Methodology to Investigate Interference using Off-The-Shelf LiDARs

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***Abstract*—With the increase of assisted and automated functions provided on new vehicles and some automotive manufacturers starting to equip high end vehicles with LiDARs, there is a need to consider and analyse the effects of having LiDAR sensors on different vehicles interacting with each other in close proximity (e.g. cities, highways, crossroads, etc.). This paper investigates interference between 360 degree scanning LiDARs, which are one of the common typologies of automotive LiDARs. One LiDAR was selected as the victim, and 5 different LiDARs were used one by one as offenders. The victim and offending LiDARs were placed in a controlled environment to reduce sources of noise, and several sets of measurements were carried out and repeated at least four times. When the attacker and victim LiDARs were turned on at the same time some variations in the signals were observed, however the statistical variation was too low to be able to identify interference. As a result, this work highlights that there is no obvious effect of interference witnessed between the selected off-the-shelf 360 degree LiDAR sensors; this lack of interference can be attributed to the working principle of this type of LiDAR and low probability of having directly interfering beams, and also to the focusing and filtering optical circuits that the LiDARs have by design. The presented results confirm that mechanical scanning LiDAR can be used safely for assisted and automated driving even in situations with multiple LiDARs.**

***Index Terms*—automotive, LiDAR, sensors, automated, vehicles**

I. Introduction

The introduction of automated vehicles promises to bring with it a number of benefits including improved safety, the release of time usually spent driving, and convenient shared mobility [1]. LiDAR is one of the perception sensors expected to be present in the sensor suite for future automated vehicles and in some cases it is described as the most important technology for higher levels of automation [2], [3].

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Other sensors expected to be present on the vehicle are camera and RADAR (and ultrasonic sensors) [3], [4]. RADARs have good all-weather capability and are good at detecting range and velocity but have poor angular resolution, particularly at longer range, and are not very good at classifying objects [3], [4]. Cameras are very good at classifying objects and provide colour information, but have poor depth perception, struggle in poor light or adverse weather and cannot detect velocity [3]. LiDARs help complement the weaknesses of RADAR and camera as they have very good angular resolution and are good at detecting range [3], [5]. Hence, LiDAR will be a necessary part of the car sensing system along with RADAR and Camera, as they complement each other to provide a more complete sensing capability.

In addition, RADAR sensors are vulnerable to interference from other RADAR sensors, affecting the accuracy of the sensing of the environment through lower Signal-to-Noise Ratio (SNR) and ghost targets [3], [4], [6]. This is further evidence for the need for a robust sensor suite that can cope when some of its sensors are unusable. Whether LiDAR sensors are also vulnerable to interference needs to be investigated.

If it is expected that automated vehicles will be equipped with LiDARs, then it is reasonable to assume that there will be occasions where many LiDAR are operating in close proximity. If a vehicle is fitted with LiDAR and is sharing the road with another vehicle that is fitted with LiDAR, will they interfere with each other, and will this affect the sensor performance? If the answer to both these questions is yes, then whether this interference affects the automated system's ability to function will need to be answered. The investigation of LiDAR interference is important as it helps us understand whether interference will affect the robustness of LiDAR sensors when implemented on a vehicle. Consider the situation where a vehicle is waiting at a junction to cross traffic lanes. Should one of the vehicles passing by have LiDARs fitted that interfere with the ego vehicle, the passing vehicle could be misplaced by the ego vehicle's perception system. This misplacement could mean that the ego vehicle performs an unsafe crossing based on inaccurate information about its surroundings, causing a collision.

This paper contributes to the knowledge on LiDAR interference by providing results that indicate no obvious effect from interference is witnessed from 360° LiDAR sensors. This is important for the trust in the robustness of the sensor and is contrary to previous literature which found evidence of interference. This literature is explored in section II. The methodology for this paper contribution is presented in section III and the findings are presented in section IV. In section V the findings are discussed and finally this paper concludes and suggests further work in section VI.

