Homework 3

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AuE 8930: Machine Perception and Intelligence

Instructor: Dr. Bing Li, Clemson University, Department of Automotive Engineering

* Refer to Syllabus for homework grading, submission and plagiarism policies;
* Submission files includes (Due March. 25, 2020 11:59 pm):
  - This document file (with answers), and with your program results/visualization;
  - A .zip file of source code (and data if any) with names indicating question number;

Note: You can use any 3rd party libraries and built-in functions

Download the Apollo "Lidar Point Cloud Obstacle Detection & Classification" dataset and description (LiDAR_datasets.zip and LiDAR_datasets_description.pdf) from Canvas/File Homework 3 folder: This Lidar dataset is collected from a 3D Velodyne HDL-64E Lidar.

Question 1) [10 pts]

Select a frame (or a few frames) of LiDAR data file, parse the file and visualize the 3D point cloud of this frame, colored by its reflectivity value.

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1] Lidar data file: bin_files/002_00000001.bin
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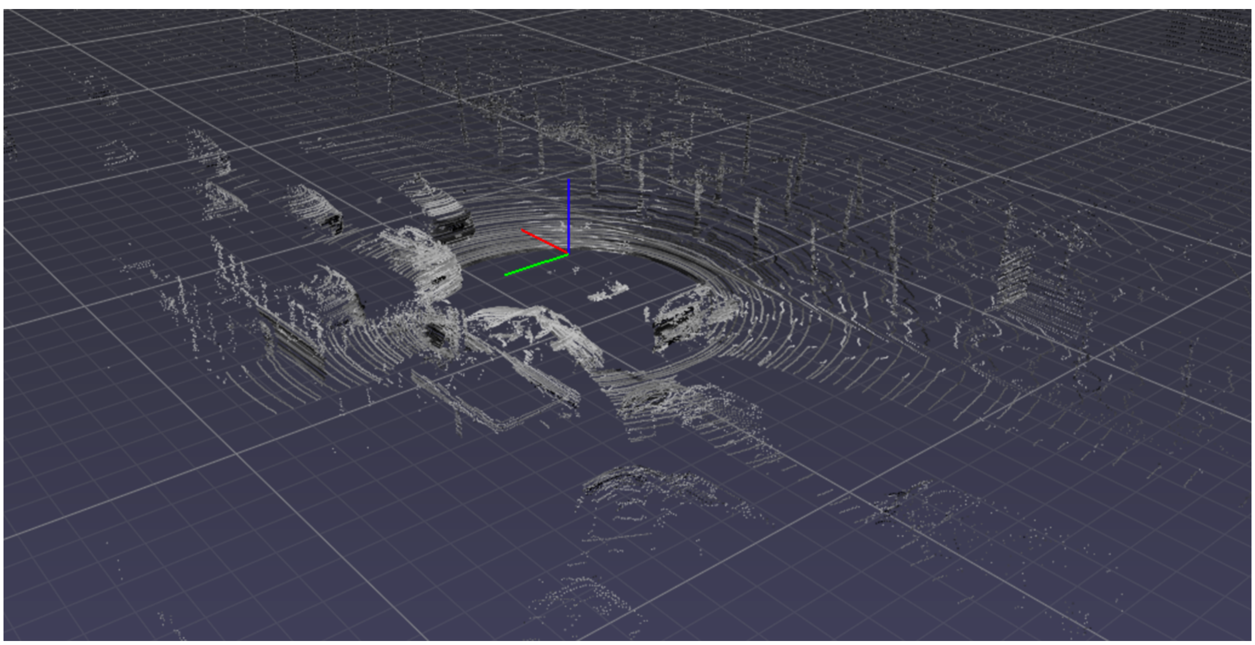
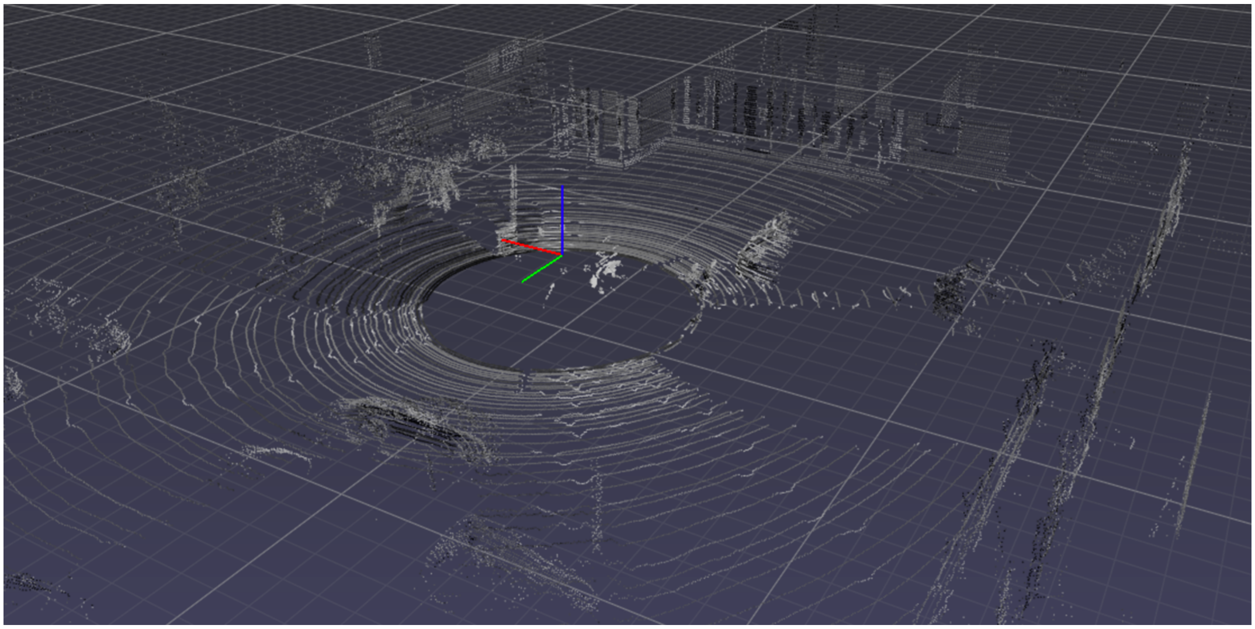
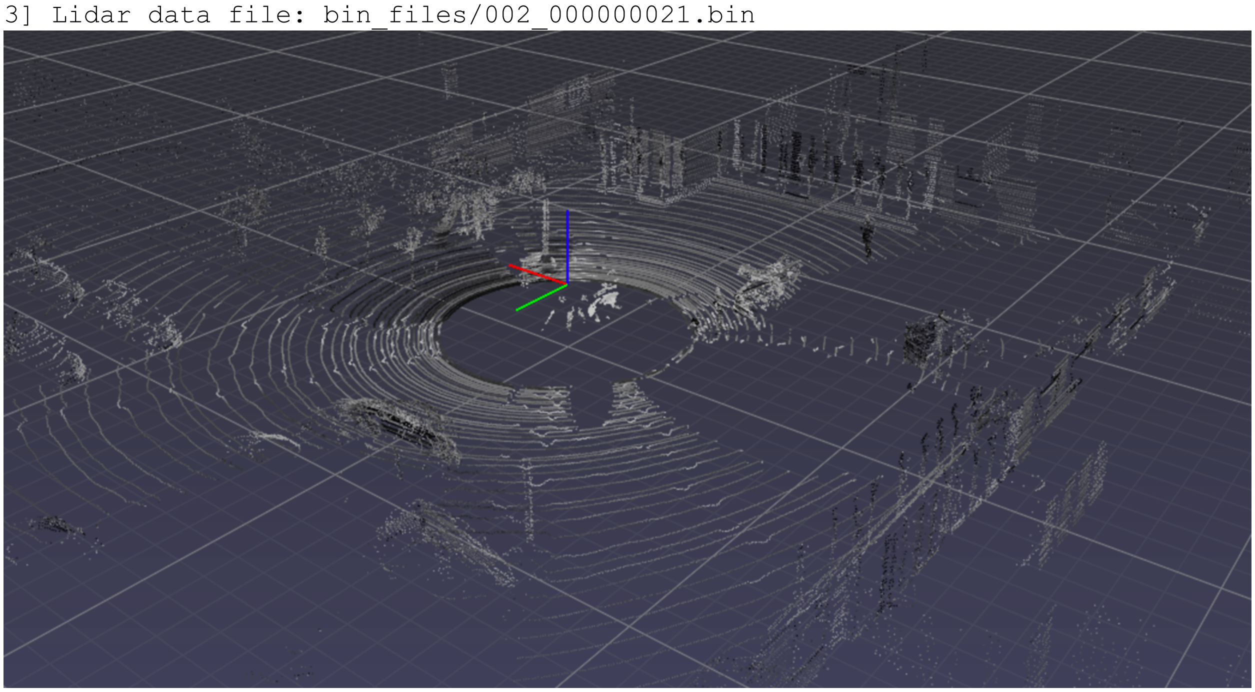


