2024 IEEE MIT Undergraduate Research Technology Conference (URTC) | 979-8-3315-3100-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/URTC65039.2024.10937590

Utilizing mmWave Radars for Autonomous Navigation of UGVs in Degraded Visual Environments

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***Abstract*—Autonomous machines minimize human risk in defense and rescue. Although most Unmanned Ground Vehicles (UGVs) use LiDAR or stereo cameras, these are easily compromised in fog, smoke, or rain. Therefore, this research explores millimeter wave (mmWave) radar due to its resilience to such occlusions, specifically o n t he J ackal U GV. C ontrolling b oth Jackal and mmWave radar through Robot Operating System (ROS) and rospy softwares allows for real-time mapping and navigation from the high-accuracy point clouds and range-azimuth data provided by the mmWave radar. Through our research, UGVs can function in additional environments compared to other sensing methods.**

***Index Terms*—mmWave, UGV, robotics, navigation, self-driving.**

I. Introduction

Human risk in fields r e lated t o d a nger a n d r e scue can be reduced with the help of autonomous machines. One of the most integral parts of any autonomous machine is the mapping and vision of its environment. Vision technology like Light Detection and Ranging (LiDAR) and stereo camera systems are currently used on most Unmanned Ground Vehicles (UGVs). However, most of these systems have a common limitation; a reduction in effectiveness in hazardous environmental conditions such as fog, rain, and dust. As an alternative, millimeter wave (mmWave) radars are more promising for use in these environments as mmWave does not use light for mapping, as it is more resistant to these occlusions.

Integrating mmWave radars with existing UGVs poses a viable concept for future robotic development, an avenue in which this research explores. This study uses the Jackal UGV in experimentation due to its powerful operating system, integration with the Robot Operating System (ROS), and capability with existing distance sensors. Additionally, this study uses a mmWave cascade radar from Texas Instruments, for its increased antennae, which can improve target detection and resolution compared to a single chip system.

Funding for project provided by George Mason University through the ASSIP program.

II. Individual Systems

A. mmWave Radar for Visionless Environment Mapping

Millimeter Wave (mmWave) radar technology has recently been recognized as an innovative alternative to commonly used sensing and imaging systems. By using electromagnetic waves, the mmWave radar offers superior resolution when compared with systems such as LiDAR and cameras. Standard mmWave radars use single chip configurations with limited range. For this research the MMWCAS-RF-EVM was used, creating a cascading radar with increased range and FOV as shown in Figure 1.

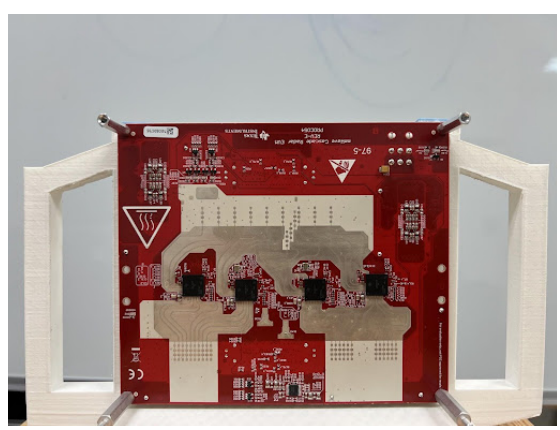

Fig. 1. The mmWave radar used in this study.

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The mmWave Radar systems rely on the transmission and reflection of electromagnetic waves. A transmitter on the radar emits electromagnetic waves in small pulses called “chirps”. Once the waves reflect back to the radar, a receiver captures these chirps. The surface of the radar consists of multiple antennas which facilitate the transmission and reception [1]. Object detection happens as a result of the emitted chirp encountering an object and reflecting back upon the radar system. By calculating the time that the waves take to leave the transmitter and come back, as well as the Doppler shift observed in the signals, the radar system can identify the distance, angle, and velocity of the objects [2]. Depending on the materials in the environments, there will be different textures on which the waves are reflected on; in this case, a property called scattering comes in. Given the different textures of the materials, not all waves will hit the object and bounce directly back. Only when a perpendicular surface exists for the wave to hit and immediately bounce back will there be the detection of a point or object. To resolve this issue, machine learning algorithms are being developed to make reasonable assumptions on the material and shape of certain objects given specific point clouds or object configurations.