II. Background

In this section the literature related to automotive LiDAR interference is examined, however, to the best of the authors' knowledge, only a few groups have been investigating this issue.

A. Related Literature

1) Diehm et al. [7]: These authors looked at the effectiveness of filters to remove crosstalk points from received point clouds using two LiDARs mounted on the roof of a vehicle. Their vehicle was equipped with two 360° LiDAR with 64 channels (namely, two Velodyne HDL-64) and positioned in an outdoor environment to collect point cloud data. Two environments were used, one with the vehicle in between a number of buildings and the other with the vehicle in an open landscape. The authors argued that interference between these two particular LiDAR sensors is witnessed in the point clouds and can be removed through processing, in close to real time. However, the measurements were carried out in real-world open environment, impossible to control. The authors themselves acknowledged possible changes due to wind moving trees and other movements, which is a potential weakness to consider in the analysis of the findings.

2) Kim et al. [8]–[10]: This group of authors have also been looking at interference between LiDAR sensors. Their experimental setup involved two 2D scanning LiDARs (namely two SICK LMS-511) and the measurements were carried out in a 4m by 5.3m room. In all of their tests the authors witnessed an increase of points in unexpected places as a result of adding the offending LiDAR. However, the used LiDAR are not the state-of-art for the sensors expected be used on vehicles in the near future.

3) Hwang, Yun and Lee [11], [12]: These authors proposed a "True-Random" LiDAR, as a robust design against interference. In the paper, the authors presented a proof of concept prototype used for the experiments. However, the study is limited by the use of a prototype in a specific test setup with selected test cases, and hence it would be necessary to confirm that the results are similar when and if the physical sensor would be realised.

4) Nunes-Pereira et al. [13]: These authors looked at interference between two LiDAR sensors looking directly at each other. The sensors used were a 1D LiDAR in combination with a 360° LiDAR with 8 vertical channels, respectively a Garmin Lite v3 and a Quanergy M8. They found that the Quanergy did not interfere with the Garmin which was to be expected as the Garmin 1D LiDAR uses highly unique and identifiable laser pulses [13]. However, The Garmin was shown to interfere with the Quanergy producing ghost targets which were concentrated in the direction of the Garmin LiDAR and present in all vertical channels. This result suggests that we should expect to see LiDAR interference, however, the Garmin Lite v3 is not representative of a LiDAR that would be used to support assisted and automated driving functions on a vehicle in the near future.

5) Popko, Gaylord and Valenta [14], [15]: These three authors have completed experimental work similar to Kim et al. mentioned earlier [8]–[10]. In this case, all tests were completed in a basement of a building using two 2D single channel scanning LiDAR with a field of view of 190°, namely two SICK LMS532; one LiDAR was used as the victim and the second one as the offending LiDAR. Interference points were identified using tolerance on the distance returned for each measurement. In all test cases some interference was witnessed between the two LiDAR, with between 0.0225% and 1.04% of returns resulting from interference, according to the authors. However, since the LiDAR used were quite basic LiDAR, it is difficult to understand whether these percentages are representative of what we would see from more advanced LiDAR, with more channels, that one will likely see equipped to vehicles.

6) Briñón-Arranz et al. [16]: These authors set up an offending LiDAR and victim LiDAR at a distance of 5m, 10m, 15m and 20m from each other and looked at the effect this distance had on the victim LiDAR. They used cardboard to hide all but the optical window of the LiDAR and tested with 3 scanning LiDAR (two of which were used as the victim), and two non-scanning LiDAR, the names of which were kept anonymous. They found that as much as 70% of points in some tests were lost as a result of the offending LiDAR and some of the returned points were several hundred metres in range [16]. As the authors give no information about the specifications of the LiDAR used, it is not possible to say whether these were representative LiDAR for assisted and automated driving. The environment used appears to be controlled, however the use of cardboard to block all but the optical window of the LiDAR seems to be an attempt to force interference.

