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Automotive LIDAR Sensor Development Scenarios for Harsh Weather Conditions

Matti Kutila, Pasi Pyykönen, Werner Ritter, Oliver Sawade, Bernd Schäufole

Abstract—This article focuses on development baseline for a novel LIDAR for future autonomous cars, which require perception not only in clear weather, but also under harsh weather conditions such as fog and rain. Development of automotive laser scanners is bound to the following requirements: maximize sensor performance, assess the performance level and keep the scanner component costs reasonable (<1000 €) even if more expensive optical and electronic components are needed. The objective of this article is to review the existing automotive laser scanners and their capabilities to pave the way for developing new scanner prototypes, which are more capable in harsh weather conditions.

Testing of scanner capabilities has been conducted in the northern part of the Finland, at Sodankylä Airport, where fog creates a special problem. The scanner has been installed in the airport area for data gathering and analyzes if fog, snow or rain are visible in the scanner data. The results indicate that these conditions degrade sensor performance by 25%, and therefore, future work in software module development should take this into account with in-vehicle system performance estimations concerning the visual range of the scanner. This allows the vehicle to adapt speed, braking distance and stability control systems accordingly.

I. INTRODUCTION

Autonomous driving is one of the main development targets in the automotive industry today. Although current automobiles include various driver assistance systems, electronics, and communications, requirements of automation are creating a whole new level of demands. The transition from manual driven cars to automatic ones will take years and need to evolve one step at a time. [1]. One actual challenge is different weather conditions, when even a driver may experience difficulty in

driving (e.g. snowfall, icy roads, spraying water, etc.) [2]. This becomes a far more serious problem when software is created to steer an automated car that needs to be able to adapt to various outdoor conditions, in a manner similar to that of humans [3]. Previously, these types of road weather performance estimation systems have been used in roadside units to support cooperative vehicle-to-road unit (V2X) interaction [4], [5].

The RobustSENSE project aims to develop environment perception systems, which have extended capabilities in harsh weather conditions. One of these special areas is fog, which not only causes problems for human drivers, but for autonomous cars as well. Therefore, this is one of the key components in transition from being a semi-autonomous system to an autonomous one. LIDAR performance improvement in foggy conditions is also the main focus of this article. Therefore, this study is not related to the snowy conditions even if this also critical for future autonomous driving [6]. Snow problems will be part of the second step of the project.

The main intention for increasing the visibility range in foggy conditions is to develop laser scanner technology for automotive usage. Two major targets are relevant for meeting the new level of visibility demands:

1. *The system should be able to penetrate through dense fog by optimizing the used wavelengths and optical components.*
2. *Laser scanner component costs need to be optimized to maintain a reasonable level of feasibility in passenger car implementation in the future (< 1 k€).*

This article introduces the preliminary results of the European joint initiative RobustSENSE. The overall goal of the introduced measurements is to review dependencies between light fog transmission/absorption and wavelengths. The results will be further utilized in designing the LIDAR prototype.

This paper is structured as follows. First, in section II we give an overview of the system architecture of the RobustSENSE system. After that in section III, the requirements for the LIDAR are defined. Consequently in section IV the foggy conditions that are tackled by the LIDAR development are described. In section V we describe possible vehicle integration scenarios. How the tests are arranged is explained in section VI, while the results are presented in

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section VII. A discussion about the results follows in section VIII before we close with the conclusion in section IX.

II. SYSTEM ARCHITECTURE

The RobustSENSE system consists of different layers (see Figure 1). The layers relate to the data/information flow within an intelligent sensor system reacting on real world conditions and managing the diversity and complexity of automotive systems, today. The layers are:

1. Sensor layer
2. Data fusion layer
3. Understanding and planning layer
4. Performance assessment layer

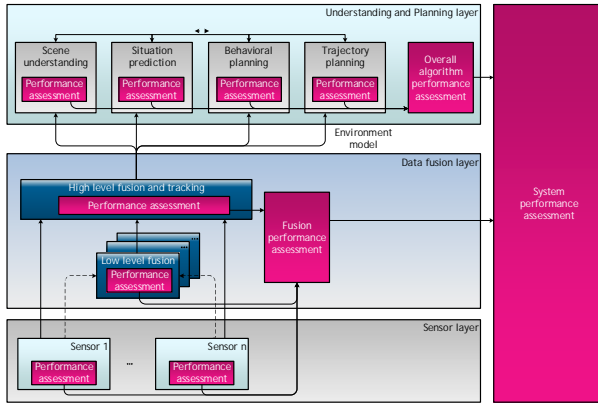


Figure 1. Architecture of the RobustSENSE system to which the LIDAR detection and performance assessment are connected

