Indoor Radar SLAM

A radar application for Vision and GPS Denied Environments.

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***Abstract* — Indoor navigation especially in unknown areas is a real challenge. Simultaneous Localization and Mapping (SLAM) technology provides a solution. However SLAM as currently based on optical sensors, is unsuitable in vision denied areas, which are for example encountered by first responders. Radar can be used to overcome this drawback, however no fully suitable solutions are reported yet. This paper presents radar SLAM technology for indoor use and shows its operational applicability. Modern electronically scanning antenna technology is used to obtain a portable radar front-end that in combination with FMCW processing provides a high resolution 2D radar image. The radar image is fed to a mapping and localization algorithm. An iterative closest point algorithm is used to determine the radar location and movement, whereas a particle filter optimizes measurement performance. The SLAM radar is evaluated under test conditions to reveal its mapping capabilities and under operational conditions in the EU-DITSEF project, to reveal its added value for human operators. The radar provides a reliable map and location functionality.**

Keywords—FMCW radar, self localization, SLAM, first responder

I. Introduction

First responders ignore exploration in vision denied environments unless under the most dire circumstances. This paper proposes technology that aids in navigation and exploration in the harshest of vision denied environments. Navigation and exploration in vision denied environments is usually avoided due to dangers associated with the impossibility of timely escape due to lack of orientation and knowledge of the current situation.

Adequate and up to date map information is a prerequisite for safe vision denied exploration and navigation. Mapping information is available for any outdoor area. In the civil domain mapping information is abundant, for example Google™ maps and TomTom®, and military information generally exceeds this level. However, navigation in vision denied indoor environments is hampered by the lack of adequate mapping sensors. Current portable mapping sensor system are based on Lidar or (stereo/infrared) camera systems [15][16] and do not provide imaging capabilities in environments filled with smoke.

A specific EU study devoted to sensor systems for first responders, has been conducted, This study, DITSEF [1], has paid specific attention to indoor navigation and location. Indoor radar SLAM was one of the technologies considered. TNO acted as partner in the study and evaluated the radar concept. This paper illustrates radar technology that A) is capable of near-real-time radar mapping without additional devices apart from the carried device and B) provides an outlook on future systems vision denied environments navigation aids.

II. Background on self Localization and radar

Simultaneous Localization And Mapping (SLAM) is a technique that solves the twofold problem of A) mapping of an unknown environment and B) self-localization in this environment [14]. Illustrative application examples are the Mars rovers and the upcoming autonomous car from Google [5].

Around the start of the millennium SLAM provided a breakthrough for robot localization and mapping with the fastSLAM algorithm [4] using highly accurate lidar data, which provided the first robust algorithm to self-localize and map. Sensors in the SLAM literature were ultrasonic, lidar and IR sensors. The last decade the SLAM sensors have been extended to video [3] and processing has improved in efficiency and accuracy providing the driving technology (literally) for the Google autonomous cars [5].

SLAM using radar remains rare, predominantly because no commercial of the shelve radar sensor provides the 360 degrees panoramic high resolution range information that lidar systems provide. Systems reported in literature are in lab build. Searching for literature on SLAM using radar with the terms “Simultaneous Localization and Mapping” and either “Radar” or “Microwave” provide some results. In 1991 a rotating 94 GHz FMCW radar (bandwidth 750 MHz ~ 25 cm range resolution and 1.5° azimuth resolution) illustrated the imaging possibilities of such a system [6]. In 2003 an UAV SLAM radar solution was used map an area of 10 by 8 km [7]. The first ground based outdoor SLAM system was shown in 2004 [8]. In second ground based radar system (2009) showed results comparable to the lidar results from a decade ago with the fastSLAM algorithm [9], but on a larger scale (outdoor vs indoor). In 2010 a sea based radar system mapping coastal terrain is published [10]. To the authors knowledge no indoor radar SLAM solution has been published yet.