B. Summary

When considering all of this previous work, it is clear there is a gap in the literature that needs filling. This is the need to test LiDAR interference on off-the-shelf physical LiDAR using off-the-shelf physical LiDAR as the offending LiDAR as well, and in the real and controlled world, not only in simulation. While Diehm et al. have attempted this task to some extent, their work only includes two identical LiDARs and in environments that are not controllable [7]. Hence, it is difficult to know whether their baseline is consistent and accurate. As a consequence, a methodology to test multiple different off-the-shelf advanced LiDAR in a real-world environment is needed. It will be investigated whether interference occurs, without trying to create conditions for this to occur like in Briñón-Arranz et al. [16]. In the following sections we present a robust methodology for testing 3D scanning automotive LiDAR interference. As a part of this work and as a starting point, the experiments have been carried out in controlled environment, however the methodology can be replicated into real conditions. Later we will present the results obtained from this methodology and discuss what this means in the context of vehicle automation.

III. Methodology

As discussed in the previous section, to achieve the aim of this work, a controlled location was selected. Controllability of the location was identified as a key aspect to ensure repeatability of measurements and that data collections with different LiDAR sensors are directly comparable. However, the measurement procedures described in this section can be reused in the future to carry out measurements in the open and to have them comparable to the results reported in this paper. They can be also used to test LiDAR models/manufacturers not covered by this work.

A. Test Environment

The 3xD simulator facility at WMG, University of Warwick shown in Fig. 1 was selected as the controlled environment for the experiments. This facility is a 360° immersive simulator that uses 8 projectors to project simulation visuals onto the surrounding circular walls. The walls are very smooth and coated with a special reflective paint to ensure the image is clearly displayed. While it is unclear how reflective this paint is for light in the near infrared, it should be fairly uniform in its reflection around the 360° chamber. The simulator is built in a Faraday cage, meaning that beyond these walls there is a highly absorbent material that should limit the possibility of LiDAR beams being reflected back to the LiDAR from objects beyond the simulator walls. While it may be that the material absorption is slightly degraded in the near infrared (maximum absorption is designed for other wavelengths), it should help ensure a consistent reflection in sequential data collections.

B. Noise in the Environment

To determine the presence and magnitude of interference in our experiments we need to be able to differentiate suspected interference from the measurement noise, both from the environment and inherent to the sensor. To do this, we positioned the victim LiDAR alone in centre of the simulator and recorded its output. This process gives point clouds for the environment when there are no objects to reflect off. Hence, any differentiation in the range measurements observed for a particular point will be due to noise. Therefore, by looking at 100 frames of the LiDAR output one can understand the magnitude in variability of range which can be attributed to noise. Standard deviation and statistical range were used to assess this variability, as standard deviation will give a representation of the distribution of the variability and statistical range will help determine whether large changes in range are observed.

Fig. 1. Left) Image showing how the 3xD simulator operates as a simulator for driver-in-the-loop applications. Right) Image showing how the 3xD simulator at WMG was adapted to carry out interference measurements. In the image there is a single LiDAR (i.e. the victim LiDAR) mounted on a trolley in the centre of the simulator

C. Test Setup

Fig. 2 shows a representation of the test setup used for the experiments. The blue circle represents the walls of the simulator. In the centre there is the victim LiDAR and around 2m in each axial direction is where the offending LiDAR would be situated. There are ‘four’ offending LiDAR positions here, as for each offending LiDAR an experiment is performed with it in front, behind, to the left and to the right of the victim LiDAR. The behind experiment allows it to be determined if any scattered interference is witnessed, as the offending LiDAR is situated in a shielded zone that is blocked by the apparatus that holds the victim LiDAR. In the results and analysis these points are excluded to remove the shielded section. The left and right side here allow it to be determined if any effect witnessed in the front direction is repeated in the side directions. Theoretically no difference should be observed for 360° LiDAR as they scan in all directions. Each experiment for each direction involved two data recordings, with 100 frames each, with the offending LiDAR off and two data recordings, with 100 frames each, with the offending LiDAR on. The level of variability between measurements can be assessed by comparing the two data collections when the offending LiDAR is off to create a ‘baseline’. Then, the data collections with the offending LiDAR on can be compared against the data collections with the offending LiDAR off to create a ‘test’. By comparing the test and baseline and accounting for intrinsic sensor noise such as range resolution, it is possible to assess if there is interference caused by the offending LiDAR.

