Comparison of Two Radar-based Scanning-techniques for the Use in Robotic Mapping

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Abstract: This paper will introduce two radar-based scanning-methods and evaluate their application in robotic mapping. Both approaches base upon a rotary joint, but with a fundamentally different angle estimation method to estimate object locations inside the scanning area. The first part of this paper describes the relevant theory behind both techniques and presents our considerations on erroneous influences. The focus of the second part of this paper is laying on experiments. We discuss the results of our experiments and take a look on the usability of both methods for occupancy grid mapping.

1 INTRODUCTION

The following article introduces two scanning methods, for mapping purposes in mobile robotics. Our first method is based on a rotating mono-static radar network, which determines the positions of objects inside the scanning area via a continuously running lateration algorithm. Our second method is based on rotating radar sensors with an angle offset and a determination of the positions of objects through the Amplitude Sensing Ratio (ASR) technique.

A precise model of the environment is essential in many areas of mobile robotics and builds the fundament for localization and navigation. Commonly, popular sensors like laser-scanners, sonar-sensors and stereo-cameras have established themselves as state of the art for most tasks in mobile robotics. Nevertheless, radar sensors frequently appear in field and rescue robotics (Adams et al., 2012) (Tadokoro, 2009), but are seldom used to perform tasks like mapping and localization. Radar can penetrate certain materials, basically non-conductors, which provides advantages in dusty, foggy, rainy or other harsh environments. But, limited resolution, noisy data, influence of optical effects like refraction, reflection and absorption make the application in mobile robotics challenging.

The use of radar sensors in mobile robotics is challenging but not impossible. The first appearance of radar sensors in the robotic community is tracing back to the Australian Centre for Field Robotics in the early nineties, where fundamental work on probabilistic SLAM algorithms in combination with radar was developed (Clark and Whyte, 1998). Because of their limited resolution and other aforementioned drawbacks, radar sensors are not very suitable to use in indoor environments. Nevertheless, (Detlefsen et al., 1993) were investigating the use of radar sensors in an industrial environment and (Marck et al., 2013) in an office. As far as we can see, most radar sensor principles in mobile robotics are based on mechanical beam-forming. Usually, the radar beam is focussed via a parabolic antenna and panned mechanically over the environment. Electrical beam-forming through phased array antennas is not seen very often in mobile robotics rather in automotive systems of the car industry.

Besides beam-forming techniques, position estimation can be achieved through lateration, which is a common technique in radar networks for aircraft surveillance. Lateration is a measurement method, where the position of a point target is calculated of distance information from n Sensors with known locations. The term trilateration refers to the measurement of three distances to define the position of an object (in contrast to triangulation, where three angles are used to calculate an object's position). The estimation of surfaces with ultra-wide band (UWB) radar networks has been studied experimentally in lab environments, especially with lateration by (Mirbach and Menzel, 2011) , envelopes of spheres by (Kidera et al., 2008) and inverse boundary scattering algorithms by

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(Sakamoto, 2007). But, we can not see a link to the field of robotic mapping with mobile robots, where laser scanners are dominating. ASR techniques on a rotary joint are common techniques in ground-based radar systems for air-traffic control (Agilent, 2014).

For our experiments, we use frequency modulated continuous wave (FMCW) radar sensors, which provide distance but no angle information of objects inside the observation area. The sensors work in 24 GHz ISM band and accordingly are limited in Germany to a bandwidth B of 250 MHz, which corresponds to a theoretical distance resolution Δd of 0.6 m in dependency of the speed of light c_0 (See Equation 1).

$$\Delta d = \frac{c_0}{2B} \tag{1}$$

The resolution Δd of a radar sensor is equal to its minimum detection range. The availability of sensors with a high resolution depends on national and international bandwidth regulations. An UWB channel between 22 GHz to 26,65 GHz has been closed in 2013, but is moved to 79 GHz for automotive purposes recently (Schmid and Neubauer, 2007, p. 20).

A radar's resolution is its capability to distinguish objects. If the difference between the radial distances of two or more objects to the sensor is less than its resolution, then the sensor merges the two or more distance information to one. Additionally, the detection of objects depends on their radar cross section (RCS) and the background noise of the environment.