2] Lidar data file: bin_files/002_000000011.bin



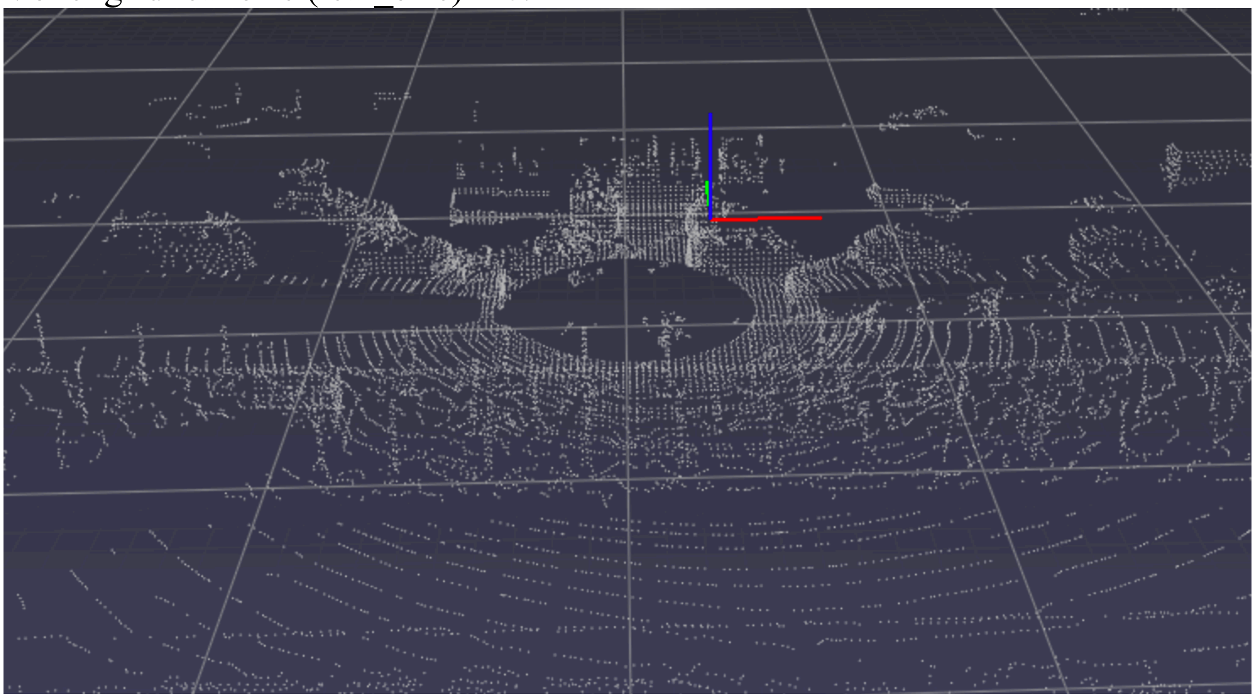
3] Lidar data file: bin_files/002_000000021.bin



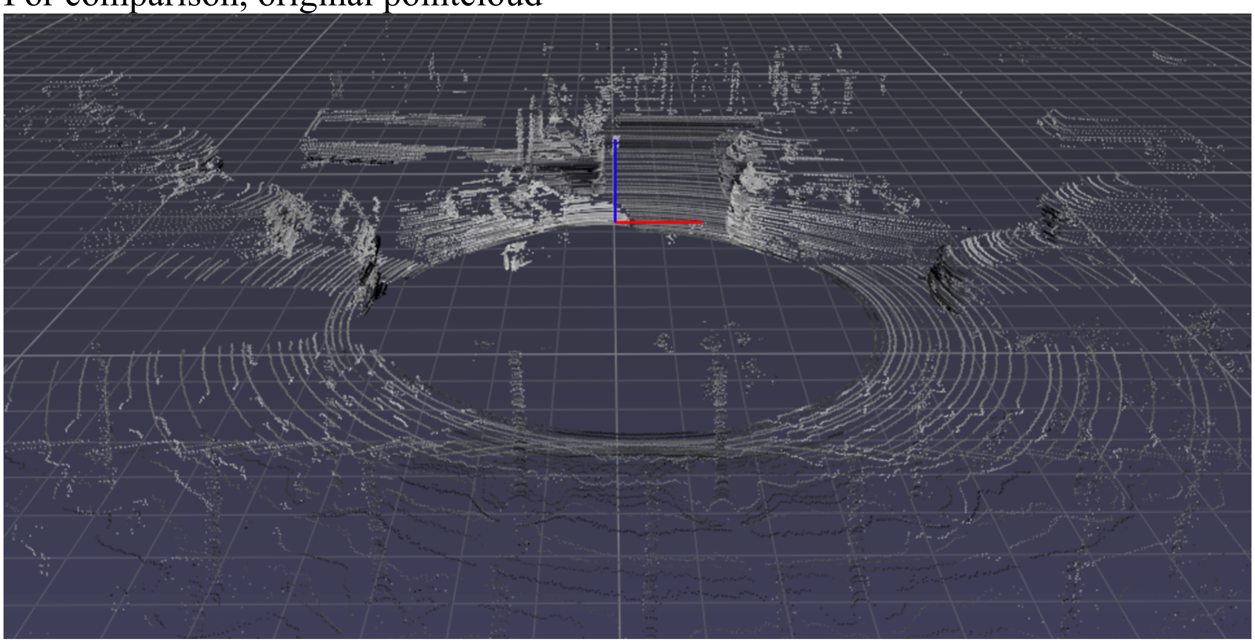
Question 2) [10 pts]

Choose a 3-D resolution granularity, perform voxel filter (or box grid filter) to down-sample all the 3D point cloud points to the 3D voxel space points, and visualize the result points; Lidar data file: bin_files/002_00000001.bin