The resulting data from each data collection from when the offending LiDAR is on and for when it is off is a point cloud for each frame repeated 100 times (i.e. 100 frames or 100 point clouds). From these point clouds the range returns for each point in each frame was extracted. Baseline 1 and Baseline 2 variables were created by repeating the measurements 4 times. Four test variables were created. Each one was calculated

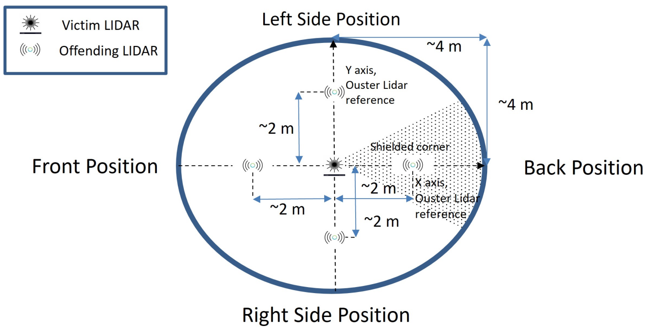

Fig. 2. Top view (not at scale) of the circular WMG 3xD simulator chamber used for the tests setup with the positions of the victim and offending/attacking LiDARs

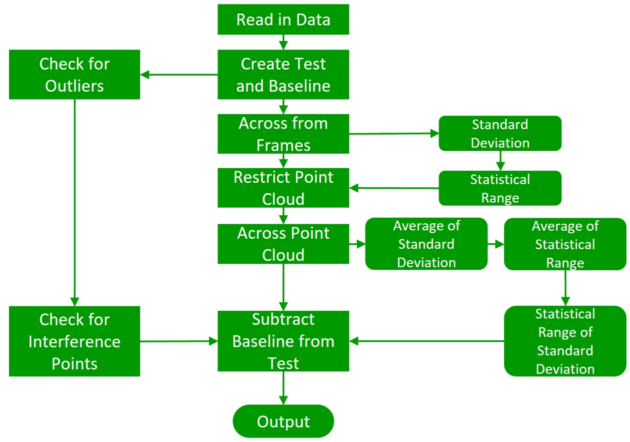

Fig. 3. Flow Chart showing schematically the process used to analyse the collected point clouds

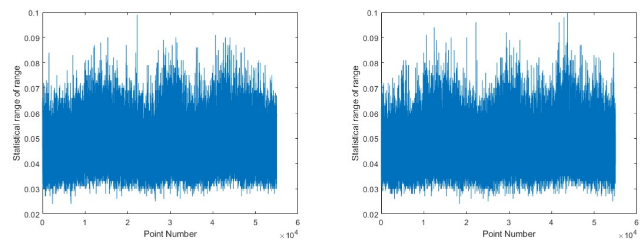

Fig. 4. Statistical range of range measurements for each point in the point cloud that returns a value, for data collection 1 (left) and 2 (right).

by subtracting the offending LiDAR off data collection from the corresponding offending LiDAR on data collection (i.e offending LiDAR off 1 from offending LiDAR on 1) and then taking the absolute value. Then the average across all the frames was calculated for each test and baseline variable for use in the standard deviation calculations, excluding the 0.000m range returns which represent points where there was no return. Next, the standard deviation across all the frames and the statistical range across all the frames for each point in the point cloud for each test and baseline variable was calculated, again excluding those with range magnitude equal to zero.

The standard deviation and statistical range across the point cloud for each test and baseline variable were evaluated and also the statistical range of the standard deviation across the point cloud was calculated. Finally, the baseline 1 variables were subtracted from the Test 1 and Test 2 variables and the baseline 2 variables subtracted from the Test 3 and Test 4 variables. These are the output metrics.

