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4D LIDAR and Sensor Fusion for Autonomous Rover Missions

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Abstract

The most effective way to explore an undiscovered territory is to conduct experiments on site. However, the outer space environment is often too dangerous and unpredictable for humans. Thus, using robotic rovers would be advantageous since they cover a wider land area and perform experiments providing ground-truth data and information safely.

The recent advance of 4D LIDAR (Light Detection and Ranging) technology has opened up a new set of possibilities to explore space in much greater detail. This innovative technology is based on the principle of the Doppler effect, which enables it to compute instant velocity in real-time and hence adds a fourth dimension to its preceding technology. In 2022, AEVA, a company specializing in the production of autonomous driving sensors, developed the 4D LIDAR, a new tool that will revolutionize autonomous driving. This new generation of LIDARs offers a better performance in terms of depth, instant velocity, reflectivity, and vision.

In recent times, the exploration of the lunar surface and utilization of lunar resources has become a dominant agenda of several government space agencies and private companies. Furthermore, with the rapid growth in the New Space sector, organizations would continue to highly invest in lunar exploration. With an apparent increase in rover missions in the near future, the ability of the rover system to identify other moving rovers and compute their velocity would become a critical design parameter.

The purpose of this paper is to study the performance of the 4D LIDAR combined with other onboard components using sensor fusion and how it can help achieve better results when covering an undiscovered area with unknown environmental parameters. Moreover, we will study its impact in the future with muli-rover communication or even in planetary settlements where two or more independent rover systems need to avoid collisions and ensure successful data collection throughout their mission life cycle.

We plan to integrate the 4D LIDAR technology with different onboard sensors, evaluate its performance theoretically using software simulation, and present our final data illustrating the overall results. This would help us demonstrate the higher performance parameters and precision levels that could be achieved for future rover missions.

Our group consists of members from the Space Exploration Project Group at the Space Generation Advisory Council. Please note that the present abstract is submitted as a part of the Space Exploration Project Group's research, under the supervision of the Space Generation Advisory Council.

Keywords: 4d LIDAR, lunar exploration, sensor fusion, multi-rover communication

1. Introduction

This research aims to surpass the threshold of the traditional 3D light detection and ranging (LIDAR) systems that capture spatial data in three dimensions, 4D LIDAR adds the crucial element of time, enabling dynamic tracking and monitoring of objects in motion. This temporal dimension equips rovers with the ability to anticipate and respond to changes in their environment more effectively, enhancing their autonomy and adaptability. By offering real-time information on object trajectories and velocity, 4D LIDAR can significantly improve obstacle detection, navigation, and path planning, making it a strong candidate to replace or augment 3D LIDAR systems in rover applications. However, the successful adoption of 4D LIDAR will depend on factors such as cost-effectiveness, integration complexity, and the specific needs of the rover's mission, all of which should be carefully considered in the pursuit of enhancing rover autonomy.

1.1 Focus on 4D LIDAR sensor technology

This research paper stands out as a distinctive contribution in the field of space applications by pioneering the integration of 4D LIDAR Systems, specifically in the context of autonomous lunar rovers. This innovative approach introduces a temporal dimension to traditional 3D LIDAR technology, enabling our rovers to track and adapt to dynamic lunar terrains and obstacles in real-time. By merging the cutting-edge capabilities of 4D LIDAR with the challenges and intricacies of lunar exploration, our research opens new horizons for autonomy, navigation, and obstacle avoidance in space missions, setting it apart from existing literature and advancing the frontier of space technology.

This paper is structured, starting with an introduction section on the significance of using a 4D LIDAR for a lunar exploration mission and how fusing LIDAR with other sensors would benefit the overall system. Section 2 covers the methods, processes, and tools we used for our research. Section 3 highlights the working principles and theory of LIDAR sensors. The next section is where we summarise the results of our research. Section 4 discusses the significance of the findings during our research. Some other works that could be further explored are mentioned in the future work section. Finally, in the last section, we conclude with the main findings of our research.