III. System Description

The SLAM radar system contains a rotating antenna, a 24 Ghz frontend and processing.

A. Front end description

The indoor SLAM system (Figure 1) contains a rotating antenna (480 RPM), an 24 GHz front end (Figure 2) and data acquisition hardware. This system is used for the mapping experiment given its high temporal and spatial resolution.

For evaluation by use of first responders, the system of Figure 1 is too bulky. An electronically scanned phased array radar is used. This radar lacks some resolution, however its small size (10*20*1 cm) and weight combined with the absence of moving parts made it an excellent candidate for evaluation under operational conditions. Moreover, the radar output is digitized and available on USB, which also provides power. The radar can be operated in combination with any Windows or Linux PC.

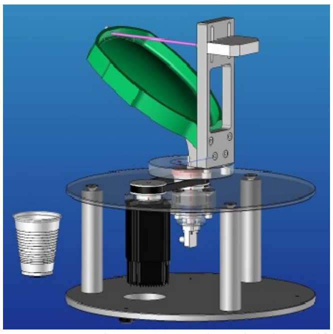

Figure 1 the TNO SLAMradar system, the plastic coffee cup is for size reference.

Figure 2 The TNO 24 GHz front-end

B. Radar Processing

Radar processing has two steps: the processing for A) a single radar frequency sweep and B) the processing of a single 360 degrees scan of 500 sweeps. For A, the FMCW radar signal is fed to a Fast Fourier Transform (FFT) and normalized to determine the range with maximum reflected power. Although the radar might receive reflected power of multiple objects in a single sweep we only consider the range with maximum reflected power as the detected range.

All sweeps made during a single rotation of the antenna are combined into a 360 degrees horizontal scan. Indoor radar suffers from reflections, sidelobe detections and unwanted effects. This results in noise in the sweeps and so in the scan. To reduce noise in the 360 contour scan we remove outliers by removing sweeps from the scan whose neighbors either produced an erroneous range detection or have an detected ranges further than a set threshold from the sweep under consideration. Once the 360 degree scan has its noise removed it is ready for the SLAM algorithm.

C. The Mapping algorithm

The Grid Mapping Particle Filter (GMPF) approach is used [11]. Key to estimate A) the map of the unknown environment and B) the travelled trajectory is the joint posterior probability distribution $p(m, x_{1:t}|z_{1:t})^{p(x_{1:t},m|z_{1:t},u_{1:t-1})}$. Where $x_{1:t}$ is the trajectory from start till time t. The unknown map is m and $z_{1:t}$ are the radar scans from start till time t. This particle filter is considered a Markov process and makes use of the following factorization:

$$p(m, x_{1:t}|z_{1:t}) = p(m|x_t z_t).p(x_t|x_{t-1}, z_t).p(m, x_{1:t-1}|z_{1:t-1})$$

This allows a successive separate trajectory and map estimation. The GMPF models the potential trajectories (posterior $p(x_t|x_{t-1}, z_t)$) with a particle filter $p(x_{1:t}|z_{1:t})$. Each particle represents a possible trajectory and a corresponding map. To estimate posterior $p(m|x_t, z_t)$ an occupancy grid map [13] is used to integrate z_t and x_t into m. The GMPF incrementally processes the sensor observations to estimate the trajectory and the map. Both posterior estimations are explained below.

1) Motion estimation and weighted resampling

The standard particle filter approach is to update each particle with a sample from a proposal distribution. Weigh each particle for its quality and resample from the weight distribution to select the fittest particles. In some cases this might be an inefficient method when a lot of particles are updated into low weighted areas. The GMPF samples particles only from highly weighted areas is illustrated in [11]. This "weigh before updating" particle filter has a more accurate trajectory and map estimate and is more efficient (uses less particles to get the same quality). This method is applied in our system.

