Micron-Precision Distance Measurement Using mmWave Radars

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ABSTRACT

This paper presents advances in distance measurement using modern millimeter-wave radar with a high sampling rate and micron-range accuracy. For radar distance measurement in navigation, it is important to measure distance with high accuracy and to measure accurate distance with a high sampling rate that will enable direct estimation of acceleration and speed of the objects. We present a scenario in which autonomous vehicles rely solely on measurements done by the radar distance sensors, to provide positioning in GNSS degraded environments. Based on the given scenario, a requirement for the radar sensor is laid out, and a prototype radar sensor conforming to given requirements is developed and built. The characteristics of a prototype sensor are verified in a laboratory. The radar sensor device is integrated to the autonomous vehicle, and basic positioning and object detection test is performed on an autonomous ground vehicle.

Index Terms *- millimeter-wave radars, autonomous vehicles, GNSS degraded environments*

1.0 INTRODUCTION

Precise distance measurement using radars has been used in navigation applications for a very long time. For example, in aviation, radar distance sensors are used as altimeters, and in industrial applications, the radars provide precise measurement of distances to objects in automation and production processes. With the recent advances in robotics and unmanned systems, precise distance measurement is becoming more and more important. That requires radar distance sensors with sub-millimeter accuracy and high sampling rate, in as small as possible form factor and with as low as possible power consumption, [1, 2].

The positioning of unmanned, autonomous, and robotic devices is critical for the performance of such systems. The availability of positioning data enables the autonomous robotic devices to move to an operating position and provides collision avoidance capabilities if multiple devices are used in the same area. Many different methods are used to provide positionings of autonomous robotic devices, such as GNSS positioning, laser/lidar area scanning, and image processing from the onboard camera using artificial intelligence of predefined visual cues. In GNSS degraded environments GNSS positioning is not possible, so an alternative positioning method is required.

In this paper, we explore the feasibility of using high-accuracy, high scanning rate radar distance sensors to provide positioning data for the autonomous robotic devices operating in GNSS degraded environments. We will focus on radar sensor technology to provide accurate distance measurement from the autonomous device to one or more static reference points, and the use of radar-based distance measurement for collision avoidance between multiple autonomous devices. The sensor integration with the autonomous device and sensor fusion topics are not part of this paper.

2.0 PREMISES

We shall conceive a system consisting of one or more autonomous robotic devices, operating in a two-dimensional field. The autonomous devices are programmed to move within the area and perform predefined tasks. A good example is the use of robotic mine/IED detectors that need to scan a given area. Each autonomous robotic device needs to cover a given area (without skipping any part of it), and the devices must not collide. We shall explore the practicability of using accurate radar-based distance meters to provide positioning and collision avoidance in such a system.

To properly operate in the described scenario, each autonomous device needs to be able to determine its location within the assigned area and needs to be aware of its surroundings – it needs to detect other objects that exist or moving within the area. For all objects that are detected within the assigned area, the autonomous device needs to determine whether the object is static (so it should be bypassed), or the object is moving, so the autonomous device needs to perform a collision avoidance maneuver.

By using accurate, narrow-beam, radar-based distance meters, and two radar reflectors at known positions, the autonomous robotic device can determine its position within an area, provided that the tracking algorithm is implemented which will keep a track of radar reflectors. By measuring the distance to the two radar reflectors, the autonomous object can determine its position within the operational area.

The same radar distance sensor can be used to scan the area surrounding the autonomous vehicle. If an object is detected within the area, by rapidly measuring the changes in the distance between the autonomous vehicle and the detected object, the autonomous vehicle can determine whether the object is static or moving and can then decide how to proceed with its operation.

For the given scenario, we propose to use a single narrow-beam radar distance sensor which is mounted on the top of the autonomous device on a turntable controlled by a stepper motor. Such a turntable can accurately rotate the radar antenna left or right and point it in different directions. The radar will continuously swap between the last known positions of the reference radar reflectors to provide an update to the position of the autonomous vehicle and will periodically scan the area in front of the device for object detection and avoidance.