Voxel grid leaf size (leaf_size) = 0.2m



For comparison, original pointcloud



Question 3) [20 pts]

- Apply RANSAC algorithm (or any others you prefer) to the 3D voxel space points to find a ground plane model. Print out your plane model parameter values result, visualize the plane with the points in the 3D (10 pts);

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- 1] Lidar data file: bin_files/002_00000001.bin

- Model coefficients: 0.0145805468783 0.00373710296117 0.99988669157
  1.55821990967
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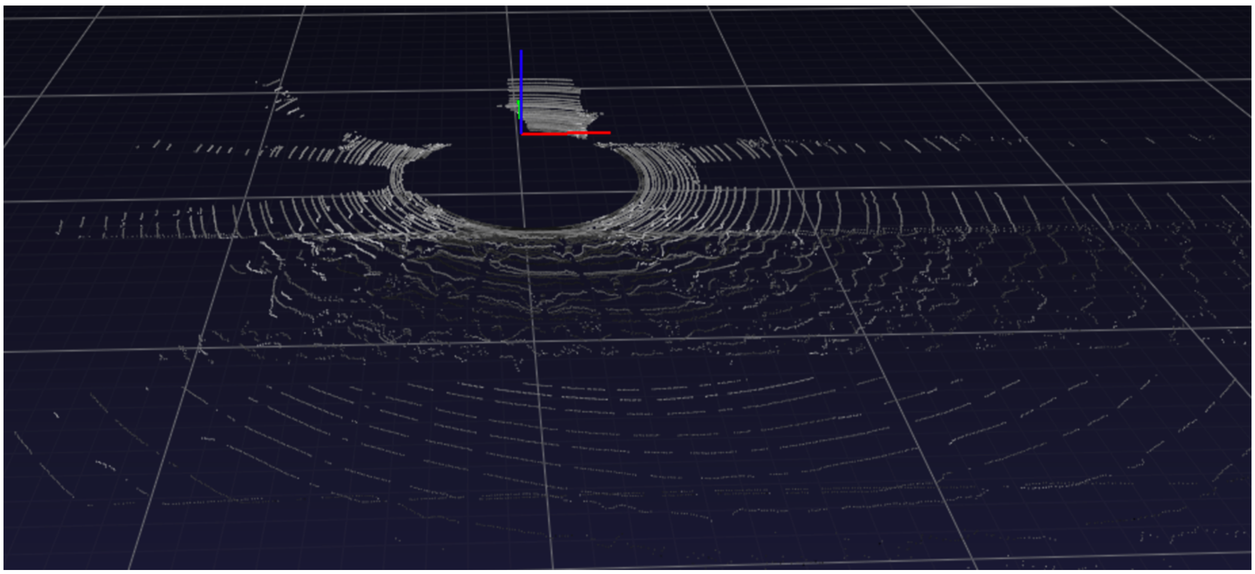
Therefore, equation of ground plane:

0.01458054*X + 0.0037371*Y + 0.9998867*Z + 1.55822 = 0

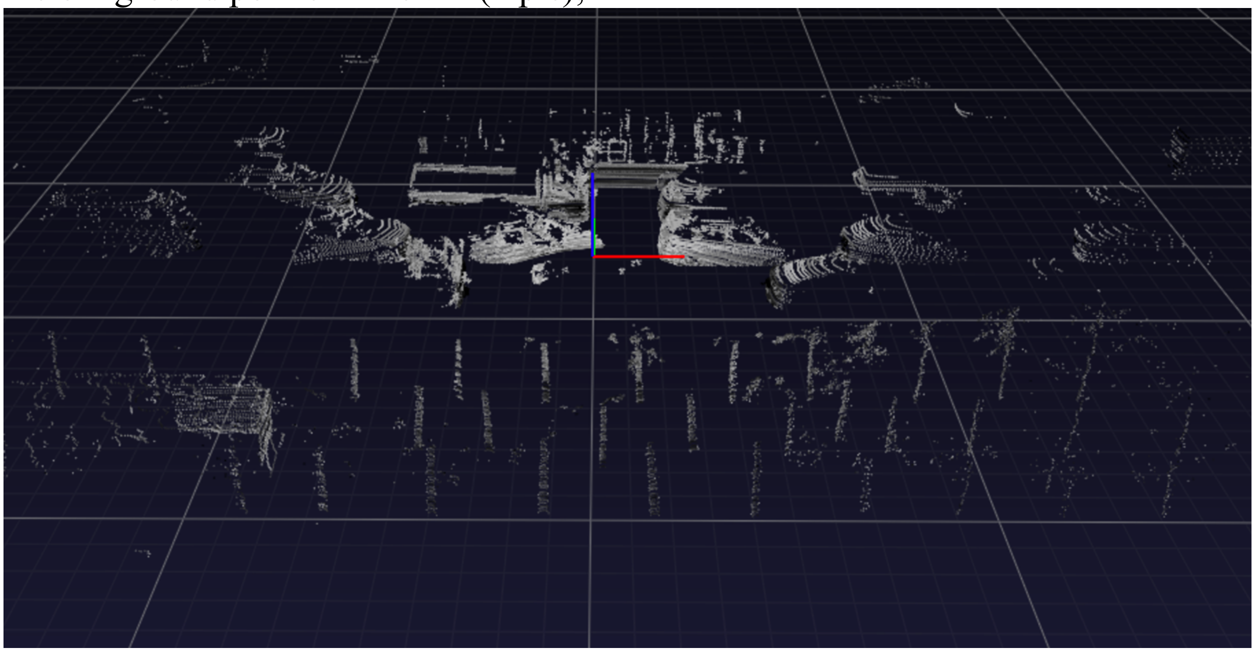


- Analyze the computational time complexity of this algorithm (5 pts).