This article is organized as follows. In Section 2, we present a short overview, how position estimation via lateration and ASR techniques are solved. Besides the theory and introduction to common terms, we explain the ghost target and non-point target problems in radar networks which are based on lateration. Additionally, we describe influences of errors related to the power and range measurement accuracy of radar sensors. The reader who is familiar to these topics might go directly to Section 3, where the sensor principles are described in the beginning. Further in this section, we will describe our experiments, which results are discussed in Section 4. A brief summation of the obtained knowledge is given in Section 5.

2 MATERIALS AND METHODS

Estimating the position of an object with a radar network can be solved by standard lateration methods or ASR techniques. In order to define an object's position in two-dimensional space, at least two sensors are necessary. In case of lateration, two radii from two range measurements at different positions can break down the object's position to two possible locations. Usually, only one location is plausible due to the antenna's direction. In case of the ASR technique, the position of an object can be estimated through the difference in the receiver power at two antennas which are located at the same position but pointing into different directions. In this paper, we investigate the usability of both methods in combination of a rotating scanning unit to generate occupancy grid maps.

2.1 Principle of the Lateration Technique

Lateration is a measurement principle to estimate the positions of points with distance informations to a known locations. If the distance to an unknown point is given, then this point must be laying on a radius (two-dimensional case) around our location. If two locations are known, then two radii result in an intersection, which is the position of the point. Figure 1 demonstrates the basic of operation of the lateration principle.

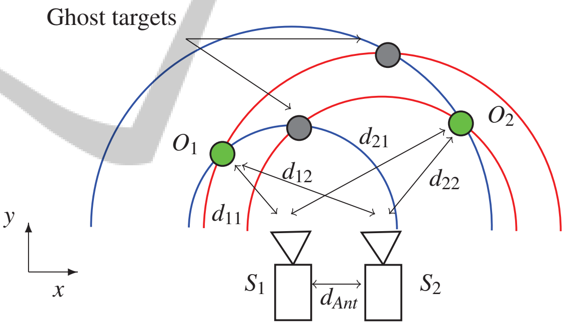

Figure 1: The position of objects O can be estimated via the distances d, which are measurend from different sensors. Ghost targets represent a geometrical ambiguity.

For a two-dimensional space, n objects O_i (i=1..n) and m sensors S_j (j=1..m) result in $m \cdot n$ equations of circle. The euclidean distances between the sensor positions $S_j(x_{Sj}, y_{Sj})$ and the object positions $O_i(x_{Oi}, y_{Oi})$ are given by the following equations:

$$\begin{aligned} (x_{S1} - x_{O_i})^2 + (y_{S1} - y_{O_i})^2 &= d_{i1}^2 \\ (x_{Sj} - x_{O_i})^2 + (y_{Sj} - y_{O_i})^2 &= d_{ij}^2 \\ &\vdots \\ (x_{Sm} - x_{O_i})^2 + (y_{Sm} - y_{O_i})^2 &= d_{im}^2 \end{aligned} \tag{2}$$

The distance between an Object O_i and an Sensor S_j is defined as d_{ij}. The general description of the linear system of equations can be achieved through subtracting the last equation (j=m) of Equations 2 from all other equations ($j = 1 \dots m-1$) (Schneider, 2013, p. 8).

$$\begin{pmatrix} 2\cdot(x_{S1}-x_{Sm}) & 2\cdot(y_{S1}-y_{Sm}) \\ 2\cdot(x_{S2}-x_{Sm}) & 2\cdot(y_{S2}-y_{Sm}) \\ \vdots & \\ 2\cdot(x_{Sm-1}-x_{Sm}) & 2\cdot(y_{Sm-1}-y_{Sm}) \end{pmatrix} \cdot \begin{pmatrix} x_{O_i} \\ y_{O_i} \end{pmatrix} = \begin{pmatrix} x_{S1}^2 - x_{Sm}^2 + y_{S1}^2 - y_{Sm}^2 - d_{i1}^2 - d_{im}^2 \\ x_{S2}^2 - x_{Sm}^2 + y_{S2}^2 - y_{Sm}^2 - d_{i2}^2 - d_{im}^2 \\ \vdots \\ x_{Sm-1}^2 - x_{Sm}^2 + y_{Sm-1}^2 - y_{Sm}^2 - d_{im-1}^2 - d_{im}^2 \end{pmatrix}$$

