure 4: *Extracted straight line elements in workspace (bold lines)*

It can be noted that the three straight line elements extracted from ultrasonic sensor data correspond to line segments in the polygonal environment model created from laser range finder data. The maximum deviation between corresponding lines is $\Delta\rho = 0.0323m$ in distance and $\Delta\theta = 7.4149^\circ$ in orientation. We remark that the three straight line elements of the ultrasonic environment model were obtained by a single ultrasonic scan around the robot from a fixed robot position. Although a chair back-rest at location $(x, y) \approx (0.99m, -0.63m)$ could be detected by some ultrasonic sensors, the number of received echoes was insufficient to extract a straight line element from this robot position. A very few laser scanner samples appear at the location of the chair back-rest as well. However, due to the fact that the scanning level of the laser range finders just coincides with the top edge of the chair back-rest, these samples are of sparse and sporadic occurrence, and the object could thus not be properly modeled in the polygonal environment model created from laser range finder data.

5 Building Global Environment Maps

In order to build global environment maps from ultrasonic sensor data, the robot must move in space and observe the environment from different points of view. On the one hand, this allows to model further distant objects, and on the other hand, it allows to model objects from various perspectives. We assume the boundary of the environment to be of polygonal shape and we model all geometric objects by straight line elements extracted at different robot positions (Figure 5).

The individual extent of each extracted straight line element can be determined. For this purpose, we consider the circular echo arcs of real sensors and the elliptic echo arcs of virtual sensors, which potentially contributed with discrete reflecting points on the arc to the constitution of straight line elements. The involved sensors can be ascertained by investigating the horizontal lines representing potential reflecting surfaces. A sensor is supposed to be involved in the constitution of a straight line element if a Hough transformed horizontal line element associated with a discrete point on the echo arc of the respective sensor contributed to the calculation of the cluster center representing the extracted straight line element in parameter space. Subsequently, we draw perpendicular reflection lines from the extracted straight line element to all real and virtual sensors involved. (The imaginary location of a virtual sensor is in the middle of the two real sensors constituting the cross echo path.) The two outermost perpendicular reflection lines limit the valid range of the extracted straight line elements, which yields straight line segments of defined length.

Figure 6 displays aggregated straight line segments derived from ultrasonic sensor data (bold lines) together with a global laser range finder environment map (thin lines). The aggregated straight line segments were extracted within a typical office at 17 robot positions (numbered crosses) with distances of $0.25m$, $0.30m$ or $0.50m$ to each other. The aggrega-