1.2 Robotic and rover exploration on the lunar surface

Human and robotic missions to the Moon will provide an operational environment to demonstrate exploration capabilities as precursors for human missions to Mars or other planetary destinations, testing human-scale exploration systems, such as surface power, habitation, and life support, and planetary mobility.

The American Apollo and Soviet Luna missions brought Moon rocks to Earth which have given us a better understanding of the origin of the Moon. By analyzing these rocks, we can study the evolution of not only the Moon but the entire Earth-Moon system. The Moon probably formed after the collision of a Mars-sized object with the Earth. The interior of the Moon is similar to that of the Earth, with a crust, a mantle, and a core. As we seek to better understand the Moon’s complex morphology, we realize it could be an important resource for space exploration. 4D LIDAR can provide highly accurate and detailed 3D maps of the lunar terrain, including elevation data. This can help rovers better understand their surroundings and navigate more effectively, avoiding obstacles and planning efficient paths. The fourth dimension, time, can be used to create dynamic maps that capture changes in the environment over time, such as shifting terrain due to moonquakes or impacts. Hence, the enhanced autonomy and speed enabled by 4D LIDAR can allow rovers to cover larger areas and collect more scientific data, leading to a more comprehensive understanding of the moon's surface, geology, and potential resources. [1]

1.3 Sensor fusion

In autonomous vehicles, Sensor Fusion is the process of fusing data coming from multiple sensors. The step is mandatory in robotics as it provides more reliability, redundancy, and ultimately, safety.

In this paper, we used a simple process of simulating 4D LIDAR on a lunar rover communicating with the moon’s environment.

The 4D LIDAR-equipped lunar rover communicates with its lunar surroundings by emitting laser pulses, receiving their reflections, and using the resulting data to create detailed 3D maps. These maps are used for obstacle detection, navigation, autonomous decision-making, and environmental monitoring. Additionally, the rover's ability to stream LIDAR data to ground stations on Earth facilitates human interaction and remote control, enhancing the overall efficiency and success of lunar exploration missions.

2. Materials and Methods

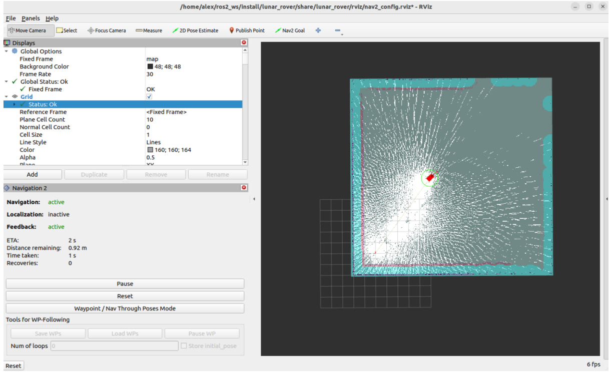
2.1 Rover simulation environment

Our research highlights the importance of having the additional 4th dimension which is the instantaneous velocity of the other moving objects. During our research on LIDAR sensors, we opted to use Robot Operating System 2 (ROS2), which is a simulation software usually used to design and test rovers for the lunar as well as Martian environment.

The first step in our process was creating a mobile robot using a Unified Robotics Description Format (URDF) file. This file contains the physical description of the rover in terms of sensors, wheels, and connectors. Furthermore, we used additional ROS2 resources such as nav2 and gazebo, that help the rover navigate through complex tasks and create simple maps respectively.

With the help of gazebo wheel odometry and IMU data were simulated, this data was fused together to provide more accuracy, minimize errors, and allow redundancy. Thus by integrating sensor fusion, we were able to obtain data on the rover's position and orientation.