$$A \cdot \vec{o}_i = \vec{d}_i \tag{3}$$

In reality, every sensor outputs measurement values with errors. The difference from the true value occur due to limited accuracy and resolution. Hence, the system of equations does not result in one single solution if it is overdetermined. The system of equation gets overdetermined if the radar network has more sensors than the dimension of its measurement space. Commonly, overdetermined systems of equation with no single solution get resolved through regression. The most popular solution is the least mean square method (Schneider, 2013, p. 8) (Fölster, 2006, p. 39).

Like it can be seen in Figure 1, ghost targets can appear in radar networks. Ghost targets represent a wrong data association, because like it is shown in Equation 2, four objects can be theoretically calculated if two objects are placed in front of two sensors. Ghost target appear if the sensor's resolution is smaller than the half antenna distance (d_{Ant}). A detailed derivation of the ghost target cases can be seen in (Rabe et al., 2009).

In order to resolve the ghost target problem, (Fölster and Rohling, 2005) present the button-up data association method. In two-dimensional space, at least three radar sensors are required. In order to distinguish ghost objects from real objects, the observation area in front of the sensor network is discretized into a finite set of possible object positions. Then, a simple minimum distance calculation is done. For each point, an error value $E(x,y)$ can be calculated from the square of the minimum distance of the point to the sensor S_j minus the distance d_{ij} between object O_i and sensor S_j, summarized over all n sensors (See Equation 4).

$$E(x,y) = \sum_{i=1}^{n} \left[\min_{d_{ij} \in OL_i} (d_{ij} - d(x,y)) \right]^2 \tag{4}$$

This calculation results in the lowest error values at points that are closest to the real objects. Afterwards, a threshold distinguishes likely ghost target from real objects.

2.2 Principle of the ASR Technique

Every location in front of an antenna, is connected to a different antenna gain factor. For example, if we walked on a radius around a loudspeaker with closed eyes, we would have a feeling when we would be walking directly in front of it, because then the sound appears to be louder. A similar effect is used for the ASR technique. If we point two radar antennas in slightly different directions, then the power at the receiver antennas would not be equal, due to different antenna gains.

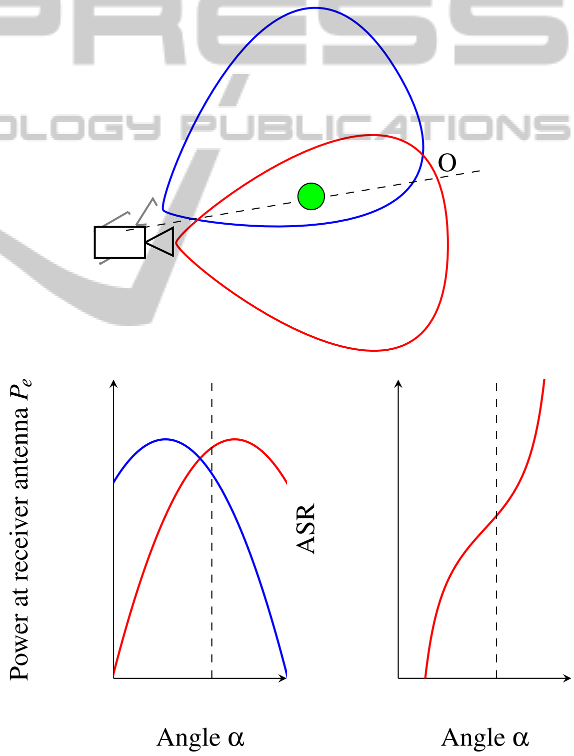

Figure 2: The position of an object O inside the observation area can be estimated via the difference of power of into different direction facing receiver antennas.

The measured power at the receiver antenna P_e of an object depends on the angle α between antenna and object. Two sensors, which are facing into different directions, but placed at the same location, measure the same distance but different power P_e. If a function for the power in dependency of the angle position of the object is given, then the object's position can be estimated via the ASR function (See Figure 2).