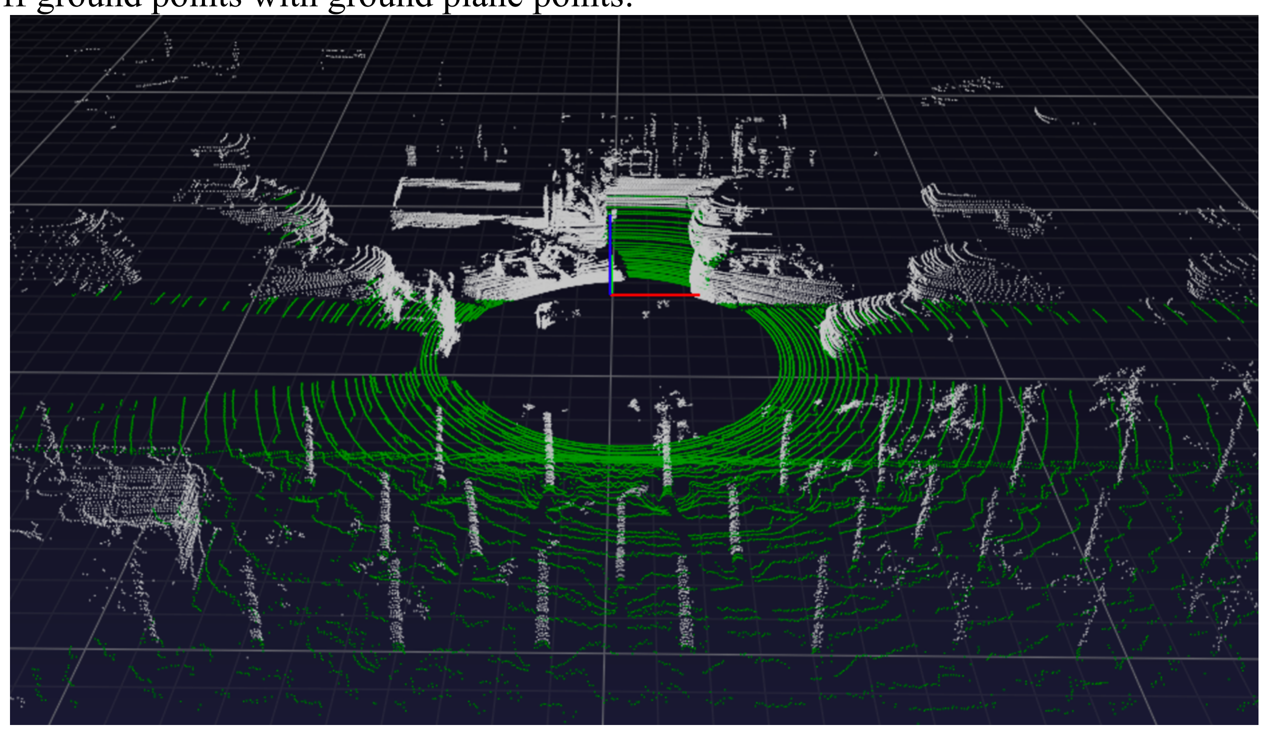
The voxel grid filters down-samples the data by taking a spatial average of the points in the cloud. The sub-sampling rate is adjusted by setting the voxel size (leaf size) along each dimension. The set of points which lie within the bounds of a voxel are assigned to that voxel and will be combined into one output point.
There are two options as to how to represent the distribution of points in a voxel by a single point. In the first, we take the centroid or spatial average of the point distribution. In the second, we simply take the geometrical center of the voxel. Clearly, the first option is more accurate since it takes into account the point distribution inside the voxels. However, it is more computationally intensive since the centroid must be computed for each voxel. The computational cost increases linearly with the number of points in the cloud and the number of voxels.

For first method algorithm, time complexity $\propto$ n*(range/leaf_size) *n
For second method algorithm, time complexity $\propto$ n*(range/leaf_size)

- Remove all the ground planes points in the 3D voxel space points, visualize all the off-ground points in the 3D (5 pts);



Off ground points with ground plane points:



Question 4) [10 pts]

Perform a x-y projection to the off-ground points and get a 2D matrix (you decide what is the element value) and visualize the 2D matrix as an image.

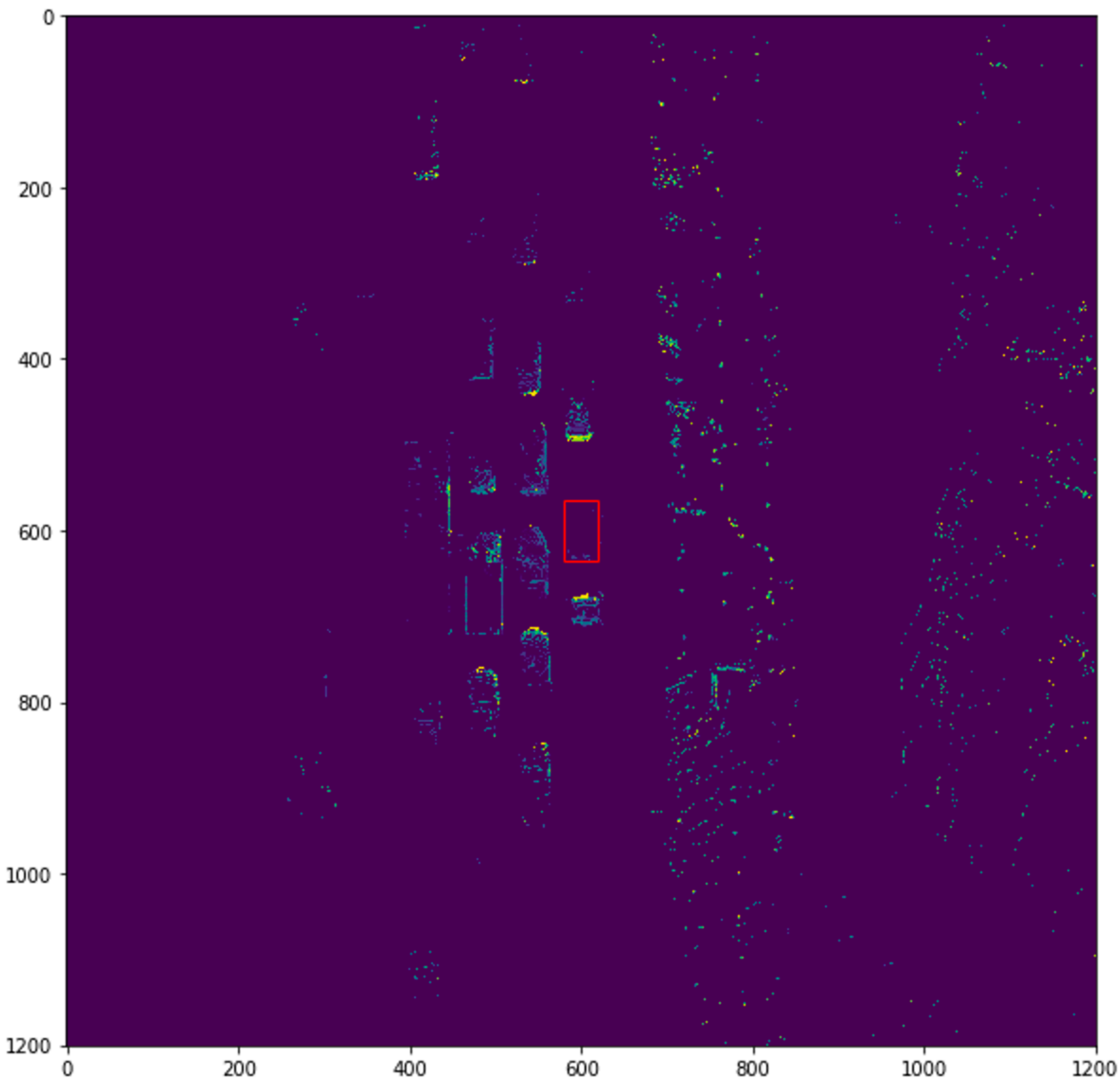
http://www.9math.com/book/projection-point-plane