In addition, all the frames and points in each point cloud were scanned for each original test and baseline variable for values greater than 0.5m to count all the outliers for each variable. The same again was completed with a threshold of 0.1m to count the interference points. Then again as above, baselines were subtracted from tests to give the output metrics. Fig. 3 shows a visual representation of this process.

D. LiDAR used

For the victim LiDAR, we used the Ouster os1-64 LiDAR which is a 360°, 64 channel, rotating Time-Of-Flight (TOF) LiDAR operating at a wavelength of 865nm. The same victim LiDAR was used for each offending LiDAR experiment to ensure direct comparability between different experiments. The offending LiDAR used are listed in Table I along with the Ouster os1-64 used as the victim LiDAR and some key specifications of the LiDAR.

IV. Results

A. Noise in the Environment

Table II, Fig. 4 and Fig. 5 show the statistical returns from the Ouster os1-64 LiDAR when positioned in the environment on its own. Fig. 4 shows the statistical range of range measurements for each point that returned a value across the 100 frames for both data collection 1 and data collection 2. Fig. 5 shows the standard deviation of range measurements for each point that returned a value across the 100 frames for both data collection 1 and data collection 2. Table II shows the average of each of these values across the entire point cloud. These results show that the standard deviation of range measurements for a particular point is in the order of a few millimeters and the statistical range is in the order of centimeters. There is an unusual peak in the standard deviation in Fig. 5. This peak is potentially due to an imperfection or feature in the simulator wall such as a bracket for the door. Whatever the cause however, since the magnitude is only 0.03m the noise here is still low and within the range resolution of the victim LiDAR for retroreflectors.

B. Interference Experiments

Table III shows the average difference in standard deviation, the range of difference of standard deviation, the average difference in statistical range, the difference in the number of outliers and the difference in the number of interference points between the test and baseline results (each averaged over the four comparisons). These results are presented for each offending LiDAR positioned in front, behind, to the left, and to the right of the victim LiDAR. Below we describe the main results with the different offending LiDARs

TABLE I
TABLE LISTING THE LIDAR USED AND SOME OF THEIR SPECIFICATIONS

LiDAR	Wavelength	Channels	Horizontal FOV	Horizontal Resolution	Range Resolution
OUSTER OS1 64	865nm	64	H: 360° V: 45°	0.35°	±3cm Lambertian ±10cm Retroreflectors
OUSTER OS1 128	865nm	128	H: 360° V: 45°	0.35°	±3cm Lambertian ±10cm Retroreflectors
HESAI PANDAR 40M	905nm	40	H: 360° V: 40°	0.2°	±5cm (0.3 to 1m) ±2cm (1 to 120m)
VELODYNE HDL64E	905nm	64	H: 360° V: 26.8°	0.08°	< ±2cm
VELODYNE VLP-32C ULTRAPUCK	903nm	32	H: 360° V: 40°	0.1°	±3cm
QUANERGY M8-ULTRA	905nm	8	H: 360° V: 20°	0.33°	<3cm

TABLE II
STATISTICAL REPRESENTATION OF NOISE PRESENT IN THE ENVIRONMENT

	Data Collection 1 (m)	Data Collection 2 (m)	Average (to nearest mm)
Standard deviation of range, averaged across all points	0.00856	0.00855	0.009
Statistical range of range, averaged across all points	0.04379	0.04380	0.044

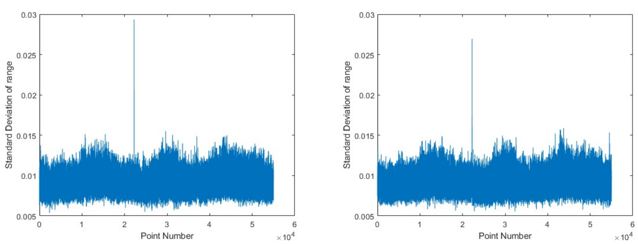

Fig. 5. Standard deviation of range measurements for each point in the point cloud that returns a value, for data collection 1 (left) and 2 (right).