The angle of an object inside the observation area can be estimated through the Amplitude Sensing Ratio (ASR). In a two-dimensional case, the ASR for the azimuth is defined by a delta signal (Δ) and a sum signal ($\sum$), which are derived from the powers at the receiver antennas (Bühren, 2008, p. 34-35).

$$ASR = \frac{\Delta}{\Sigma} = \frac{P_{e1} - P_{e2}}{P_{e1} + P_{e2}} \tag{5}$$

In order to obtain information in three-dimensional space, the elevation needs to be estimated through an additional sensor beam.

2.3 Consideration on Erroneous Influences

Estimating the position of objects with lateration and ASR requires sensors with very high range or power accuracy. Nevertheless, every sensor has a measurement error. In case of lateration, the maximum position measurement error σ_{PD} can be approximated by the maximal range measurement error $\sigma_{R_{max}}$ of all sensors and the angle α (See Equation 6). The range measurement accuracy is defined by the root-mean-square (rms) measurement error σ_R (Curry, 2005, p. 167). Figure 3 clarifies the relation between the range measurement error σ_{Ri}, the angle α and the position measurement error σ_{PD} graphically.

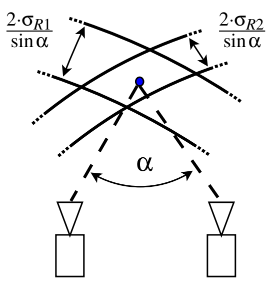

Figure 3: Area of ambuguity, which is caused by the two rms-errors σ_{R1} and σ_{R2}.

If the ratio between distance of the object and the antenna distance gets higher, then the rhomb-shaped area of ambiguity gets wider. In Figure 5, it can be seen that the area of ambiguity of a point target appears almost to be a line. From Equation 6, it can be seen that the accuracy of a lateration based radar network is getting very bad at the sides of the sensor network, where α is approaching zero.

$$\sigma_{PD} \approx \frac{\sigma_{R_{max}}}{\sin\alpha} \tag{6}$$

The rms error σ_R depends basically on the signal-to-noise ratio of the received signal. The signal-to-noise ratio is higher and results accordingly in a better accuracy, if the RCS of an object is higher. Consequently, our radar principle results in better position estimations for objects with high RCS. But, objects with a high RCS are entering the observation area of a rotating scan earlier from the sides then objects with a lower RCS, hence an object with high RCS suffers more from the position estimation error σ_{PD}.

Besides the range measurement accuracy, the resolution of a radar sensor has important impact on the reliability of the scan results. A radar sensor will not distinguish two point targets, if they are inside a so called resolution cell. For example, a radar with a resolution of 1 m, can not differ between two or more objects which are inside a band, with the wide of 1 m, around the sensor and would output the detection of only one range value somewhere between those two objects. The lateration technique results only in correct position estimation if all sensors of the radar network are measuring the same distance to the same point. But, single point targets are very rare in standard environments. Usually, every sensor of a radar network measures the distance to a different point target, which results in wrong position estimations.

The precondition for the ASR technique is the placement of sensors at the same location. The closer the antennas are placed to each others, the more exactly is the result and the same centres of reflection of a target can be assumed in a ASR radar network. Unfortunately, the accuracy and resolution of the receiver power P_e can not be defined, because it is depending on the RCS of the object as well (See radar equation). There is a fluctuation of the RCS, which can be explained by the Swerling Models. A. Ludloff explains in (Ludloff, 1998, p. 3-14) how the fluctuation can be modelled. The model is based on the idea that one radar target exists of multiple reflector elements, which are distributed over the volume of the target. The model assumes the reflector elements to be isotropic and with the same RCS and neglects the effects of reflection or shadows among themselves. Through overlapping of reflected radar waves on this multiple isotropic reflector elements, phase differences result in complex interferences. This model explains the appearance of high fluctuation of the RCS (and accordingly the receiver power), even if the aspect angle is changed only slightly. To sum it up, an exact estimation of the RCS, even of standard geometries, is not possible in the real world and fluctuation effects disturb the reliability of the position estimation results via ASR techniques.