- **Lidar data file: bin_files/002_00000001.bin**

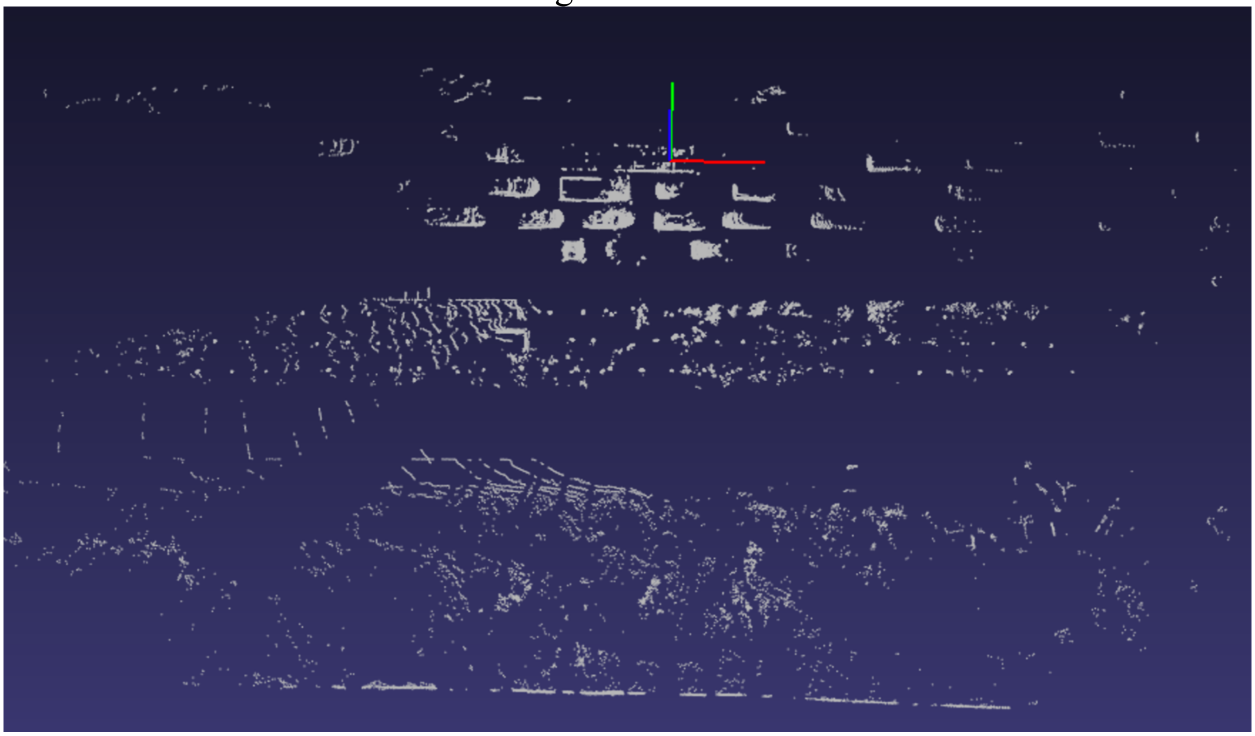
1] Projection of off-ground plane on plane of [a=0, b=0, c=0, d=0]

Here, resolution is taken as = 0.05m

Visualization of 2D matrix as an image



2] Projection of off-ground points on plane calculated in question 3
Visualization of 2D matrix as an image

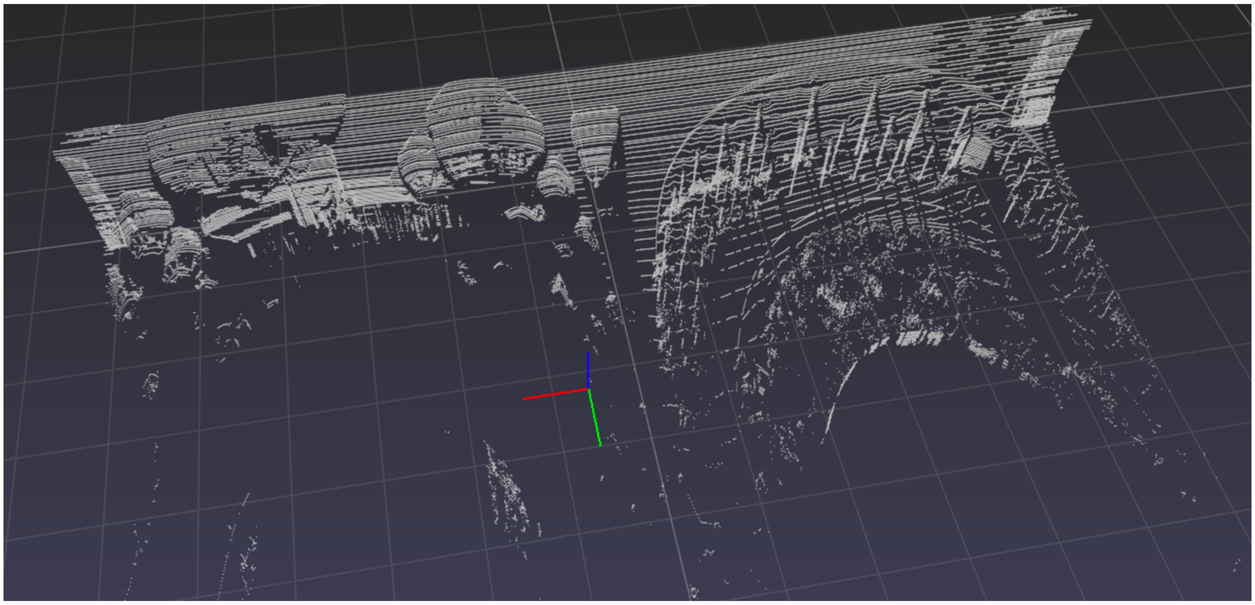


Question 5) [10 pts]

- Based on the raw point cloud data (Questions 1), which is in Cartesian Coordinate, represent and visualize all the point cloud in Polar Coordinate (with horizontal and vertical angels and distance to the original) (5 pts).

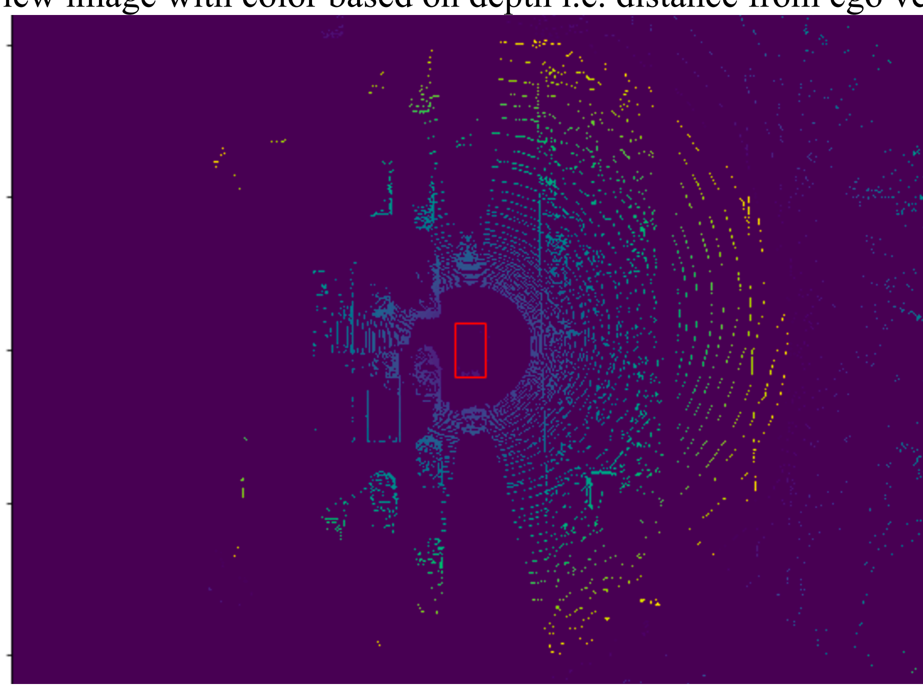
  `Lidar data file: bin_files/002_00000001.bin`

  Scaled for better visualization

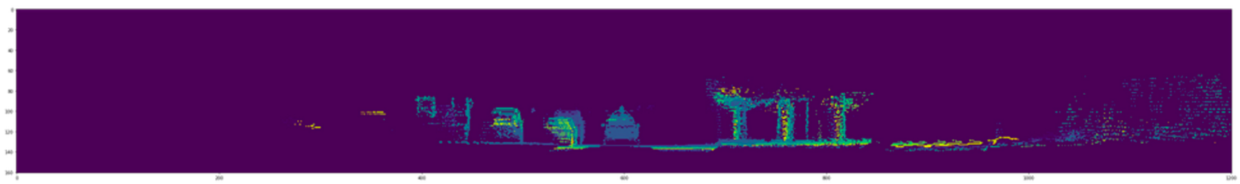
  

- Finally, generate the projected 2D depth image w.r.t horizontal and vertical angels, with intensity value using the distance. Visualize the 2D depth image (5 pts).