3.0 SENSOR REQUIREMENTS

Based on the given operational scenario and described premises, we define the radar sensor requirements. The radar sensor should have a arrow beamwidth. It should have an absolute distance measurement accuracy below 1 mm so that it can quickly determine whether a detected object is static or moving, and to be able to accurately and quickly assess the velocity of the moving objects. The scan rate of the radar sensor should be greater than 1 scan per second.

We shall put some additional requirements on the sensor, to make it more suitable for the described application. It should be power efficient, as the autonomous vehicle is operating on battery power. The radar should also be difficult to detect and should be hard to jam. If multiple autonomous devices are operating within the same area, multiple radars on different vehicles should not interfere with one another.

4.0 PROTOTYPE RADAR SENSOR

We have designed and built a prototype radar distance sensor device that fulfils the given requirements. The radar sensor is designed to operate in W-band, at a frequency range between 77 GHz and 81 GHz. A wide RF bandwidth with a 4 GHz span fulfils three of the specified requirements. When the modulated radar signal is transmitted, the transmitted energy is spread over 4 GHz, so the radar is hard to detect. The same technique is used by ultra-wideband (UWB) radars. The second requirement fulfilled by using a wide frequency range is resistance to radar signal jamming. For the jammer to be efficient, it should match the modulated radar signal with extremely high time and frequency accuracy, which is practically impossible. Finally, for the same reason, that jamming such signals is difficult, multiple radars operating within the same area will not interfere with one another.

The radar antenna is designed so that the radar transmits an extremely narrow beam. The beamwidth of the designed device is only 5° on both axes. Special consideration during antenna design was given to minimizing the side lobes of the antenna. This was achieved by designing the antenna with a system of two dielectric lenses in front of the antenna, where the first lens is manufactured using an additive 3D printing technique, and the second antenna is CNC machined from PTFE (Teflon) material.

The distance measurement resolution is 5 µm with absolute accuracy of 25 µm, and the radar can measure the distances to objects ranging between 0,2 m and 10 m. For real-world applications, the maximum detection distance could be too small, but increasing the distance from 10 meters up to 50 meters is straightforward and will be done in future research. The radar sensor makes 10 scans per second.

The extreme accuracy of the unit is achieved by using a very stable frequency-modulated continuous-wave (FMCW) radar frontend, with linear frequency modulation across the whole operational range of the unit, from 77 GHz to 81 GHz. Such unit has a very low phase noise of the oscillator and we have developed various advanced algorithms in the radar data processing domain.

The small form factor for such device is critical for use in UGV and UAV platforms. The complex antenna and dielectric lens system which was described above was developed to provide the narrow radar beam in a small package. Normally a narrow radar beam could be achieved by using a larger antenna or a single large dielectric lens, but using our proprietary technology, the complete unit size is Φ 80 mm x H 78 mm. This form factor makes the sensor easy to integrate on the robotic platforms and is very suitable for industrial robots providing very reliable navigation in indoor locations where GNSS is very complex and usually not reliable due to the multipath and metallic structures and obstacles all-around of the vehicles.

The same radar platform, with modified signal processing, is commercially available as Geolux LX-80 radar level meter.

Figure 4-1: Radar Distance Meter Device

5.0 UNIT VERIFICATION AND RESULTS

The initial device was thoroughly tested and verified in the Geolux RF laboratory, and the tests were repeated in the independent laboratory. The accuracy of the distance measurements, temperature stability, and antenna pattern was verified and found to be as specified. Initial integration tests with the autonomous vehicle were done in cooperation with RoMB Technologies [3], where the unit was mounted on their UGV, and tested in an indoor environment where there is no GNSS signal. The radar mounted on the UGV was able to detect static objects within the area such as walls and was successfully integrated with the onboard UGV computer. The radar distance measurements were found to be accurate and reliable, and the radar sensor has been found to perform according to the requirements.

More future research is required to build a fully autonomous vehicle that performs positioning and object detection solely based on the measurements provided by the radar distance sensor. The radar sensor which was developed by us can provide all the required data, but more work is required on software processing of the radar data and a higher level of integration between the radar sensor and autonomous vehicle must be implemented.