From a LIDAR development point of view, the relevant section is the sensor layer, where the laser scanner is interfaced with the data fusion layers. While LIDAR is just one part of the whole concept, it plays an important role when considering long distance (100 – 300 m) object detection, where radars and laser scanners are the crucial data sources. This article mainly bases on software based approach instead of hardware modifications to improve performance.

Performance assessment modules exist for all sensors to estimate, if online sensor performance meets the requirements of the actual outdoor conditions. In addition, a global performance assessment module checks continuously, if the overall performance of the system remains within acceptable levels for autonomous functions. This performance assessment has been developed in the project to evaluate the performance of the LIDAR, and to provide information on the overall system performance evaluation of the sub-systems, which it then assesses to see if the automation mode needs to degrade and potential driver intervention may become necessary.

The assessment data originating from each level is used on all other levels. The quality measurements from the LIDAR and other sensors are input to the data fusion modules. The reliability measurements given by the sensors are used to decide if the data from a specific sensor is included in the fused

environment model. The same applies for the reliability output of the fusion layer, which will be used by the planning algorithms.

The LIDAR performance is estimated with taking baseline data in clear conditions in certain distance, which in this case is set to be 50 m ahead of the vehicle. Due to rain droplets and fog, the laser beam is scattered and thus causing degradation to the input signal. This difference between the baseline output intensity and the measured one is used as the performance index.

$$R = \frac{I_b - I_c}{I_b} \quad (1)$$

where R is the performance ratio, I_b is the baseline intensity and I_c the measured intensity of the laser light.

On the other side there is also a feedback loop from the fusion and planning layers to the LIDAR and other sensors. As these modules check the data from the different sensors for consistency, they can detect the malfunction of one of the sensors. This information can be used to adapt the sensors.

III. LIDAR REQUIREMENTS

Driving functions have mostly been based on radar, but due to the high demand for autonomous vehicles, the radar needs optical sensors to support environmental understanding for distances between 100 – 400 m ahead of the vehicle. In this area, the capabilities of radar and cameras are limited. The radar resolution becomes too weak and the 3D camera vision range is limited to a maximum of 50 m, in front of the car. In addition, the LIDAR power input should not exceed 20 W due to limited amount power available in car generators. The horizontal resolution should be 0,4° and having 120 ° opening angle.

LIDAR plays an increasingly important role in advanced driver assistance systems (ADAS). It provides high measurement resolution for distance and extremely wide horizontal angular coverage. Furthermore, LIDAR gives a (raw) height measurement via several superimposed layers. These features allow LIDAR to be used in a variety of applications. The automotive LIDARs of today are mostly used for emergency braking, forward collision avoidance and automatic parking applications. In addition, the LIDAR supports intersection assistance in automatic cruise control (ACC) functions.

Looking at autonomous driving functions, the importance of LIDAR once again increases significantly. Autonomous driving presupposes extremely high safety requirements for redundant and mutual confirmatory measurements in environmental perception. These requirements can only be met through the simultaneous use of at least two distance measuring sensors (such as LIDAR and Radar). If one sensor fails, the driving function can no longer be maintained.

Under these considerations, this shortcoming of current LIDAR systems (as well as all optical systems) is critical. System performance decreases significantly in the case of fog, heavy rain or dense snow. Even worse, these are the cases where the comfort and safety function is most needed and desired. With the approach proposed in Section II, this last gap in system availability is closed.

This study aims to look, in greater detail, at what happens during harsh weather conditions, such as rain, snow or fog. The objective is to generate a framework for further development of sensor systems to enable autonomous functionalities in harsh weather conditions. The baseline for developing new LIDAR equipment utilizing different wavelengths in automotive use has been created.