In addition to these sensors we added LIDAR to the rover URDF, and fused with other sensors it created a map of its environment where it could recognize obstacles on its path. Figure 1 shows the map created by the LIDAR sensor in ROS2



Global Options
Fixed Frame: map
Background Color: 48; 48; 48
Frame Rate: 30
Global Status: Ok
Fixed Frame: OK
Grid: ☑
Status: Ok
Reference Frame: <Fixed Frame>
Plane Cell Count: 10
Normal Cell Count: 0
Cell Size: 1
Line Style: Lines
Color: 160; 160; 164
Alpha: 0.5

Navigation: active
Localization: inactive
Feedback: active

ETA: 2 s
Distance remaining: 0.92 m
Time taken: 1 s
Recoveries: 0

Num of loops: 0

Figure 1: A map of the environment created by LIDAR sensor

2.2. Simulation configuration and objectives

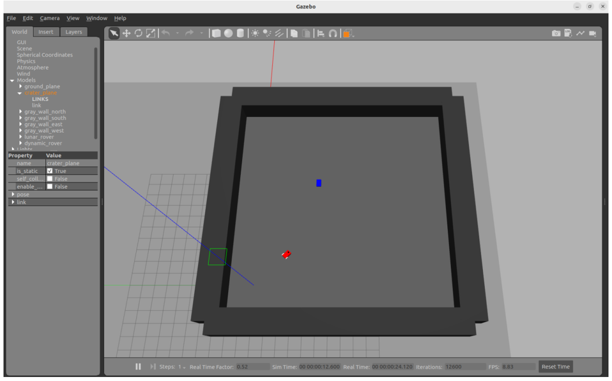
The overall approach of the simulation was to use 2 rovers and define a target destination and in case they detected an obstacle along the way they would pivot from their original path momentarily until the obstacle was no longer detected. Once that is done the rover comes back to its original path and keeps moving towards its target destination. This process is repeated until it reaches the endpoint.

To achieve this costmap files were created for each rover, allowing it to decide a path based on its environment. A costmap is a map made of grid cells with each cell having a cost, i.e. the difficulty for the rover to move through it. Cells with obstacles have high costs while cells with no obstacles have low costs. Nav2 takes care of implementing SLAM (navigating to the goal while avoiding obstacles), all you have to give it is the locations of obstacles, the location of the rover, and the location of your goal.

2.3 Comparison of 3D and 4D LIDAR operations

In our simulation, we used two cases, one with 3D LIDAR that gives only position coordinates while the other with 4D LIDAR that has information about the position and velocity of rovers.

While running the simulation of 3D LIDAR, the data from the obstacle rover is published onto the server, this data consists of the obstacle rover position. If both the rovers are within 5 units of distance from each other then the collision trigger alert goes on and the rover moves to another direction to avoid any collision with each other. Once the rovers are redirected, if there are no obstacles in their path they move back to their original path, continuing towards their goal. The collision alert only goes off if the rovers are in front of each other and not behind each other.



Property	Value
name	crater_plane
is_static	☑ True
self_coll...	☐ False
enable_...	☐ False

Steps: 1 Real Time Factor: 0.52 Sim Time: 00 00:00:12.600 Real Time: 00 00:00:24.120 Iterations: 12600 FPS: 8.83

Figure 2. The Gazebo simulation environment

Although we did not have a plug-and-play library for 4D LIDAR, we integrated the velocity dimension into the 3D LIDAR which emulated the data that would be collected in the presence of a 4D LIDAR. In the simulations for 4D LIDARs the obstacle rovers, publish the data about position and velocity to the server. The server looks at the position and velocity of the user rover, first it checks whether they are within a distance of 5 units from each other. Then the server calculates the dot product of the relative velocities of both the obstacle and the user rover.

The dot product will find if the objects are moving away or towards each other. If the dot product is < 0, that implies the rovers are moving towards each other. The next thing the server does is calculate the time to collision. If the time to collision is <= 10 seconds, trigger a collision alert. When a collision alert is triggered, the direction the rover swerves in is decided by trying to make the dot product non-zero, which means trying to make rovers move away from each other.