1) Ouster os1-128: Differences in the victim point cloud were of a few millimeters for average difference in standard deviation, average difference in statistical range and range of difference in standard deviation. There was no difference in number of outliers for back position and positive and negative differences for the other positions. The same applies with the interference points except front, left and right positions all had positive differences.

2) Hesai Pandar 40M: Differences were in the order of a few millimeters or a few centimeters for the average difference in standard deviation, average difference in statistical range and range of difference in standard deviation, but with a negative difference for statistical range of standard deviation for the front and left positions. The difference in number of outliers is mostly positive and in the hundreds or as for the right position in the thousands. When the offending LiDAR was positioned behind there were no outliers. Interference points are similar, back position had a very small difference.

3) Velodyne HDL-64E: Average difference in standard deviation, average difference in statistical range and range of difference in standard deviation was in the order of millimeters or a few centimeters for all the positions of the LiDAR. The exception was the range of standard deviation for offending LiDAR in front, where the difference was 28cm. The difference in outliers ranged from a few hundred to a few thousand for front, left and right position with all being positive and were zero for the back position suggesting there were no outliers. For interference points, differences in number of interference points were in the order of thousands. For the back position, difference in number of interference points averaged across the data collections was 155.

4) Velodyne VLP-32C UltraPuck: The average difference in standard deviation and the average difference in statistical range were in the order of millimeters for the front, left and right positions and were zero for the back position. The range of difference in standard deviation was in the order of a few centimeters for the front, left and right positions with the front position negative. For back there was an average of 2mm. For the difference in the number of outliers, the averages were a couple of hundred for front, left and right positions and there was zero difference for the back position. For interference points, the average across data collections was a few hundred for the front, left and right positions and zero for the back position.

5) Quanergy M8-Ultra: The average difference in standard deviation was of millimeters for the front, left and right position and zero for the back position. The average difference in statistical range was in the order of millimeters for the front and right position and zero for the back and left positions. The statistical range of difference in standard deviation was in the order of centimeters for front, left and right positions and negative. For back position, the range of difference in standard deviation averaged across data collections was -1mm. The differences in the number of outliers were in the order of

TABLE III
TABLE OF RESULTS OF DIFFERENCE BETWEEN TEST AND BASELINE

Victim LiDAR	Offending LiDAR	Position	*Average Difference in Standard Deviation (m)*	*Average Difference in Statistical Range (m)*	*Range of Difference in Standard Deviation (m)*	*Difference in Outliers (Difference > 50cm)*	*Difference in Int Points (Difference > 10cm)*
			Average across Data Collections	*Average across Data Collections*	*Average across Data Collections*	*Average across Data Collections*	*Average across Data Collections*
OUSTER OS1-64	OUSTER OS1-128	FRONT	0.001	0.002	-0.039	-16	131
OUSTER OS1-64	OUSTER OS1-128	BACK	0.000	0.000	0.003	0	1
OUSTER OS1-64	OUSTER OS1-128	LEFT	0.001	0.006	0.005	362	613
OUSTER OS1-64	OUSTER OS1-128	RIGHT	0.001	0.006	0.000	52	148
OUSTER OS1-64	PANDAR 40M	FRONT	0.005	0.021	-0.115	261	939
OUSTER OS1-64	PANDAR 40M	BACK	0.000	0.000	0.002	0	3
OUSTER OS1-64	PANDAR 40M	LEFT	0.003	0.007	-0.010	309	356
OUSTER OS1-64	PANDAR 40M	RIGHT	0.027	0.092	0.035	1945	2626
OUSTER OS1-64	VELODYNE HDL-64E	FRONT	0.010	0.038	0.280	2420	3356
OUSTER OS1-64	VELODYNE HDL-64E	BACK	0.002	0.008	0.003	0	155
OUSTER OS1-64	VELODYNE HDL-64E	LEFT	0.002	0.008	0.063	458	1867
OUSTER OS1-64	VELODYNE HDL-64E	RIGHT	0.003	0.015	-0.112	1797	3076
OUSTER OS1-64	VELODYNE VLP-32C	FRONT	0.002	0.007	-0.029	154	219
OUSTER OS1-64	VELODYNE VLP-32C	BACK	0.000	0.000	0.002	0	0
OUSTER OS1-64	VELODYNE VLP-32C	LEFT	0.001	0.007	0.050	153	251
OUSTER OS1-64	VELODYNE VLP-32C	RIGHT	0.001	0.003	0.010	130	108
OUSTER OS1-64	QUANERGY M8	FRONT	0.002	0.008	-0.074	108	203
OUSTER OS1-64	QUANERGY M8	BACK	0.000	0.000	-0.001	0	0
OUSTER OS1-64	QUANERGY M8	LEFT	0.000	0.001	-0.018	29	119
OUSTER OS1-64	QUANERGY M8	RIGHT	0.001	0.005	-0.065	11	126

