Radar system on a large autonomous vehicle for personnel avoidance

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ABSTRACT

The US Army Research Laboratory designed, developed and tested a novel switched beam radar system operating at 76 GHz for use in a large autonomous vehicle to detect and identify roadway obstructions including slowly-moving personnel. This paper discusses the performance requirements for the system to operate in an early collision avoidance mode to a range of 150 meters and at speeds of over 20 m/s. We report the measured capabilities of the system to operate in these modes under various conditions, such as rural and urban environments, and on various terrains, such as asphalt and grass. Finally, we discuss the range-Doppler map processing capabilities that were developed to correct for platform motion and identify roadway vehicles and personnel moving at 1 m/s or more along the path of the system.

Keywords: personnel avoidance, autonomous vehicle, radar

1. INTRODUCTION

Perception of the environment is one of the key technologies necessary to make functionally mobile robots. This perception is used to model the environment and to create plans for a path of motion, to avoid obstacles, and execute specific tasks. Unfortunately, the environment often contains moving objects like humans, vehicles, and other robots that change location and affect the planned path. Dynamic or online path planning [1] creates a path based on sensor information. This paper focuses on the sensor information that can be used to model the environment for dynamic obstacle avoidance and dynamic obstacle path prediction.

Radar emits radio waves that are reflected back to the radar from both stationary and moving obstacles. Each class of obstacle has its own radar cross section (RCS). Moving obstacles interact with the radio waves through the Doppler Effect, which gives a very accurate measurement of the velocity of the moving obstacle. Vehicles move with a combined velocity, but their RCS will change as a function of aspect angle. People move with a distribution of velocities, their arms and legs alternately moving faster and slower than their bodies as they walk [2,3]. The deviations from a single velocity in radar are called micro-Doppler. This can be used to characterize an obstacle’s motion and predict a projected path, as well as help identify the obstacle as an animal, vehicle, robot, or particular individual.

An obstacle’s motion can also be sensed through optical or infrared video. The advantage in cost can be significant, though radar costs have been falling as well. The accuracy of the video is in determining the motion of an obstacle from a transverse view by differentiating images in the video and background subtraction. This is where the obstacle is moving across the video field-of-view. The accuracy of radar is in determining the instantaneous velocity toward or away from the platform, as well as the exact distance to the moving obstacle. The combination of radar and video is compelling in determining the motion of moving obstacles because the radar distance measurement can be used to improve the accuracy of the video transverse motion. This paper mainly focuses on the radar component of the sensing and prediction of the path of moving obstacles. Once the predictions of the environment with time are made, a path can be computed.

Path planning models are either global path planning based where the environment information is all known, also known as static or offline path planning, or local path planning, also known as dynamic or online path planning. There are several dynamic planning models. The artificial potential field approach [4,5,6] is a virtual force method where the movement of a mobile robot in the environment is determined like the movement in an electric field. Obstacles repulse the robot, while the goal attracts the robot. The neural network approach [7] processes sensor information through a neural network built on training cases. Genetic approaches [8] break the individual path into a series of halfway points, then select and mutate until producing an evolved path. All of the dynamic path approaches rely on the quality of the sensing of the environment. One key issue that is often overlooked is that indoor sensor information is often limited by...
walls and doorways. Lower frequency radars operating in the UHF-band can penetrate through some walls to sense the environment within a building.

The rest of this paper focuses on the measurement of the velocity and thus the accurate prediction of moving obstacle trajectories. Section 2 focuses on the characterization of human and vehicular motion and the determination of their instantaneous velocity as moving obstacles. Section 3 focuses on operational modes of the radar. Section 4 discusses some details of the algorithms applied to data collected by the radar. Section 5 discusses measurements and analyses. Section 6 reports on the conclusion and future work.

2. HUMAN AND VEHICULAR DOPPLER

The equation for computing the non-relativistic Doppler frequency shift, $F_d$, of a simple point scatterer moving with speed $v$ with respect to a stationary transmitter is

$$F_d = F_i \frac{2v}{c} \cos \theta \cos \phi$$

(1)

where $F_i$ is the frequency of the transmitted signal, $\theta$ is the angle between the subject motion and the beam of the radar in the ground plane, $\phi$ is the elevation angle between the subject and the radar beam, and $c$ is the speed of light. For complex objects, such as walking humans, the velocity of each body part varies over time. The radar cross-section of various body parts is also a function of aspect angle and frequency. The Doppler of a moving vehicle is similar to a point scatterer, but humans and animals have a larger spread of velocities due to their bipedal or quadrupedal motion.

The radar sensed range and Doppler of walking humans, vehicles, and bicyclists are shown in Figure 1. The range-Doppler map was integrated for approximately six seconds. The vehicles are strong point-like scatterers whose track is a smooth line. The walking humans and bicyclist have more spread to their Doppler. This vehicular radar will need to detect and respond to moving objects like humans and vehicles, so the ability to sense their range and velocity as well as project a future path for the moving obstacles is important.

![Fig. 1. Time-integrated range-Doppler map of two walkers, a bicyclist, and two vehicles.](image_url)
3. RADAR SYSTEM SPECIFICIFICATIONS

The design and characterization of the radar has been documented in [9, 10, and 11]. Specifications pertinent to this paper are reproduced in the following sections and summarized in Table 1.

3.1 Radar Antenna

The radar antenna consists of 16 ports, offset by 2°, covering an azimuth field-of-view of 32°. The elevation field-of-view covers 30°. Figure 2 shows the antenna system in the lab (left) and as configured on an SUV (right).