1) Benefits of mmWave Radar Sensors: Given the resilience from light-prohibiting occlusions, the mmWave radar works effectively in all environments. Imagers such as stereo cameras or LiDAR have substantially reduced performance in the presence of occlusions such as fog, rain, and dust, making mmWave a superior technology [3]. In addition to occlusion resilience, mmWave signals have higher resolution. The mmWave signal’s high frequency translates to short wavelengths which allows for higher resolution of the objects identified from reflection. The precision of the mmWave Radar can reach up to millimeters of accuracy in the identification of an object’s location. Given this sensitivity, the radar is able to detect minute movements as well as small objects, something most systems cannot do.

2) Applications of mmWave Radar Sensors: When it comes to autonomous vehicles, the mmWave radar will be incredibly crucial to the improvement of self-driving systems. Current self-driving models are often rendered useless when weather conditions block the cameras and LiDAR sensors on the car [2]. By integrating the mmWave radar, these systems would become substantially more effective. Similarly, military UGVs will commonly operate in hazardous environments during missions. For example, quipping mmWave radars on autonomous vehicles may allow for a UGV to scope out the terrain before the risk of humans entering the area. The ability of mmWaves to stay fully-functioning and have effective mapping in obscured conditions makes this radar system extremely valuable in military and rescue contexts.

3) Signal Processing and Shortcomings: Once data has been collected, certain visualization softwares can be used to view the data. This visualization creates graphs showing certain values calculated and captured by the mmWave radar. For example, Range-Azimuth Diagrams (RADs) allow for a user to identify the distance and relative angle of the objects from the radar as shown in Figure 2. Distance-velocity graphs can provide the velocity of the object at a specific distance from the radar in Figure 3.

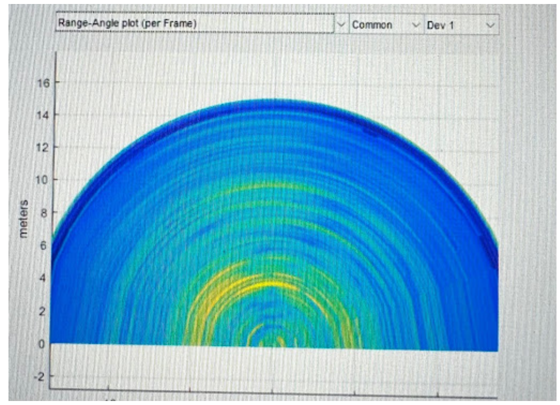

Fig. 2. Example range-azimuth diagram.

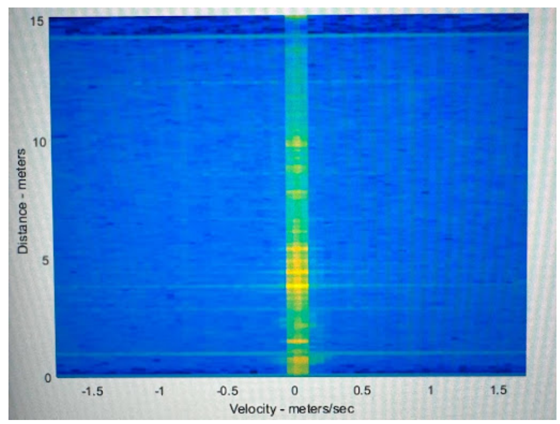

Fig. 3. Example distance-velocity diagram.

The main issue with the current system operation is the need for individual steps and long wait times between the intent to capture data and the final RAD and point cloud graphs are created. Additionally the format of the graphs make it hard to understand intuitively, which requires a system which can read the information and interpret it into navigational data that a UGV can understand.

B. Jackal UGV and LiDAR

Due to its customization options and overall versatility, our UGV of choice was Jackal from Clearpath Robotics. As it is relatively small, weatherproof, and all-terrain [4], this also serves to be an ideal candidate for a real-world rescue operation. It has a top speed of 2.0 m/s and utilizes the Robot Operating System (ROS), making communication and data processing protocols very easy. Attached to the Jackal was the Velodyne VLP-16 LiDAR, which is a 360-degree LiDAR capable of scanning until 200 meters of range with precise accuracy. Although the LiDAR has 360-degree horizontal scan, this was shortened to 120 degrees in order to mimic the real field of view of the mmWave sensor; the robot has access to range readings from 60 degrees towards the left of the current direction of travel to 60 degrees towards the right of it.