3. Theory and Calculation

3.1 Previous research on autonomous navigation and control for surface craft in space

4D LIDAR technology in autonomous lunar rovers reveals its potential as a groundbreaking innovation. Research highlights its ability to improve obstacle detection in autonomous vehicles, spacecraft relative navigation, SLAM systems, and path planning on the Moon's challenging surface. However, this technology poses some challenges such as advanced algorithms, integration of cross-domain capabilities, costs, risk, and human interaction. Overall, this technology emerges as a promising asset in advancing the capabilities of autonomous lunar rovers, marking a critical development in lunar exploration efforts.

3.1.1 Requirement of high autonomy for spacecraft operating outside of the solar system

Human missions beyond the Earth's planetary system will require autonomous systems to control the spacecraft.Once the vehicle has traveled 2 light minutes from Earth, tactical

situations will be handled onboard as response time will take 5 minutes. While nominal communications have shown tolerance to 5 minutes of communication delay (round trip), mission-critical or crew safety issues will require more immediate responses.Engineering such a complex and inaccessible system (relative to the Earth) is a challenge. Understanding the physics in these situations is crucial to making decisions that maintain vehicle integrity, crew safety, and mission success.

3.1.2 Demonstration by DARPA and DLR

In order to enable robot systems to enter areas inaccessible to humans, autonomous navigation is key. The perceived map of the environment has to be accurate

enough to allow for analyzing whether a particular region is drivable or not. Besides that, the efficiency of the perception system is important since the operation in these environments often requires online mapping and localization in real-time with limited onboard computers. Our Robot was developed based on the requirements of DRC and was to foster research for robots that are able to assist humans in responding to catastrophic situations, such as the nuclear disaster at Fukushima in 2011.While the DRC showed the potential of robots for tasks found in disaster response scenarios, it also showed that fully autonomous navigation and manipulation in unstructured environments—also due to the lack of applicable perception methods—is still beyond the state of the art.

3.1.3 Importance of autonomy

There are two sets of constraints that drive the need for autonomy: (1) operational constraints derived from mission objectives and (2) system/environment constraints based on the spacecraft design and the remoteness and harshness of the environment.For the operational constraints, the use of autonomy is traded against non-autonomous approaches. Based on risk and cost, mission objectives may get adjusted, often leaning toward state-of-the-art non-autonomous approaches wherever possible. These may include scaling back on the minimum required science, which relaxes requirements on productivity or access to more difficult sites. For the system/environment constraints, autonomy is required (not just desired) if the three conditions below are met. These conditions occur when: Changes in the environment or spacecraft occur, Changes are not predictable, and the required response time is shorter than the next communication cycle.

3.2 Sensor fusion using 4D LIDAR technology

3.2.1 Latest developments of 4D LIDAR fusion

Companies such as Aeva have manufactured 4D LIDAR systems for autonomous driving vehicles that would be used for commercial terrestrial use in the automobile industry[2]. The 4D LIDAR has the technological advantage of computing the instantaneous velocity of other moving objects in its field of view along with other parameters such as the distance, width, and height of the object. This helps autonomous automobiles to be aware of the objects moving automobiles, pedestrians, and objects in the street and thus control the speed and direction automatically.

This same technology could be beneficial to rovers on the moon. At present the is not crowded with any moving objects or human habitats which is the reason that 3D LIDAR sensors are sufficient for the current generation of lunar rovers. However, as planned by many space agencies as well as private companies, there would be human settlements around the South Pole of the moon. The next generation of lunar rovers would be challenged with not only complex lunar terrains but also human settlements, habitant astronauts, moving vehicles, and other moving rovers. In such an environment having ground in the loop or lunar habitation in the loop would be time-consuming and routine tasks. Thus having 4D LIDAR would improve the efficiency of the next-generation lunar rovers, increasing their autonomy to perform technical and scientific tasks.