tens (108 for front) for front, left and right and were zero for the back position. For the interference points, the differences for front, left and right positions were positive with average across the data collections in the order of a few hundreds and were zero for the back position.

V. DISCUSSION

Table III shows that no obvious effect due to interference was witnessed. Some unusual cases show difference in range of standard deviation of tens of centimeters. However, since there are also examples of this magnitude being negative, it is hard to attribute this to interference. There is a variability in the data collections not just between different tests but also between two non-interference data collections. Since little noise was observed when there was just the victim LiDAR in the environment, just adding the offending LiDAR setup into the environment has increased the noise. Potentially the apparatus used to support the LiDAR in position may be creating noisy returns. When used on the roads, the environment will contain many objects and hence this could be evidence that a busy environment will cause a large amount of variability in LiDAR point cloud data, although this effect needs more investigation.

Having a difference in interference points, and even outliers, for the Velodyne HDL-64E into the thousands is a significant result though. This is such a strong effect that it cannot be attributed solely to noise and hence must be resembling some changes due to interference. Since the average difference in standard deviation, averaged across the data collections, is less than 30cm yet there are thousands of points that have greater than 50cm difference between the test and baseline, it is likely that the offending LiDAR was causing points to randomly spike in range creating anomalies in the point cloud. If there is a number of these spikes in the same area of the same frames, we could start to see effects that cause issues to the performance of the LiDAR sensor. If these spikes in range are occurring, it is likely that they would be exasperated when more offending LiDAR are added to the scene.

VI. Conclusion

There is an expectation that LiDARs will be equipped on future automated vehicles. LiDAR might complement the weaknesses of camera and RADAR, due to LiDARs' better angular resolution combined with its ability to accurately detect range. If this is the case, there will likely be situations where lots of LiDARs are operating in close proximity creating potential for interference to occur. For situations such as junctions or busy highways, this potential could cause collisions if the environment is perceived inaccurately.

After examining the literature for work already completed looking at the effect of interference on LiDAR it was identified that there were gaps that had not been explored yet. It was unclear whether the resulting interference witnessed in previous work was representative of LiDAR in the real-world operating on automated vehicles.

Based on the identified shortcomings of previous work and the need to analyse in depth LiDAR interference, this paper aimed to investigate interference between 360° scanning LiDAR for assisted and automated driving functions. This study used a clean and controllable environment with LiDAR sensors representative of those likely to be used on automated vehicles. The level of noise in the environment was tested to better interpret the study results. By the design of the methodology it was ensured that a base level of noise and variability was measured against such that any difference greater than the range resolution of the victim LiDAR could be interpreted as interference. Based on our methodology, no clear evidence of interference had been found from the experiments in the case of this rotating LiDAR. This lack of evidence is probably due to a very low probability of interference for this type of mechanical LiDAR, due to the nature of the generated beams and also filtering implemented on the detectors. It is also possible that detectors would discard signals which are too strong with respect to expected received power. Further work will be carried out to test other types of LiDAR as well as to repeat the experiments in the real world and with different victim LiDARs to compare findings with these preliminary results in a controlled environment.

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