III. System Integration

A. Self-Driving

Our specific customization of Jackal receives data from the Velodyne LiDAR approximately 20 times a second [5]. This data gives angle and range readings, from which the robot must keep or adjust its current course to avoid obstacles and crashing into walls. In this study, we utilized LiDAR for implementing self-driving, then validating the applicability of this same logic with the mmWave sensor.

Logically, in any hazardous circumstance where the robot needs to uncover the maximum amount of area without crashing, following the direction where there is more to explore would allow the robot to map more terrain. This translates to allowing a robot to travel in the angle where the LiDAR reading is a maximum. For instance, if the robot's LiDAR detects that there is an obstacle straight ahead at 4 meters away, which happens to be the farthest detectable obstacle by a LiDAR or other distance detecting unit, then the robot will travel towards the obstacle and cover as much ground as it can, until it realizes a new area to explore. Figure 4 illustrates this concept in the case of a straight hallway.

In essence, this is the logic behind the DisparityExtender algorithm. At its core, this algorithm will find the longest possible straight traversable path that starts from the robot's distance detection unit and drive towards it [6]. However, it isn't this simple. As the robot has some amount of width, this will make turning significantly harder, especially if it is a sharp turn as opposed to a curved turn.

To avoid such crashes into corners, it is important to factor in distance measurements a few degrees on either side of the angle with the largest distance to an obstacle. This will help detect a significant difference in range-azimuth readings, which will correspond to impediments that do not block a LiDAR for detecting an optimal path, but will prevent the robot from achieving this optimal path. For example, in the case of a corner turn to the left, the robot might see the optimal path to round the corner as 6 meters away, but a few degrees left reads a range of only 2 meters. This means that the robot is too close to its left wall that is trying to go around and therefore must opt for another route. In this case, the robot can opt for setting course to a few degrees to the right of this optimal path just to ensure that it does not hit the corner or wall, as shown in Figure 5.

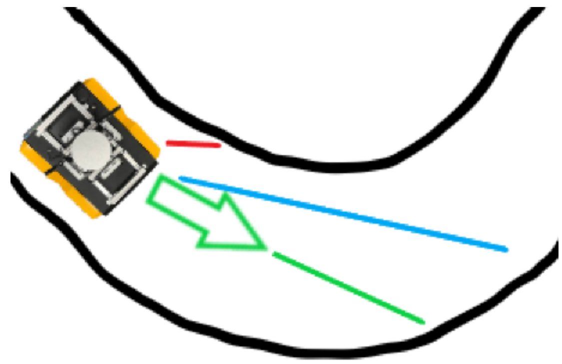

Fig. 5. Jackal analyzing its surroundings and choosing the path with the farthest disparity.

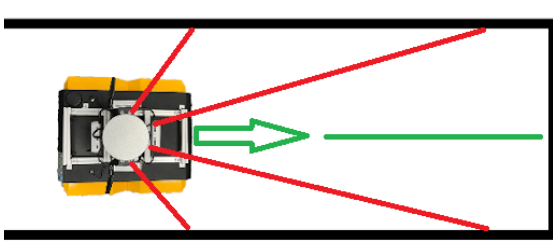

Fig. 4. Jackal analyzing its surroundings and choosing the path with the farthest disparity.

In some cases, the robot may need to make sharp turns, making constant velocity very impractical. Therefore, the intended steering angle must define the velocity and angular velocity of the UGV. As velocity should be a minimum at very extreme intended turning angles (closer to +60 degrees or -60 degrees azimuth) and a maximum at 0 degrees azimuth, whereas angular velocity is the opposite, we have utilized equations 1 and 2 to define the velocity and angular velocity of the robot. In these equations, θ is treated as the intended angle of travel, with -60 indicating as left as the LiDAR can detect, 0 indicating forward, and +60 indicating as right as the LiDAR can detect. Note that Jackal treats positive angular velocities as turning to the left, and negative angular velocities as turning to the right. Maximum velocity (v_{max}) and maximum angular velocity (ω_{max}) can be set manually by the user. For testing, v_{max} was set to 0.3 m/s and ω_{max} was set to 0.7 rad/s to ensure minimal damage in case Jackal hit a wall.

$$\omega = \omega_{max} \cdot -\frac{\theta}{60} \tag{1}$$

$$v = v_{max} \cdot \frac{60 - |\theta|}{60} \tag{2}$$

In sum, this procedure defines a simplified version of the DisparityExtender algorithm. While it is designed specifically to race smaller autonomous miniature cars in the F1Tenth competition [6], the F1Tenth racing environment that it is purposed for has only a single possible direction to travel with no intersections or forks. However, in rescue situations, it is imperative that the robot can explore a maximum area even with such forks in the road. Therefore, identifying isolated peaks in the RADs from the LiDAR and later mmWave sensor would allow for the robot to identify possible directions of travel.