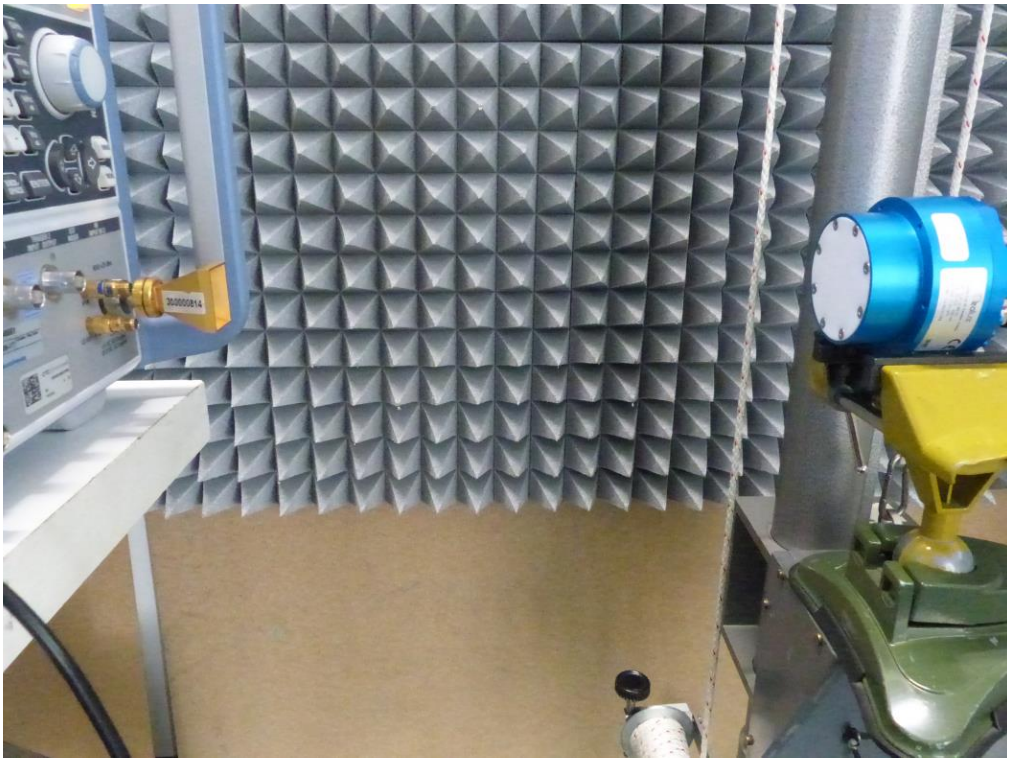

Figure 5-1: Verification of Radar Sensor in the Laboratory

CONCLUSION

Highly accurate, narrow beam, radar distance sensors can provide positioning information and data observations required for collision avoidance for autonomous devices operating in GNSS degraded environments. We have developed a narrow beam radar sensor that operates in W-band, with sub-millimeter accuracy, and have done initial tests with an autonomous vehicle to assess the usability of such device for positioning and object detection. We have found out that the radar performs well, that the technology can be used as expected, and we plan to continue our research efforts. In the production-grade system, multiple sensors should be used: laser/lidar, camera, radar, ultrasound. A device taking advantage of various physical properties from different sensors will outperform autonomous devices relying on single sensing technology.