3.2.2 Process of integrating 4D LIDAR sensor data

As mentioned by Zhu et al., 2021 [3], combining LIDAR sensors with SLAM and IMU sensors produces a low-cost and effective method to achieve higher autonomy in rovers. Their proposed framework uses LIDAR sensors manufactured by Livox. Other than rover LIDAR is also used in other space applications such as spacecraft rendezvous and docking [4].

Active sensors are those that are capable of producing their own signal and in the case of LIDAR it does produce a light beam that it sends out to the target and thus can be categorized as an active sensor. LIDAR works on the fundamental principle speed = distance/ time,

$$c = \frac{d}{t}$$

we denote speed by c since LIDAR uses LASER which is nothing but an electromagnetic wave of light which is traditionally denoted as c. [4]

The working principle of LIDAR is that it sends a light pulse to the target object and waits until the light pulse hits that object and returns back to the LIDAR sensor. Now since the laser pulse travels the same distance twice the equation is further modified to:

$$c = \frac{2d}{t}$$

$$d = \frac{c.t}{2}$$

The speed of the laser pulse is known and the time difference between the sent and received pulse can be computed by the sensor, thus the unknown parameter, the distance can be easily calculated. [4]

This forms the basis for 2D LIDAR, where the distance of an object is known, the industry already has 3D LIDAR which also are capable of calculating the height of the target object. [5]

3.2.3 Comparison of using different LIDAR sensor types

There are different types of LIDARs based on how they operate and on how they calculate the time of flight i.e. the time taken by the laser pulse to return from the target.

The first type is the scanning LIDAR, where a narrow light beam scans the target and the reflected light pulse is detected by a single radar. This type of LIDAR has higher accuracy to detect target objects, however since it scans the field of view, mechanically the probability of physical damage to the system is higher due to constant movement. [4]

The second type is a detector array, where the light beam is broad and covers the entire target thus does not require moving parts. These LIDARs are more suited for space applications. The final type of LIDAR is spatial light modulation [4].

Some of the time-of-flight measurement techniques that the LIDARs use are pulsed/flash LIDAR, continuous wave LIDAR, and a pseudo-random number. [4]

4. Results

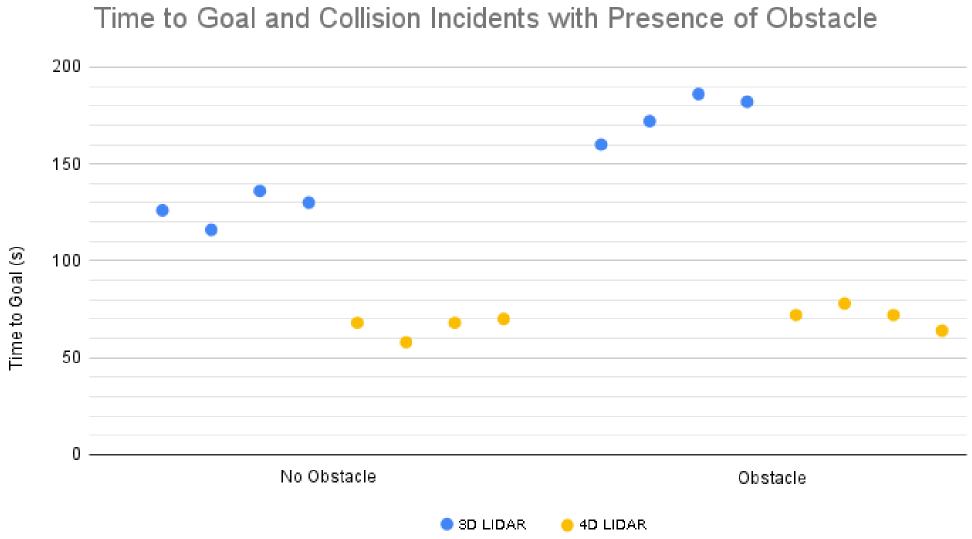


Figure 3. Comparison of time to reach goal (y-axis, unit: seconds) for no obstacle situations (left) and obstacle situations (right). Comparison of 3D LIDAR sensors (blue) and 4D LIDAR sensors (yellow)