  2D top view image with color based on depth i.e. distance from ego vehicle

2D front view image with color based on depth i.e. distance from ego vehicle



Question 5) [40 pts]

Write 2~3 pages of survey on a 3D data measurement related to vehicles.

The grading of this question is based on the contents which the survey covers:

- The importance of this physical quantity measurement (5);
- The challenges of measuring this physical quantity (5);
- Existing solutions of measuring this physical quantity (15);
- Existing problems of measuring this physical quantity (5);

There will be other grading factors (such as novelty, organization, et al) (10);

* You are encouraged to include any drawing/table in the report;

* Attention: use "…" [1] to cite any sentence you literally copied and use … [1] to cite a content you referred to, with reference list in the end;

3D data measurement by LiDAR

Introduction

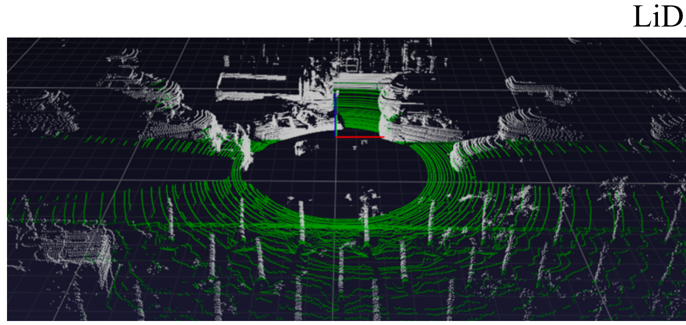
LIDAR stands for light detection and ranging, it is an active form of remote sensing. It does not require electromagnetic radiation rather it record laser pulses that strike the object and back to the sensor. LIDAR measures the distance from the sensor to the object by determining the time between the release of laser pulse to receiving of the reflected pulse. Then multiplying this time by the speed of the light and dividing by two will give the distance between the sensor and the target.

LIDAR systems allow scientists and mapping professionals to examine both natural and manmade environments with accuracy, precision, and flexibility. Lidar uses ultraviolet, visible, or near infrared light to image objects. It can target a wide range of materials, including non-metallic objects, rocks, rain, chemical compounds, aerosols, clouds and even single molecules. A narrow laser beam can map physical features with very high resolutions; for example, an aircraft can map terrain at 30-centimetre resolution or better.
Wavelengths vary to suit the target: from about 10 micrometers (infrared) to approximately 250 nm (UV). Typically, light is reflected via backscattering, as opposed to pure reflection one might find with a mirror. Different types of scattering are used for different lidar applications: most commonly Rayleigh scattering, Mie scattering, Raman scattering, and fluorescence. Suitable combinations of wavelengths can allow for remote mapping of atmospheric contents by identifying wavelength-dependent changes in the intensity of the returned signal
Autonomous vehicles may use lidar for obstacle detection and avoidance to navigate safely through environments, using rotating laser beams. Cost map or point cloud outputs from the lidar sensor provide the necessary data for robot software to determine where potential obstacles exist in the environment and where the robot is in relation to those potential obstacles

Velodyne LiDAR: HLD 64-E

Velodyne – PuckLite

Uber: Autonomous vehicle with LiDAR sensor

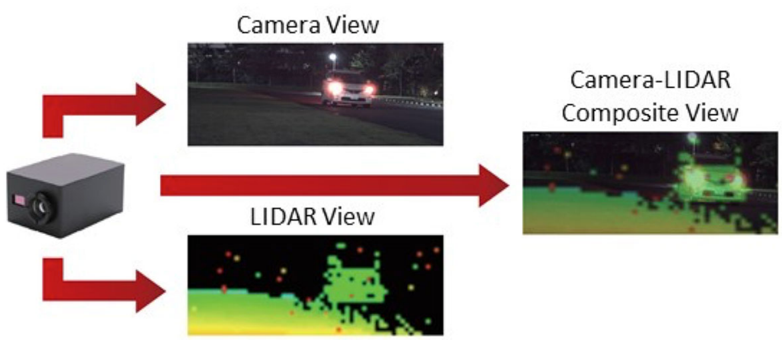


LiDAR data visualization

The importance of LiDAR data measurement

1] LiDAR: Lidar uses active sensors that supply their own illumination source. The energy source hits objects and the reflected energy is detected and measured by sensors. Distance to the object is determined by recording the time between transmitted and backscattered pulses and by using the speed of light to calculate the distance traveled.[30] Flash LIDAR allows for 3D imaging because of the camera's ability to emit a larger flash and sense the spatial relationships and dimensions of area of interest with the returned energy. This allows for more accurate imaging because the captured frames do not need to be stitched together, and the system is not sensitive to platform motion resulting in less distortion.

2] LiDAR – camera fusion: Roadside reflectors that indicate lane border are sometimes hidden due to various reasons. Therefore, other information is needed to recognize the road border. The lidar used in this method can measure the reflectivity from the object. Hence, with this data road border can also be recognized. Also, the usage of sensor with weather-robust head helps detecting the objects even in bad weather conditions. Canopy Height Model before and after flood is a good example. Lidar can detect high detailed canopy height data as well as its road border. Lidar measurements help identify the spatial structure of the obstacle. This helps distinguish objects based on size and estimate the impact of driving over it. [1]



3] LiDAR – RADAR fusion: Lidar systems provide better range and a large field of view which helps detecting obstacles on the curves. This is one major advantage over RADAR systems which have a narrower field of view. The fusion of lidar measurement with different sensors makes the system robust and useful in real-time applications, since lidar dependent systems can't estimate the dynamic information about the detected object

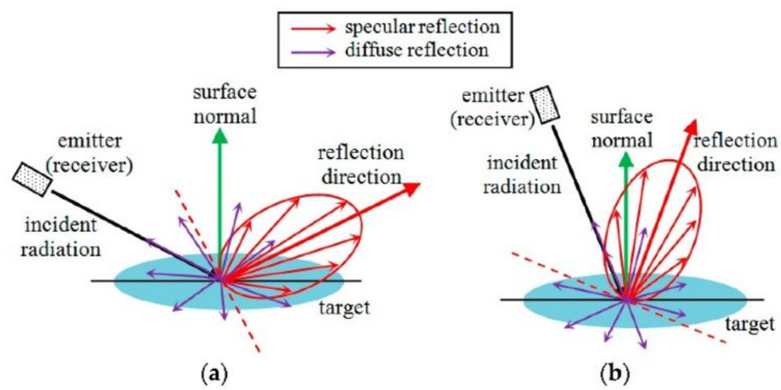
4] Mapping: Surface model created from LIDAR is used to add graphical value to maps. DEM (from LIDAR) is added underneath of all layers that shows the 3D view of the land. Especially LIDAR data (DEM) is added on the aerial photography to show the 3D view which makes easier to plan roads, buildings, bridges and rivers.