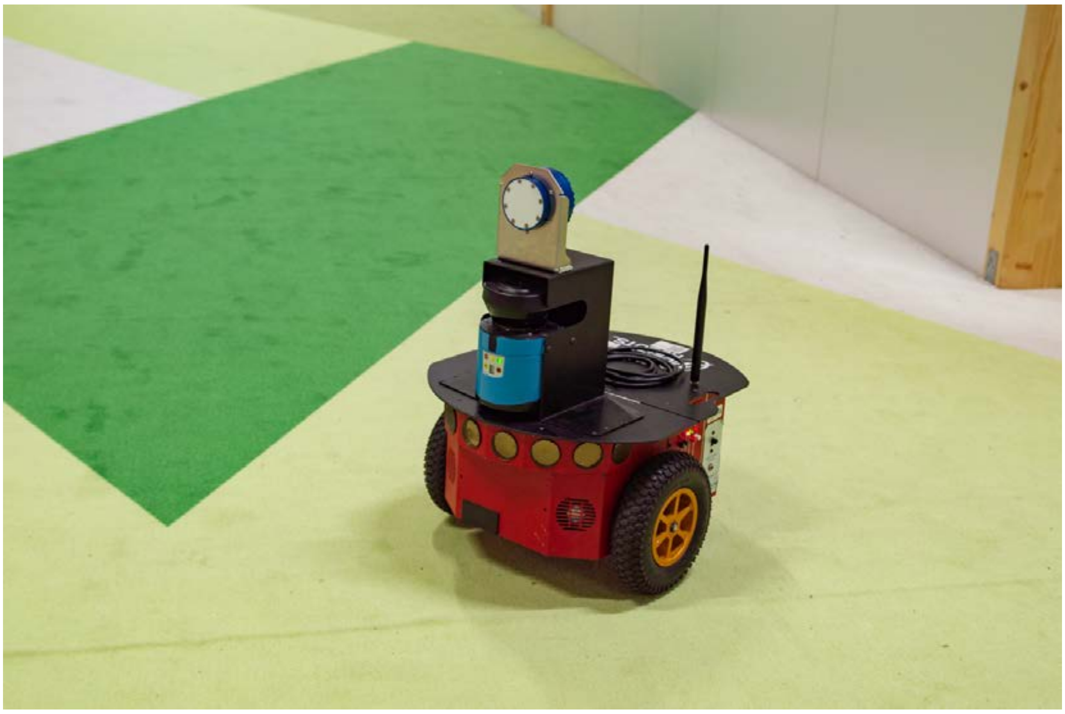

Figure 6-1: Radar Sensor Mounted on an Autonomous Ground Vehicle

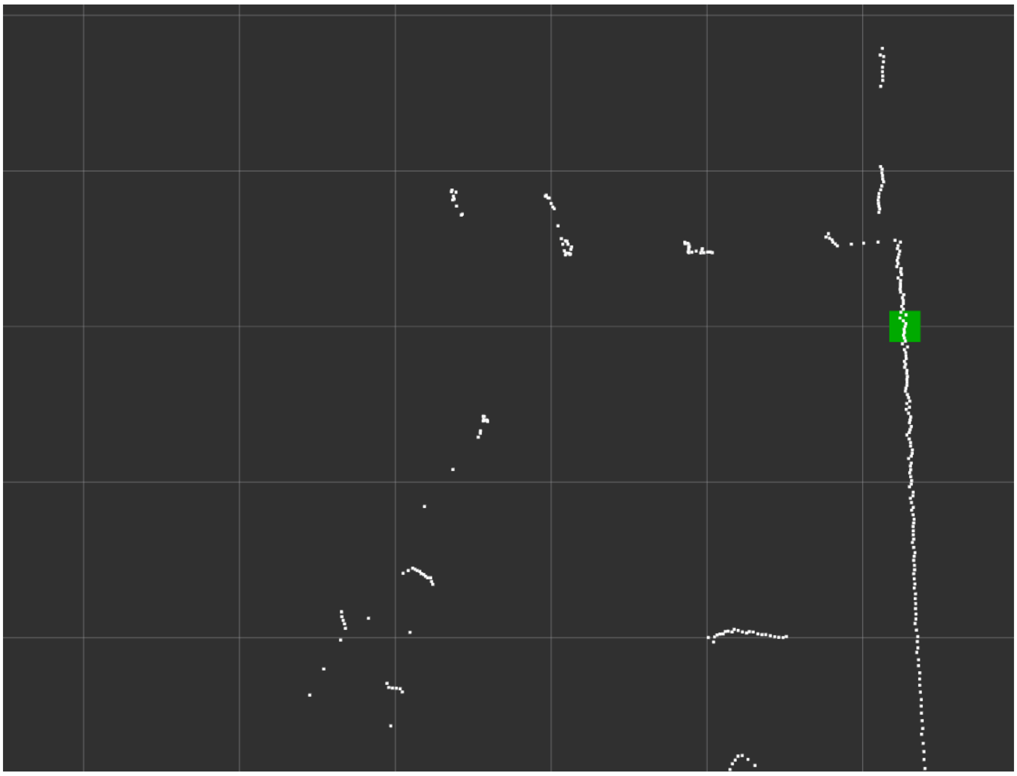

Figure 6-2: Static Objects in the Environment Detected by the Radar Sensor Mounted on the Autonomous Vehicle

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