IV. FOGGY CONDITIONS

Fog is a complex phenomenon and is characterized by multiple factors such as droplet microphysics, aerosol chemistry, radiation, turbulence, large/small-scale dynamics, and droplet surface conditions [7]. In one definition [8], fog is a collection of small water droplets in air, with diameters less than 100 micron. Visibility is typically reduced to less than 1 km, when relative air humidity is 100%, which is the full saturation level. In dense fog, visibility is even further limited to that of only a couple of meters. The density of fog depends on parameters such as liquid water content, particle size distribution, average particle size, and visibility reduction.

According to Kim et al. [9] a small increase should occur at the 1550 nm band, due to fog as opposed to a smaller decrease due to haze where the attenuation appears at the 785 nm band. However, although the difference is very small it still exists, which is beneficial for this study. The aim is to improve performance of the LIDAR sensor especially in dense fog where scattering of laser pulse is significant problem.

The foggy conditions differ when comparing fog at sea, in the atmosphere and on the ground. The droplet size on the ground is smaller compared to fog droplets in cumulus clouds. The peak value on the ground is about 4 microns, whereas in cumulus clouds, it is about 9 microns, thus, it is twice as big [10]. Therefore, laser scanning components used in aircraft are not directly suitable for automotive on-surface transport, even though the greater obstacle is the price. Aircraft components may cost more than 70 k€ whereas a passenger car sensing system should remain below 1 k€

V. VEHICLE INTEGRATION SCENARIOS

Today, automotive laser scanners are typically installed beneath the vehicle front bumper (see Figure 2) even if mounting behind the windshield would keep the scanner windshield clear on rainy days. The reason for mounting the scanner in this non-ideal place, considering the need for protection against dirt and spraying water, is to ensure sufficient coverage of obstacles near the front of the car (< 5 m).

One key component for improving the robustness of the automotive sensing system is to generate a software based watchdog to assess performance levels of the LIDAR during the actual driving conditions. This allows the vehicle to optimally use the available sensor systems by weighting the results of the other sensors (cameras, radars, etc.) more when the LIDAR performance starts to degrade (see Figure 3). The main idea is that the radar and cameras are the complementary sensors when LIDAR fails and providing data which the LIDAR cannot see.



Figure 2. Laser scanner mounting location.

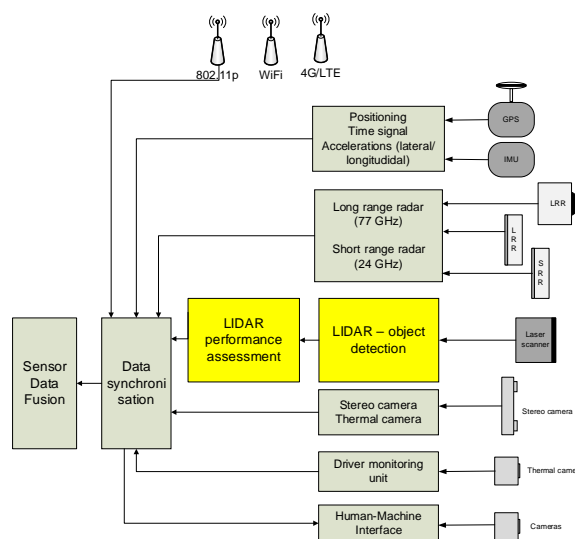


Figure 3. Autonomous car system architecture with advanced LIDAR.

VI. TEST ARRANGEMENTS

Before doing any vehicle integration, the test arrangements were created in order to gain an understanding of how the LIDAR system works in real outdoor conditions. To test fog detection, a laser scanner stationary roadside unit (RSU) was

installed at the Sodankylä Airport in Lapland. This airport was selected as the testing environment because of its reputation of having poor visibility due to fog. The particular reference point, the airport, was also selected based on the harsh weather conditions found in Lapland (cold, ice and snow). The installed RSU included a laser scanner based fog detection system with an IR sensitive camera. Figure 4 and Figure 5 show the installed RSU at the Sodankylä Airport.



Figure 4. RSU installed in the visibility pole in Sodankylä Airport.