3 EXPERIMENTS

The following section describes first experiments with both sensor principles. Therefore, two scans at the same location but with different sensor principle have been performed. Both sensor principles, the lateration technique and the ASR technique, have been set up on a rotating platform. Our radar sensors work with a center frequency of 24 GHz with a bandwidth of 250 MHz, which is the reason for the low resolution. Furthermore, our radar beam is not very focussed. The setup of both experiments can be seen in Figure 4.

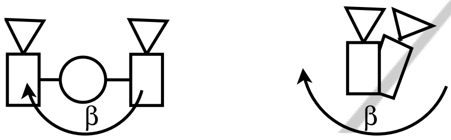

Figure 4: The left drawing shows the scanner with the lateration setup. The right drawing presents the ASR setup. Both setups are based on a rotating joint and its angle position β.

Our first scans have been performed in an indoor environment. We neglect that we perform a 2D scan inside a 3D environment. In order to have a landmark, we were placing a point target (an aluminium corner reflector), at the same hight like our sensor unit, inside our scan area. A serial of scans of a hallway with both principles has been performed for further evaluation.

3.1 Single Scan with the Lateration Technique

In order to evaluate the sensor principle, we were performing first scans of standard objects in an indoor environment. The goal of the first experiment is to find out about error influences in our sensor principle. As mentioned before, a limited resolution can be problematic in an indoor environment, like our office. There might be metallic radiators, steal-beams behind the walls, computer towers and many other objects that can have a RCS huge enough of being detected by our radar sensor. Our first scan results are presented in Figure 5.

The measurement contains the accumulation of five 360° degree scans with a step size of 0.7° degrees. Not every measurement cycle leads to a successful position estimation. A successful position estimation can be processed if both sensors detect an object.

The probability of occurrence of two objects, with a smaller difference of their radial distances to the sensor than the radar's resolution, is high, hence we can rarely trust our scan results, if performed in an indoor environment. For fundamental research, our radar sensors with an resolution of approximately 0.6 m are sufficient.

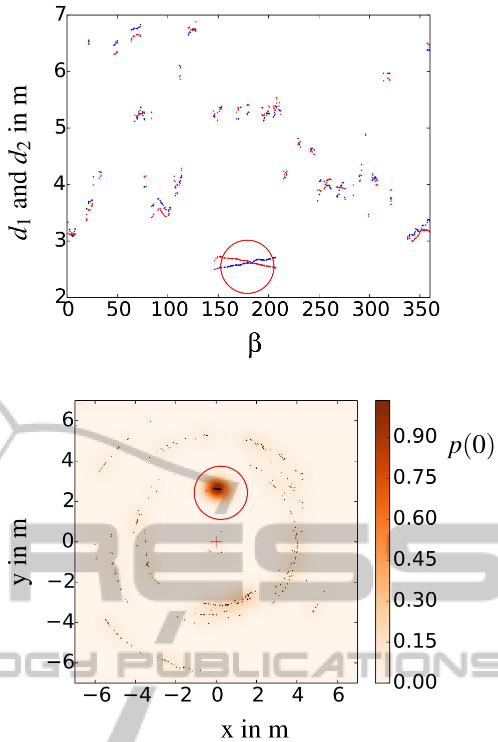

Figure 5: Above: This diagram presents the distance informations of the two sensors during a 360° scan of the rotating platform. It can be seen that the corner reflector is the only trustful point target in our office environment (See red circle). The characteristics of the distances of the two sensors d_1 and d_2 is caused by the rotation of the platform, where one sensor is approaching and the other sensor gets more far away during a rotation. The distances of non point target do not have a symetric characteristic. Below: This diagram depicts a top view on our scanning area. The red cross represents the location of the sensor unit. The point target results in an accumulation of distance values. The remaining spread is only cause by the sensor measurement error σ_R. Accordingly, the point target has the highest probability $p(0)$ for its correct position estimation.

3.2 Single Scan with the ASR Technique

For our investigation on the ASR technique, we were using exactly the same scene and same sensors. Instead of placing the sensor at two different positions, the ASR technique works the best if both sensors are placed close as possible, but with a small shift regarding the antenna direction. Our scan results are presented in Figure 6.