![Fig. 2. Images of the vehicular radar](image_url)

3.2 Radar Waveform

The radar carrier frequency is 76.6 GHz. The radar transmits a frequency-modulated continuous waveform (FMCW) at 100 mW with a bandwidth of 150 MHz. This bandwidth results in a range resolution of 1 meter. The range span of 193 meters results from acquiring 386 real-valued samples during the waveform sampling.

Table 1. Radar System Specifications Summary

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>76.6 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>150 MHz</td>
</tr>
<tr>
<td>Transmit Power</td>
<td>100 mW</td>
</tr>
<tr>
<td>Waveform</td>
<td>FMCW</td>
</tr>
<tr>
<td>Doppler Resolution</td>
<td>0.25 m/s</td>
</tr>
<tr>
<td>Doppler Ambiguity</td>
<td>±64 m/s</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>1 meter</td>
</tr>
<tr>
<td>Range Span</td>
<td>5-193 meters</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>2°</td>
</tr>
<tr>
<td>Azimuth Total Field-of-View</td>
<td>32°</td>
</tr>
<tr>
<td>Elevation Field-of-View</td>
<td>±15°</td>
</tr>
</tbody>
</table>

4. ALGORITHMS

The methodology selected for representing the radar sensor data was based on the occupancy map framework introduced by Elfes [12]. A discrete spatial lattice was defined over the region to be traversed by the radar platform. Sensor observations were used to update individual lattice locations. Occupancy maps were separated into a stationary object map (SO-Map) and a moving object map (MO-Map) [13]. The occupancy maps for the current work used a resolution of 1 meter by 1 meter.

4.1 Stationary object map

Stationary object maps were created using the zero-Hertz Doppler measurement from the range-Doppler map of each beam. Each cell of the map was checked to see if a given beam had made a measurement within the area covered by that
cell. When the platform was in motion, the zero-Hertz location shifted to a frequency bin in the range-Doppler map proportional to the velocity of the platform. Note that if a GPS estimate of the platform velocity is available, the frequency bin can be computed. An alternative method for estimating the zero-Hertz bin when INS or GPS data is not available is to use a voting method based on the range-Doppler frequency bins with the maximum signal over ranges of interest. This assumes that clutter from the ground is the dominate signal over most of the ranges.

4.2 Moving object map

Moving object maps were created by examining the non-zero Hertz Doppler bin in the range-Doppler map. If the platform was in motion, the zero-Hertz frequency appeared at other bins within the range-Doppler map. Persistent moving objects can be extracted from the MO-map as candidates for a tracking algorithm (Figure 3).

5. MEASUREMENTS

The radar antenna system was attached to the roof of an SUV and driven past typical highway and off-road scenarios. Measurements were collected at two sites, around the Aberdeen Proving Ground (APG) in Aberdeen, MD and the robotics testing facility at the NIST Nike Annex in Gaithersburg, MD. Rural and urban areas around APG were used. The NIST site included buildings, cars, and pedestrians typical of an urban scenario. Most of the NIST course consisted of concrete pavement, but one section of the course involved driving on grass.

5.1 Aberdeen Proving Ground

A 13-second measurement collected at APG was identified for detailed analysis. The scene consisted of a pedestrian walking along the right side of the road and an SUV parked behind a tree at a distance. The moving object map was used to extract detections. The pedestrian was tracked from a starting relative range of 55 meters to a final range of 15 meters, at which point the near-range clutter dominated. The SUV began moving around 7 seconds and was detected at a relative range of 115 meters.

Fig. 3. Doppler detections of moving objects.
Road boundaries, a fire hydrant, picnic table and utility poles can be identified in the stationary object map (Figure 4).

5.2 NIST Nike Annex

A Real Time Kinematic (RTK) differential GPS system was available to measure ground coordinates at the NIST site. Two position sensors were placed on the roof of the SUV. The relative position of these sensors provided a method for measuring the heading of the platform. Each measurement provided an absolute location, so this method did not accumulate errors.

However, there were some spots around the course that experienced location measurement drop-outs. The video from a camera mounted on the SUV provided a secondary method for estimating heading. The frame rate of the video was 30 Hz. Every fourth frame was compared to detect changes in the scene. The pixel shift of the frame was converted to a change in heading angle. Errors in estimating the heading angle can accumulate using this method due to integer frame shifts. Figure 5 shows the heading based on GPS measurements (red) and video frame changes (blue) as well as the velocity estimates based on GPS (red) and the range-Doppler map stationary clutter frequency bin (blue). A third method for estimating the platform heading could be derived from the shifts in the stationary object map. This method was not attempted with this data. Figure 6 compares an aerial photo and the stationary object map produced by the radar system.

Fig. 4. Stationary objects sensed in front of the radar. Note that the edges of the road are clearly defined for more than 50 meters.

Fig. 5. Left: heading estimates based on GPS (red) and video frame change (blue). Right: speed (m/s) estimates based on GPS (red) and range-Doppler map stationary clutter frequency bin (blue).
6. CONCLUSIONS

The collision-avoidance radar discussed in this paper can generate stationary object maps, which can assist the platform in avoidance of non-moving objects. In addition, the radar can also generate moving object maps using Doppler signals to assist in avoiding objects that may move into the path of the radar.

Future work to improve the system capabilities includes integration of a digital compass to aid in measuring the heading of the platform and integration of a GPS/INS module for more accurate position and orientation measurements.

REFERENCES