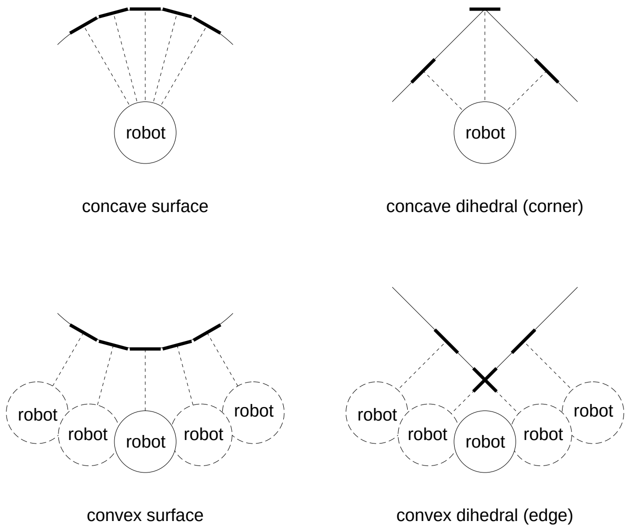

Figure 5: *Modeling of geometric objects by straight line elements*

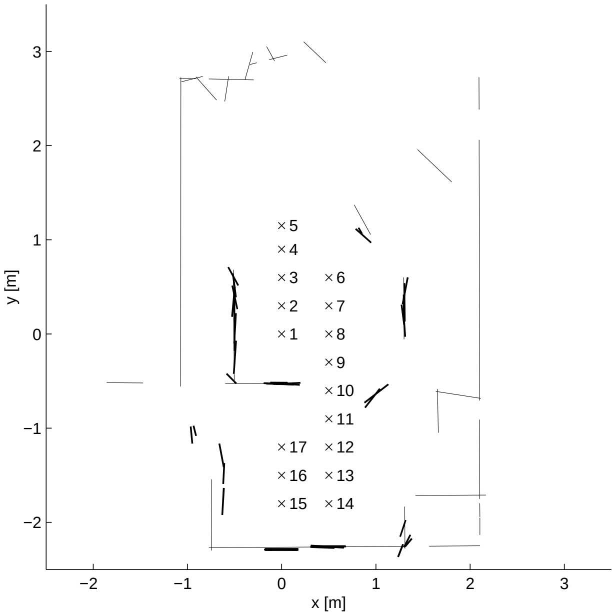

Figure 6: *Aggregated straight line segments (bold lines)*

tion is achieved by transforming all locally extracted straight line segments from robot coordinates into world coordinates and by representing them together as a global ultrasonic environment map. From some view points the above mentioned chair back-rest at location $(x, y) \approx (0.99m, -0.63m)$ could be modeled and is thus represented in the global ultrasonic environment map. The chair back-rest is not contained in the global laser range finder environment map, since it could not be properly modeled in the polygonal environment models created from laser range finder data at different robot positions. A few other inconsistencies appear between the ultrasonic and the laser range finder global environment maps because of varying object extents on different heights.

Figure 7 illustrates the replacement of aggregated straight line segments from different robot positions by merged straight line segments (bold lines). We emphasize that only 17 ultrasonic scans were taken at relatively distant robot positions. More comprehensive global ultrasonic environment maps can be created if more scans are taken at closer robot positions. The developed merging algorithm first clusters aggregated straight line segments in workspace by their midpoints such that within each cluster all segments can be reached by a sequence of segments whose midpoints lie sufficiently close. The distance criteria for the connectivity of midpoints is deduced from the distance the robot has moved between two successive scan positions. Clustering of segment midpoints can, for instance, be performed by a single linkage clustering algorithm. All aggregated straight line segments belonging to the same cluster in workspace can now be merged in parameter space. For this purpose, the straight line segments are extended to straight lines of infinite length and Hough transformed into parameter space. A 100×100 occupancy grid is deployed in parameter space with a cell size of $0.10m$ in ρ-dimension and a cell size of $0.0628rad$ in θ-dimension. Subsequently, it can be proceeded as described in section 4 to obtain cluster centers which represent merged straight lines in parameter space. In workspace, the endpoints of the aggregated straight line segments are projected onto the merged straight lines. The two outermost projection points limit the valid range of the merged straight lines, which yields merged straight line segments of defined length. The same steps are carried out for all clusters in workspace in order to replace all aggregated straight line segments by merged straight line segments.

A slightly modified version of the described approach allows incremental map building by integrating extracted straight line segments iteratively. In this mode of operation the robot only maintains the global environment map and discards the local environment models after integration. For simultaneous localization and mapping (SLAM), the robot position can be updated at each scanning instance by matching the local environment model with the global environment map.

6 Conclusion

Firstly, we have described how wide-angled ultrasonic transducers can be used to obtain substantial

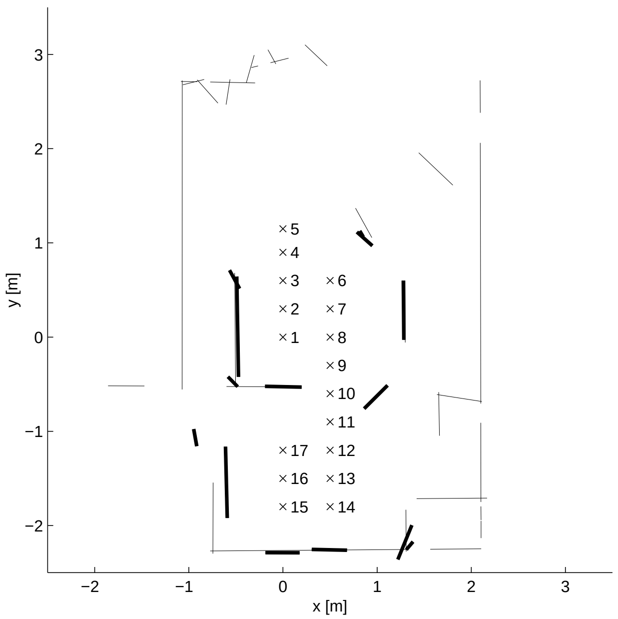

Figure 7: *Merged straight line segments (bold lines)*

information of the environment by exploiting the overlapping of detection cones from neighbor sensors and by receiving cross echoes between them as well as multiple echoes per sensor. Subsequently, we have created local environment models by extracting straight line elements at fixed robot positions from single ultrasonic scans around the robot. Finally, we have spatially integrated the straight line elements derived from different robot positions in order to build a global environment map.

Acknowledgments

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