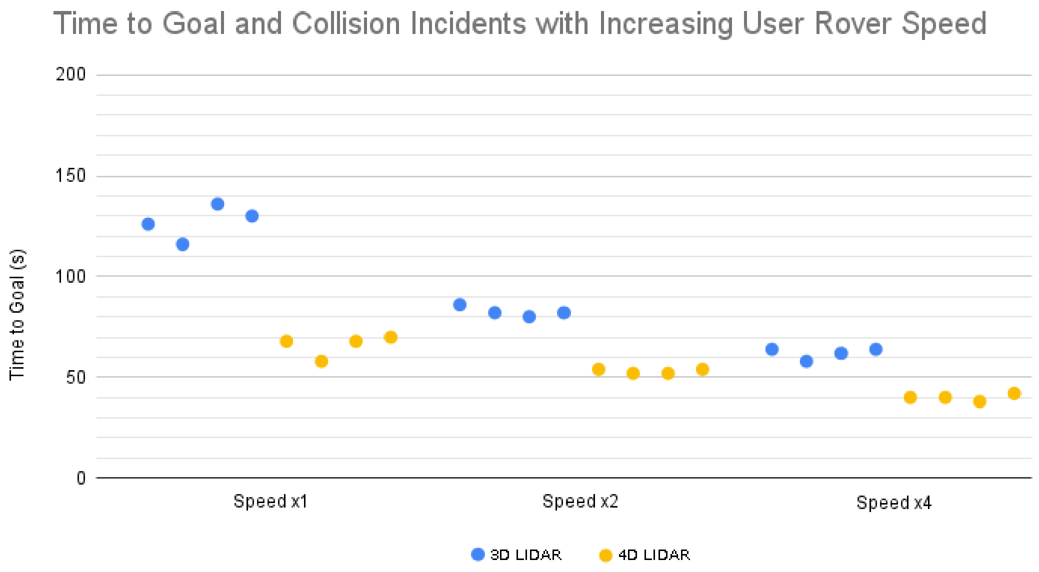


Figure 4. Comparison of time to reach goal (y-axis, unit: seconds) for three different types of speeds. Comparison of 3D LIDAR sensors (blue) and 4D LIDAR sensors (yellow)

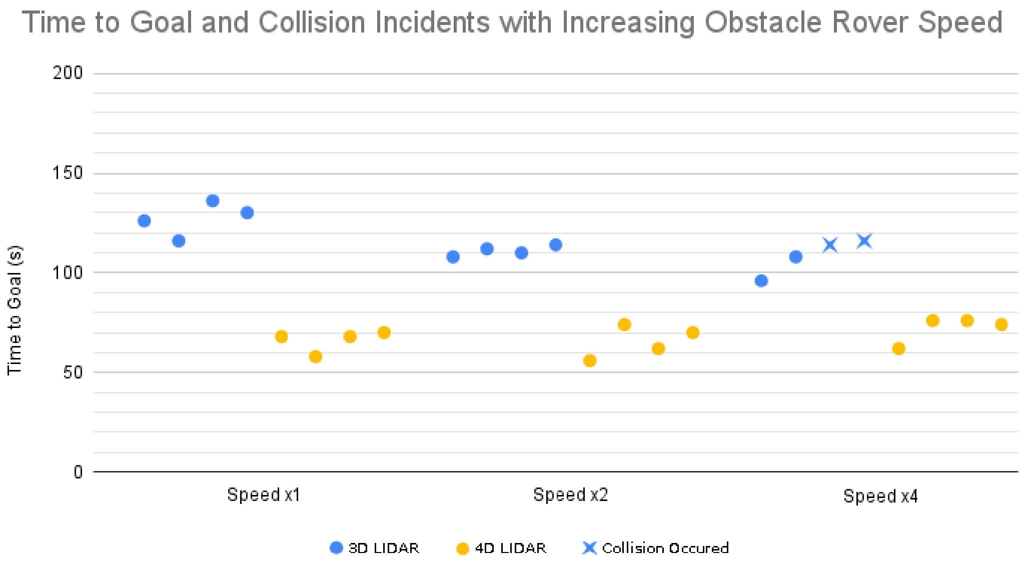
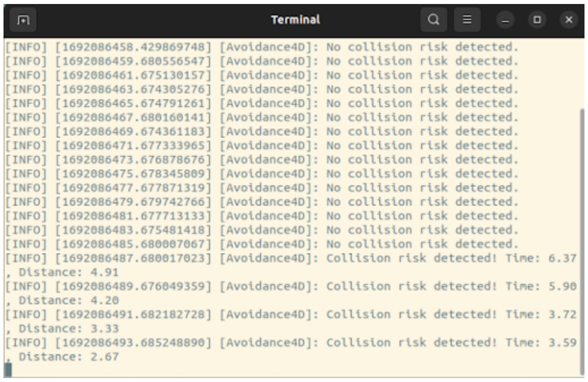