For the purposes of this study, these isolated peaks needed to have a range of at least 2.5 meters from the main LiDAR sensor and be 24 degrees from any other peaks. Both the -60 and +60 degree azimuth endpoints were also considered to be peaks. Also, range readings 10 degrees to the right and left of the main lidar needed to be greater than 60% of the candidate peak or have a range more than 4 meters. If either the 10 degrees right or 10 degrees left measurements fail this requirement, the candidate peak will need to be adjusted, and if both fail, this candidate peak would not be considered to be an ideal path of travel for the safety of the robot. A result of applying this method on a range graph is shown in Figure 6.

After evaluating which angles the robot can safely travel, running a left-hand rule wall follower algorithm would allow the robot to prefer routes of travel towards the left of the robot over the right [7], allowing for greater area exploration. Perfecting this algorithm, the multipath DisparityExtender (MPDE), on its intended LiDAR sensor then allowed us to easily port this algorithm for the mmWave sensor.

B. mmWave Substitution for LiDAR

LiDAR maps usually contain a 2D model of the environment they are in. Depending on the range, a majority of the environment will be mapped, but in other cases only the nearby parts of the environment will be mapped by the sensor. LiDAR maps have the benefit of providing specific detail on the location and position of each object in the surroundings around the sensor. However, when it is compared with the mmWave radar, the radar can also provide enough information to make meaningful statements on the location and position of the object. The mmWave Radar will create RADs and Point Clouds for the position of the objects nearby. Using the distance, angle, velocity, and XYZ point cloud values, the radar provides enough information for the robot to use in navigation. Integration of the mmWave Radar with the Jackal UGV has other benefits for efficiency as well. Instead of having an operator manually run radar configurations and data captures, the ROS on the Jackal robot can run multiple subsequent capture programs to create a nearly live feed of data. On the same ROS server, scripts can be immediately run to use the live captured data and immediately process it into

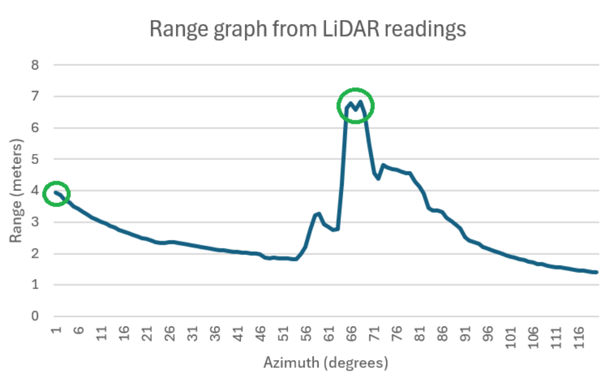

Fig. 6. Range graph from the LiDAR sensor. Target angles of travel are indicated by green circles. In this graph, 0 degrees indicates maximum left and 120 degrees indicates maximum right.

the RAD and point cloud graphs. This processed point cloud graph is shown in Figure 7.

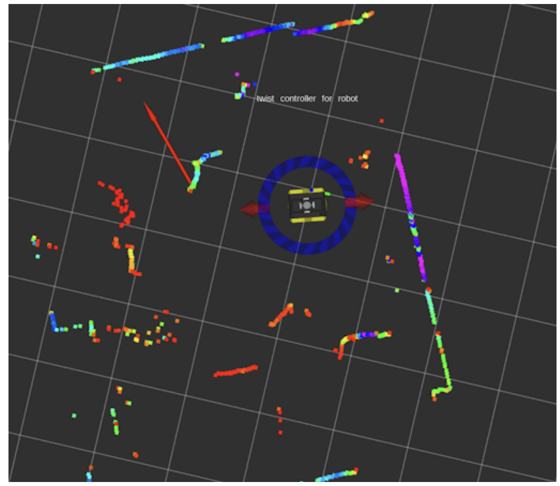

Fig. 7. Point cloud rendering on the ROS server

IV. Testing

In order to test our UGV, LiDAR, and mmWave assembly, different testing environments had to be considered. First, the robot would need to be able to travel along a straight path without hitting any walls. This means that for the first testing environment, a simple hallway in an office environment should suffice given its minimal obstructions and overall linearity. DisparityExtender would ideally target the end of the hallway and correct its angle heading only minimally. However, to prove the effectiveness of DisparityExtender on the LiDAR and mmWave sensor, it is imperative to factor its ability to turn corners, meaning that a second testing environment with corner turns is needed. This testing environment will also be of a single path, but this one will have corner turns unlike the first testing environment.