To determine posterior $p(x_t|x_{t-1}, z_t)$ the GMPF combines A) a motion estimate and B) a likelihood determined from a match between the current scan and the immediate surrounding map (an aggregate of all scans). To explain this method in detail is beyond the scope of this paper. Interested readers are referred to [11]. We will explain some details of the motion estimation because this differs slightly from the lidar implementation, because lidar rangefinders are more accurate than radars.

As in [11] we use the Iterative Closest Point algorithm (ICP) a well-known algorithm that is used to determine the rotation and the translation that best aligns two 2D or 3D point clouds [12]. Applying ICP to two successive scans (illustrated in Figure 3) provides an estimation of the angle of rotation and 2D translation of the radar between the two scans [12]. Radar scan matching is less accurate than lidar scan matching due to clutter, reflections or missed detections. We compensated by adding artificial variance to the ICP motion estimation. This required an increase in particles when compared to the number of particles often mentioned in lidar SLAM.

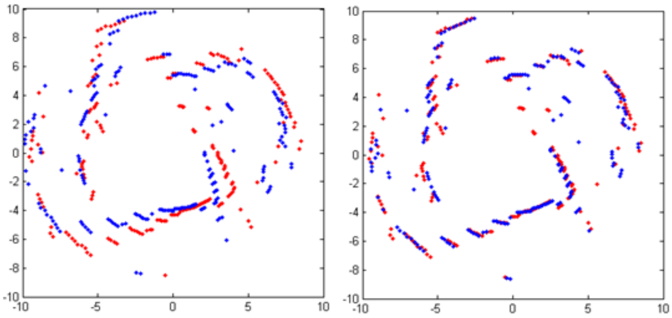

Figure 3 The ICP algorithm finds the best correspondence between two successive panoramic scans to determine the rotation and translation between the two scans.

2) Map Construction

Occupancy grid mapping (OGM) is used to estimate posterior probability $p(m|x_t z_t)$ [13]. OGM uses a fine grid to model a 2D map. Each grid cell models the probability that it is either occupied or free using a Bayesian filter and logodds [14]. The area in the radar beam before the range detection is probably empty and the area at detection is probably occupied. Range accuracy, beam width and the range of the detection determine this detection area. This is illustrated in Figure 4. Using the position estimation the panoramic scans are integrated in the grid map resulting in a map.

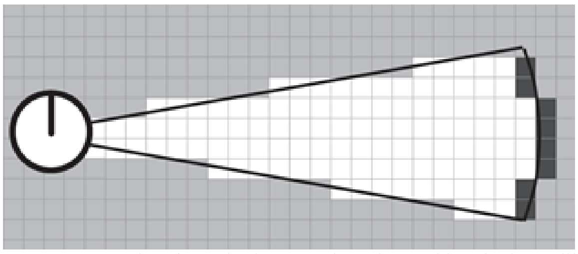

Figure 4 A map update for a single range detection. White pixels are likely empty space. Dark is likely occupied area. Grey is unknown. The properties of the beam are determined by radar/antenna specifications.

IV. Experimental Setup

Two experiments were done. The first was a proof concept mapping test. The second was a proof of concept application tested with firemen.

A. *Mapping proof of concept*

We choose the cantina of our laboratory as a test site. It has various objects that we expected to have different effects on the mapping capability: Brick walls, window walls, wooden dividers, metal radiators, a raised area, a wooden bar, a small pillar and two lamps placed on metal tubes. The system was positioned on chest height and was moved along two lines as is shown in Figure 7.

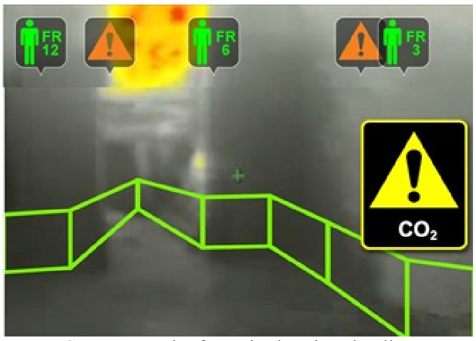

Figure 5 DITSEF HMI. The fence is showing the distance to the wall.