Figure 5. Comparison of time to reach goal (y-axis, unit: seconds) for three different types of speeds, and with obstacles. X-marks denote collisions. Comparison of 3D LIDAR sensors (blue) and 4D LIDAR sensors (yellow)



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[INFO] [1692086458.429869748] [Avoidance4D]: No collision risk detected.
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[INFO] [1692086461.675130157] [Avoidance4D]: No collision risk detected.
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, Distance: 4.91
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, Distance: 4.20
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, Distance: 3.33
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, Distance: 2.67
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Figure 6. Terminal readout of location and collision

5. Discussion

5.1 Significance

The significance of this development lies in the improved efficiency and speed offered by 4D LIDAR compared to its 3D counterpart. Contrary to initial expectations, 4D LIDAR does not replace 3D LIDAR but rather enhances computational speed. This enhancement can potentially result in higher rover autonomy, translating to reduced fuel consumption, shorter mission durations, and increased rover speed. The key difference between the two lies in the level of control they provide over when and how maneuvers are executed. For instance, when faced with an obstacle moving downward while the rover is moving upward, 4D LIDAR enables the rover to swerve left and ascend to navigate around the obstacle effectively. In contrast, 3D LIDAR would prompt the rover to swerve right and descend, as it perceives the obstacle as a static wall, missing the opportunity for more efficient avoidance. It's important to note that both collision avoidance algorithms are equally effective at preventing collisions, making the time improvement offered by 4D LIDAR the primary distinguishing factor.

5.2 Future research

Our research primarily relies on software simulation, although this approach has demonstrated its efficiency, it is imperative to underscore that validation through alternative methods is essential.

Firstly, it is noteworthy that the 4D LIDAR technology is exclusively accessible within drive sim simulators and is primarily designed for urban applications. By integrating this sensor into different environments, we have the potential to subject it to diverse testing conditions, potentially yielding enhanced accuracy.

Furthermore, it is crucial to emphasize that the 4D LIDAR sensor is not originally intended for space applications. Thus, there is room for further exploration and investigation into the adaptation of this advanced technology for use in space rovers.

To bolster our findings, a complementary hardware-oriented analysis could be conducted to provide additional support for our study.

6. Conclusion

In the course of our research, the authors concluded that the 4D LIDAR algorithm outperformed the 3D LIDAR algorithm in terms of both efficiency and safety across all three tested scenarios. The 4D LIDAR system consistently achieved its objectives in significantly less time and, importantly, without encountering any collisions. These results emphasize the substantial advantages of incorporating 4D LIDAR technology into lunar rover systems, enabling safe autonomous rover operations in complex environments aside from rapid task completion.

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