After validating single path DisparityExtender on these two environments, it is then necessary to validate MPDE by deploying the UGV, Lidar, and mmWave assembly in a third environment where there are intersections where the robot can correctly choose a path to travel and backtrack without hitting any of the corners in the fork. For the purpose of simplicity, an office environment involving multiple turns and intersections was chosen. This environment would easily validate that our UGV assembly can correctly traverse and map out all terrain using the basic left-hand wall follower method. Figure 8 illustrates the overall layout of these environments. For the third environment where MPDE was tested, arrows in repeating rainbow color order show the exact sequence of moves our UGV should take (starting at the red arrow, then orange, yellow, and so forth until pink and then restarting from red).

During some of these tests, the radar was mounted onto the robot in order to mimic active scenarios as demonstrated in Figure 9. As the robot moved along in such tests, both the

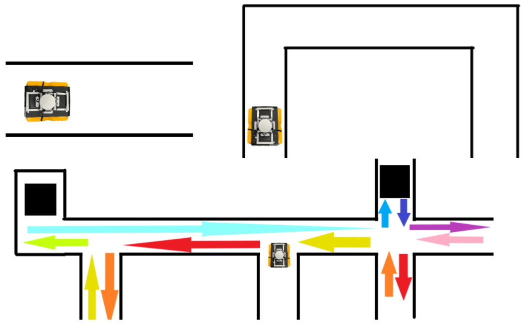

Fig. 8. Test environment 1 (top left), 2 (top right), and 3 (bottom) for evaluating steering, turning, and environment mapping, respectively.

LiDAR and the mmWave radar captured data. Data formats shown demonstrate the comparable data values deducible from the RADs and distance-velocity graphs. By running these tests, the accuracy of the radar data with respect to the environment is compared with the LiDAR data.

V. Conclusions

At the current state of the research, creating a closed loop system of data capture and movement from Jackal was not achieved for mmWave radar. While this closed loop system was functional and proved for our UGV-LiDAR system to function in all three test environments, such a system was not tested with the UGV responding from mmWave data. Although the Jackal UGV did not respond to data from the mmWave sensor, its data reportings in the same hallway and office environments have very significant similarity to measurements from the LiDAR sensor, especially for the range-azimuth diagrams; mmWave has the added advantage of identifying positional velocity, which was not tested in this research. Given the similar range-azimuth diagrams, our MPDE would output very similar directions of travel for both the tested LiDAR system and the mmWave system. In practice, the mmWave radar can be mounted on the UGV and then both data systems can direct a UGV.

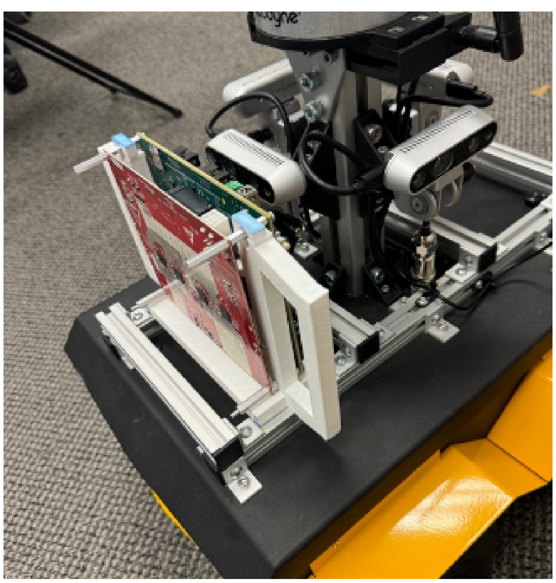

Fig. 9. mmWave sensor mounted on Jackal

Acknowledgment

This research was made possible through the support of George Mason University's College of Science, which supports the ASSIP Program.

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