The measurement contains the accumulation of

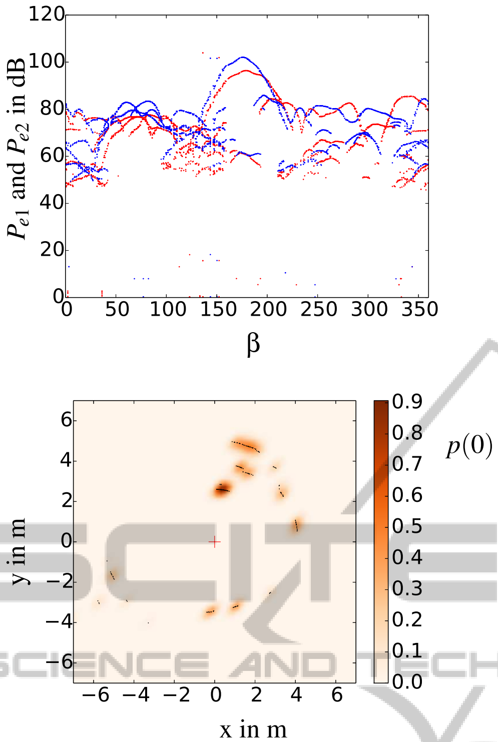

Figure 6: Above: This diagram depicts the power at the receiver antennas P_{e1} and P_{e2} during a 360° scan. The non-point target effect does not effect the results. The main error influence is caused by the low resolution and the wide beam size of the radar sensor. An angle estimation of objects through the ASR in an traditional way is impossible, because of the non-uniform distribution of the power values. Below: This diagram presents a 2D scan of our office environment via the ASR technique. The red cross shows the location of the sensor unit.

five 360° degree scans with a step size of 0.7° degrees as well. The distribution of the powers at the receiver antennas is not suitable for a traditional ASR based position estimation, because the high amount of objects does not allow to develop regression functions for the ASR of our experiment. Nevertheless, we can assume to have an object perpendicular in front of the sensor unit if the ASR is close to zero. The ASR method requires, besides calibration of the range measurement of the sensors an calibration of the antenna directions.

3.3 Scan of Hallway

In order to compare the suitability for robotic mapping of both sensor principles, a serial of scans has been recorded of a hallway. To avoid influences of control and odometry errors of our robots, all scans have been performed at known poses (See Figure 7).

The locations of the sensor unit have been chosen under the consideration of the minimal detectable distance of the radar sensors, which is equal to their resolution. The minimal detectable distance is a reason, why radar sensors with low resolution are only suitable for outdoor environments with larger scale.

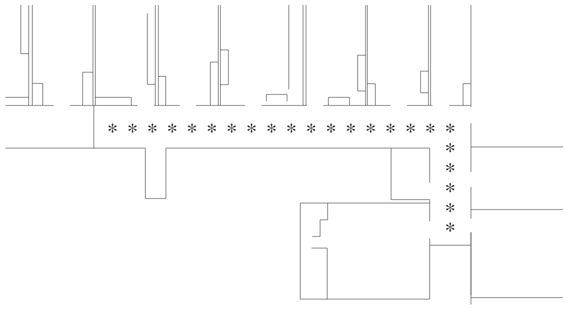

Figure 7: Ground truth of the office environment with scan positions of the sensor unit.

Like mentioned before, a 2D experiment in performed in a 3D environment, hence metallic objects with rectangular shape elements, like office lamps, get layered into the map as well. Occupancy grid maps, which are obtained via classical inverse sensor model (Elfes, 1989), are presented in Figure 8.

Figure 8: Above: This occupancy grid map is built from raw data of the lateration technique. The wide spread of the sensor data is caused by non point target situations. Below: This map is obtained from of the ASR technique.

4 RESULTS AND DISCUSSION

This section will give an interpretation of the obtained results of the experiments, which have been described in Section 3.