5] Imaging: LIDAR technology is used to create 3D image of the object that is in distance. 3D imaging is done with both scanning and non-scanning systems. There is a technology which uses combination of fast gated camera and LIDAR to created 3D image (3D gated viewing laser radar).

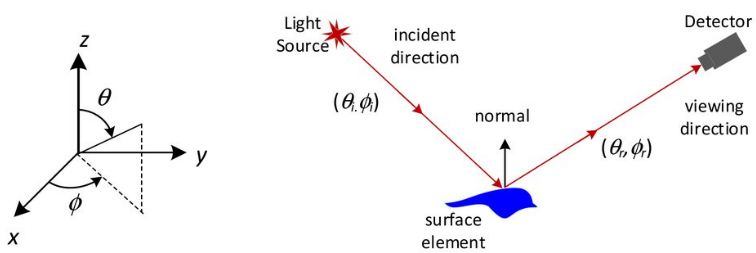
The challenges of measuring LiDAR data

1] High operating costs in some applications: Although LiDAR is cheap when used in huge applications, it can be expensive when applied in smaller areas when collecting data.
2] Ineffective during heavy rain or low hanging clouds: LiDAR pulses may be affected by heavy rains or low hanging clouds because of the effects of refraction. However, the data collected can still be used for sensor fusion.
3] Degraded at high sun angles and reflections: LiDAR technology does not work well in areas or situations where there are high sun angles or huge reflections since the laser pulses depend on the principle of reflection.
4] Very large datasets that are difficult to interpret: LiDAR is a technology that collects very huge datasets that require high level of analysis and interpretation. For this reason, it may take a lot of time to compute/ analyze the data.
5] No International protocols: There are not strict international protocol that guide the collection and analysis of the data when using LiDAR technology hence it is done haphazardly

Diffuse and specular reflection by a surface. At large incidence angles, only diffuse reflections reach the receiver of the LIDAR unit (a); at smaller incidence angles, both diffuse and specular reflection reach the receiver.



Reflection of light by a surface is described by the bidirectional reflectance distribution function, BDRF.



$$BRDF = f(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{L^{surface}(\theta_r, \phi_r)}{E^{surface}(\theta_i, \phi_i)}$$

$$E^{surface}(\theta_i, \phi_i) = Incident\ irradiance\ at\ surface\ in\ direction\ (\theta_i, \phi_i)$$

$$L^{surface}(\theta_r, \phi_r) = Radiance\ of\ the\ surface\ in\ direction\ (\theta_i, \phi_i)$$

Existing solutions of measuring LiDAR data

1] Lasers and detectors for LIDAR / Flash LiDAR: The operation of a time-of-flight lidar requires a pulsed laser capable of producing laser pulses a few nanoseconds long and with a high repetition rate. Wavelength, power, pulse length and repetition rate, as well as beam divergence are key parameters that impact the construction and performance of the lidar unit. Eventually, the selection of a given laser for a lidar unit is determined by the specific mode of lidar operation (more on this later) and by the performance, availability and cost of not only the laser itself, but also of the required photodetectors. The three most common currently used or explored wavelengths for automotive lidar are 905 nm, 940 nm and 1550 nm.

One consideration in lidar design is the presence of ambient light which can interfere with its operation. As such, an operating wavelength that corresponds to a local minimum in the solar spectrum at the surface of the Earth is preferable. The solar spectrum has such minima around 905 nm, 940 nm and 1550 nm caused by absorption by water vapor in the upper atmosphere. Of course, the same absorption can have a detrimental effect on the roundtrip propagation of the lidar laser beam itself. Nonetheless, 905 nm has long been the standard wavelength for range-finding lidar, and its use in the well-established and widely deployed in Velodyne 360° spinning lidar. since 905 nm is within the range of detection by silicon, and thus also compatible with CMOS detector array technology.

One drawback of 905 nm lasers is that they fall within the range of wavelengths that can penetrate through the front and the interior vitreous humor of the eye and reach the sensitive retina. Thus, safety rules limit the allowed power density that can be employed in lidar operation, and through that, they limit the 905 nm lidar range to within tens of meters to 100 m. The 1550 nm wavelength offers a significant advantage in this respect, as it falls beyond the ~1400 nm retinal hazard limit. Light beyond 1400 nm gets absorbed in the front layers of the eye (cornea, aqueous humor and the lens) mainly because of watery absorption and does not reach the retina. Power levels as much as 10 times or even 40 times higher than at 905 nm can be used. Also, the number of 1550 nm photons to be detected at any power level is 1.7 times larger than that of 905 nm photons at the same power, and less sunlight reaches the ground at 1550 nm compared to 905 nm. Because of all these, 1550 nm lidar can achieve longer range. The use of the 1550 nm laser diodes as well as other components for fiber optics communications networks is also an advantage exploited in the development of coherent Frequency Modulated Continuous Wave (FMCW) lidar. [11]

Since this type of lidar requires continuous wave lasers with long coherence length, narrow-linewidth distributed Bragg reflector (DBR) diode lasers are used. The downside of a 1550 nm lidar is the increased cost of the detector, as well as the lack of detector array offerings (for flash lidar), since more exotic materials like Ge, InGaAs, or InGaAsP detectors have to be used. The use of optimized detectors is paramount to the lidar performance, and another way to improve the range of a lidar unit. Because only a small fraction of the photons emitted by the laser make it back to the detector, selecting the right photodetectors with high detection sensitivity, high internal gain and low noise is critical. For 905 nm lidar, silicon avalanche photodiodes (APDs), single photon avalanche diodes and silicon photomultipliers (SiPMs) are popular detectors, each with its specific advantages and limitations. For 1550 nm lasers, mostly InGaAs photodiodes or avalanche photodiodes are used.

Aside from its 1550 nm DBR diode lasers, for example, Lumentum also offers 940 nm vertical cavity surface emitting lasers (VCSEL) optimized for high resolution flash lidar. The use of 850 nm laser offers better performance in humid weather due to lower water vapor absorption at 850 nm (but not through rain or fog). The 850 nm wavelength also results in improved sensitivity (by a factor of 2, when compared to 905 nm) of the silicon CMOS detector array used in the flash lidar, to the point where "the lidar is the camera."