B. *Application concept*

The indoor SLAM radar was evaluated in the EU DITSEF project. The project not only provided a platform for the radar, it also provided a sophisticated HMI (Human Machine Interface), a necessity to evaluate the DITSEF system under operational conditions. The HMI concept output is shown in Figure 5 and is integrated on a small head-mounted display worn by the first responder. To allow evaluation of human performance using the radar, the small electronically scanned radar front-end was used. The radar image is converted to a fence, thereby indicating the free space for the firemen. The fence provides an easy way of indicating the distance to objects. The fence is overlaid with the IR image (IR has smoke penetrating properties, depending on the wavelength). Symbols are showing the position of other first responders and of known dangers. In a series of test runs the system was evaluated.

V. Results

A. *Mapping*

An example of the results of mapping our cantina is shown in Figure 7, using 24 GHz. The system shows good ability to map wall and other relevant structures. Also a variety of materials present are detected. Around point B the walls are lined with metal radiators, which are clearly visible. The Northwest corner is a raised area, the North side are brick walls, with a wall coming down. Two spots can be identified, these are lamps on metal poles. The west side are windowed walls. Around point D is the vending area of the cantina. It has a crowded setup with complex partly metal objects. This area is not mapped well, the rest matches the walls reasonably well. Not clearly visible but the southwest corner is also mapped, proving the "through the wall" capability of radar and algorithm, while using 24 GHz. This capability is certainly of added value to first responders.

Preliminary results with a 100 GHz frontend [17] show significantly improved results and a pathway to a smaller system.

B. *Application proof of concept*

The SLAM radar was tested under operational conditions. Test were performed to reveal test person's ability to navigate in a building and to perform tasks like finding a wounded person in this building. Especially the ability to navigate without "touching the wall" increased this performance. The fence proved to be an easy way of interpreting distances, whereas the small size of radar-computer-HMI did not hamper human operation in any way. There were some issues where sidelobes (aiming up and down) resulted in misranging. In the DITSEF project The SLAM radar was successfully demonstrated and evaluated under semi-operational conditions in Montana (Bulgaria), see Figure 7.

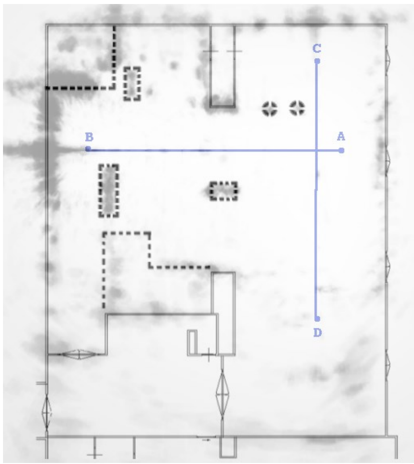

Figure 6 Resulting grid map with an overlay of the corresponding map. The cantina is 20 by 30 meters. The system was moved from A to B and from C to D. The gridmap was constructed without positioning information.

VI. CONCLUSION

The paper has presented a suitable processing for a radar based SLAM radar. This algorithm does not need any additional kinematic sensors, which is of great added value in operational context. Experiments have shown the good mapping performance of the presented algorithms, while using a 24 GHz FMCW radar. The main structure of the building is clearly visible, a prerequisite for navigation. In addition, even small objects are detected which eases the ability of the operator to move around.

The promising results and the positive first responder reception indicate a possible unexplored application area for future radar SLAM systems. Although the rotating antenna will probably not be part of future systems. The DITSEF project clearly indicated the added value of an indoor SLAM radar for operation in a vision denied environment. It shows radar information can be presented in an easy to interpret way, allowing for enhanced performance of human operators.

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Figure 7 Operational test environment.

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