Figure 5 presents the results of one single scan inside an office environment, where a point target has been placed. The position of the point target gets estimated very well and the remaining spread of the estimated points is caused by the range measurement error σ_{R_i} of the sensors. Tests with different distances between corner reflector and sensor unit have proven, that a rhomb-shaped area of ambiguity is achieved. This has been explained for a static case on Figure 3. The position of non point targets gets not estimated very well. The sensors measure distances to different points. This results in a non symmetric characteristics of the distance values d_1 and d_2. Consequently the lateration algorithm calculates the wrong positions.

Figure 2 presents the result of a single scan with the ASR technique. The corner reflector gets the highest accumulation of detected object locations, like in case of the lateration technique. Theoretically, the characteristics of the receiver powers P_{e1} and P_{e2} supposed to have a phase difference equal to the angle shift of the antenna directions. But, the fact that we can not place both sensors in exactly the same point leads to the fact that again we can not measure exactly the same point target. Furthermore, we can not guarantee both antenna diagrams to be exactly the same due to fabrication tolerances. Nevertheless, we can assume a position of an object, if the ASR is close to zero.

In order to evaluate if the lateration and ASR technique are suitable for robotic mapping, we built two occupancy grid maps with an inverse sensor model (Thrun et al., 2005, p. 279-300) which we applied on the raw data that has been recorded during a scan of a hallway (See Figure 7). The wide of the hallway is approximately 2m and it has a curve at 20m. Figure 8 displays both results. The ASR technique results in a quite good map. Consequently, we see possibilities to map even indoor environments with radar sensors of low resolution. The minimum detection range, which is equal to the resolution of the sensor, should be considered (See Equation 1). To enhance the result of the lateration technique, more sensors should be used. In general, both principles suffer from bad resolution of the radar sensors. Optical effects like double reflections inside a narrow hallway have a negative effect on the methods as well.

5 CONCLUSION

Robust localization and navigation in hazardous and tough environments are still a difficult issue in field robotics research. Dust, rain, fog or inadequate illumination are conditions, which make popular sensors, such as laser scanners or cameras, not suitable. Radar overcomes the aforementioned difficulties.

In this article, we were investigating two new scanning methods for mobile robotics and took a closer look on failure influences. We were focusing on three influences. First, the range measurement error of the sensor itself. Second, the influence of wrong position estimation due to non point targets regarding the lateration technique. Third, we investigated if the received power of the receiver antenna is reliable for position estimation, in an environment with multiple targets. We discovered that the influence of non point targets has a huge influence, especially in a setup with only two sensors. This effect can be scaled down by increasing the number of sensors.

There exists several mapping algorithms. An overview is given by Thrun in (Thrun, 2002, p.7). Thrun introduces algorithms, which are suitable for mapping with unknown robot poses, which is named simultaneous localization and mapping (SLAM). In this article, we focus on mapping with known poses, which is simpler. But, mapping with known poses is leading to more promising results, because odometry and control errors do not influence the map. Occupancy grid mapping with Bayes filter is the most popular probabilistic representation of a map. Our proposed scanning methods are suitable for occupancy grid mapping with a classical inverse sensor model. As far as we can see, the ASR technique results in better maps.

The proposed radar-based scanning methods are an alternative to mechanical and electrical beam-forming methods. Mechanical beam-forming techniques require an antenna and electrical beam-forming techniques need phase array radars, which are commonly more expansive. Although no antenna construction is required, our methods needs more than one sensor.

From one single 360°-scan of a radar-scanner, which pivots mechanically a focused beam over a surrounding, a more continues distribution of the measurement can be expected. Our proposed methods base on antennas with a very large beam width and objects with a high RCS occlude a larger scene consequently. However, the lateration technique is recording more than one measurement of an object during one scan rotation, which raises the possibility of a correct detection of an object. An advantage over techniques with focused beams is the possibility to perform 3D scans as well, which would be mechanically complicated in case of mechanical beam-forming techniques and is only known in combination with electrical beam-forming radars. Unfortunately, the lateration technique suffers more from bad accuracy and resolution, wrong calibration or asynchronism of measurements than traditional techniques. The detection of different centres of reflection is the main problem of the lateration technique. The ASR technique results in pretty well raw data, although a traditional ASR curve approximation is not possible in an environment with multiple objects. In this article we propose the simple solution of filtering all data, with a threshold close to a ASR of zero. This results in less wrong position estimations than the lateration technique.

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