2] Propagation of light in LIDAR operation: Three fundamental optics phenomena bear heavily on the performance of a lidar system: absorption, scattering and reflection of light. In poor weather conditions (rain, snow, heavy fog), LiDAR's poor performance is mainly due to absorption of light by water and to atmospheric scattering of light out of the directional laser beam, thus reducing the photon flux available for reflection by the target and eventually for detection by the lidar unit. The reflection of light, on the other hand, is what allows the lidar to detect the world around it. The reflections used for constructing the 3D point cloud images are obviously mostly the diffuse reflections from the various points of the target scene, but both diffuse and specular reflections contribute and affect the performance of the system. In the case of a Lambertian surface (ideal diffusion surface), the radiance of the surface is isotropic and the BRDF of the surface is a mere constant:

$$BRDF_{Lambertian} = f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{\rho}{\pi}$$

where ρ is the reflectance (reflectivity) of the surface. This shows that the brightness of a Lambertian surface appears uniform from any direction of view. The reflectance of the different elements in a real-life target scene is one of the wildest cards in the operation of a lidar. the lidar will scan over vehicles and static surrounding objects (some highly reflective, some not), highly reflective license plates and road signs, lane and road-side marking retroreflectors and others, that could each flood (saturate) the detector. At the same time other surfaces and objects like the road pavement, car tires, trees without foliage, etc. typically have low reflectance. The reflectance of the target and the desired detection range can impose rather stringent demands on the required performance of the photodetector(s) in the lidar unit. The problem of ambient light – which can result in a degraded signal-to-noise ratio of the detected signal – and that of the losses within the lidar unit itself brings about another fundamental light phenomenon and major component of any optics or photonics course: interference of light, with focus on thin film interference, narrow band-pass filters and antireflection coatings. to minimize the reflective losses of the useful signal at the operation wavelength while also maximizing ambient light rejection, the lidar unit must incorporate appropriately coated optics with multiple capabilities. This includes narrow band-pass filters at the lidar operating wavelength in front of the detector, and appropriately coated external windows for the entire lidar unit. The problem of (multiple) reflections gets even more complicated when the lidar unit is integrated with other components of the vehicle.
"For example, Magneti Marelli, an automotive supplier company with strong presence in the automotive lighting market has introduced the concept of Smart Corner™ which aims for the integration of all sensors (cameras, radar and lidar) into the headlight and taillight fixtures of the vehicle. This approach, while desirable and attractive from the vehicle design aesthetics point of view, potentially creates additional light reflection problems that have to be identified, quantified and addressed." [12]

Existing problems of measuring LiDAR data

While the deployment of lidar imaging systems for autonomous vehicles seems unstoppable, and major automotive manufacturers are starting to select providers for data collection units and introducing them in commercial vehicles, the final technology implementation is still uncertain in several relevant details. The selection of the most appropriate technology and scanning strategy among the different competing alternatives in terms of cost and functionality still needs in-depth work and becomes one of the most visible examples of the current uncertainty in the industry. However, beyond the final technology of choice, there are still several relevant issues that need to be worked out for the full implementation of lidar imaging systems in commercial vehicles.[3]

1] Spatial Resolution: Dense point clouds with a large spatial resolution both in the horizontal and vertical directions are one of the cornerstones of object detection. While detectivity at long range has been achieved even for objects with low reflectivity's, the reliable identification of objects at significant distances needs enhancement, as shown by the trend in larger and larger spatial resolution.
"A rule-of-thumb number says objects above 10 cm can hit the bumper of some cars, and braking or evasion at highway speeds needs at least detection of hazards at 150 m. This brings on a spatial resolution of 0.67 mrad for detecting a point on the object. If five to ten points are considered for reliable identification of an object, then spatial resolution in all directions needs to be reduced to just 67 μrad, a number which is really demanding. Although cumulative detection procedures, statistics and machine learning may help to improve detection." [4]
It is still clear that larger spatial resolutions, especially along the vertical axis, will be required if autonomous vehicles need to drive at fast speeds on highways. Approaches with a spatial resolution close to 1 mrad in the horizontal and vertical directions preserving real-time operation start to be available.

2] Sensor Fusion and Data Management: Despite lidar being the sensor in the headlines, a complex sensor suite involving a number of sensors is expected to be required. Such sensors need to have complementary measurement principles and failure modes to get a safe and reliable solution for fully autonomous cars. In general, short and long-range radar and lidar, combined with ultrasound and vision cameras are generally accepted as parts of the potential final solution. Such amounts of information, without including the high-density point clouds mentioned above, need to be fused and processed in real-time to detect hazards and react timely to them.
"This information has been estimated to be somewhere between 11TB and 140 TB per day, with bandwidths in the range of 19 TB/h to 40 TB/h" [7]
which becomes a relevant storage, processing and management problem by itself. Regarding sensor fusion procedures, they may be dependent on the operative conditions of the moment, but even with this assumption, processes are not obvious, involving different approaches for different lidar principles: fusing information from a camera and a mechanical scanning lidar covering 360 deg is harder than in the limited FOV of a voice coil or MEMS scanner. Such procedures are not as obvious as parallax errors are prone to appear due to the different position and geometry of the sensors, while posing demanding requirements on the computing power of the vehicle in any case, even for embedded solutions.

3] Sensor Distribution: If the components of the sensor suite are still under definition and in an early stage within the production cycle for manufacturing, its potential distribution along the vehicle is not a simple decision to take. The number of sensors reasonably mounted on the self-driving car is estimated to be somewhere between 20 and 40.
Further, data collection and machine learning procedures may become affected by relevant changes in the pose of the sensor, its position and field of view, in the worst cases forcing the tedious data collection process to be started again. It is generally accepted that the current approach is taken for robotaxis in controlled environments or data collection vehicles, with lidars and sensors fixed on the roof of the vehicle, which is not acceptable for commercial units. Where to place the lidar, if not on the roof, has relevant implications related to covered FOV and the number of units required, with the associated cost consequences. The decision has relevant implications also on the vehicle itself, where currently not much free space is available for sensors with dimensions of current units proposed in the 10–20 cm range in all dimensions. Further, the distribution and position of the sensors are key for aspects such as reliability, dirt management, servicing or survival of the unit after minor crashes. Despite the most usual approach is to embed the lidar in the central front panel of the vehicle, there are alternatives such as e.g. headlamps as potential lodging of lidar sensors. [8]

4] Bad Weather Conditions: Autonomous driving tests are, up to now, handled mostly in sunny environments, such as California or Texas. However, the quality of the detection under fog, rain and snow, especially if they are extreme, becomes severely degraded, especially regarding range due to the absorption and scattering events induced by water droplets. This introduces a large number of false detection alarms from the backscattered intensity, reducing the reliability of the sensor. Further, snowflakes, fog and rain droplets have different shapes, distributions and sizes and affect different aspects of the detection, complicating a precise modeling. Managing lidar imaging in extreme weather conditions is a pending subject of the technology which needs to be tackled in the near future for commercial deployment of automated vehicles.

5] Mutual Interference: In world full of self-driving cars each with its lidar imaging system emitting pulses or waves at high frequency. Imagine them in a traffic jam, or in an area with large vehicle density. The uniqueness of the signal emitted by each lidar needs to be ensured, so the source of one vehicle does not trigger the detection in other vehicles in their surroundings. Although some measurement principles may have advantages over the others, the implementation of discrimination patterns among each individual vehicle may be challenging. [9] For instance, FMCW detection appears to be better than direct pulse detection as the modulation frequency and amplitude, combined with the coherent detection implemented, may help to add personalized signatures to each lidar. However, the implementation of this concept at the mass scale needs to be carefully considered, and possibly supported by improved data processing to filter out false detections while preserving the reliability of the unit.

References:

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3] https://www.mdpi.com/2076-3417/9/19/4093/html

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10] https://www.mdpi.com/2076-3417/9/19/4093/htm (very resourceful)

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13] https://www.researchandmarkets.com/research/cvwt57/lidar?w=5

14] https://www.aeye.ai/technology/rethinking-the-three-rs-of-lidar-rate-resolution-and-range/