Figure 5. Roadside ITS station sensor system. From left to right: Laser scanner (1), NIR camera (2), IcOR stereo camera system (3), roadside unit PU (4) and air temperature sensor (5).

In the testing area traffic density was relatively low. However, the benefit was that fog formation was more common than traditionally in South part of Finland. In our test we used an Ibeo LUX laser scanner, which provided an accurate distance map of the environment. The used laser scanner has the following specifications:

- Wave length: 905 nm
- Range: 0.3 – 300 m
- Field of view: 90°
- 4 scanning layers
- Pedestrian detection range: > 65
- Update rate: 25 Hz (40 ms)
- Dimensions: 128x93x85 mm
- Power consumption: <12 W

We tested our fog detection system during the winter, when snowfall and fog reduced visibility. During the verification period, the sensor was installed and working, no false alerts due to reduced visibility were produced. Thus, the system was running the whole evaluation period without any technical problems.

VII. TEST RESULTS

The tests were conducted over a longer period in the fall of 2015, in order to check the stability of the system. There were two system failures during the period that resulted in approximately 3 weeks of interruption in the data sampling. However, the detection system turned out to be reliable, with over 90% accuracy in detecting actual visibility at the test site (see Figure 6). The results clearly show three different levels: no fog, light fog and dense fog when comparing visibility ranges 0 m, 50 m, 110 m.

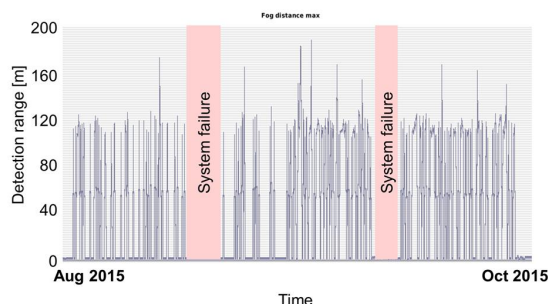


Figure 6.

The system performance test over the longer time (3 months).

Figure 7 shows the more precise results of the measurement of the laser scanner over the 10 hour data gathering in snowy and foggy conditions. The figure shows the average distance before the laser reflection measured the motorway in meters. During fierce snow flurries and fog, the distance decreased significantly from, on average, 30 m to 10 m. In the red box on the left, the snow flurry is very dense.

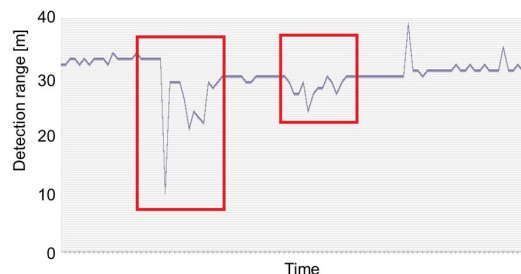


Figure 7. Average visibility distance measured by the laser scanner in meters. Two areas are marked during which there was dense snowfall and fog.

Figure 8 shows the maximum visibility value measured by the laser scanner over the monitored area in the corresponding time with the average data gathering. During the snow flurry, the value decreased significantly, from about 200 m to 160 m.

In the red box on the left, in Figure 8 the snow flurry is very dense. The change in the maximum value is, however, much smaller than the change in the average value.

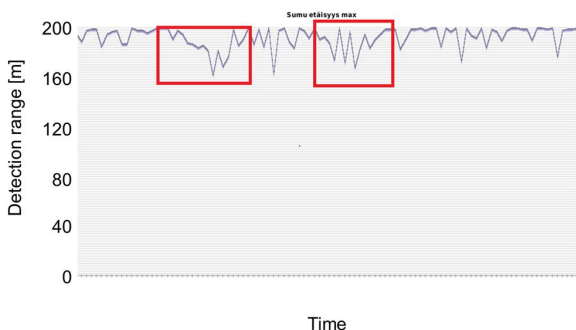


Figure 8. The maximum value of the laser scanner measurement in meters. Two areas are marked when there was dense snow flurries and fog.

As shown in Figure 7, dense snow flurries, in particular, affect the measured average value of the distance measured by the laser scanner. The relative change in the maximum value is considerably smaller, as seen in Figure 8. This result can be partially explained by the operation principle of the scanning laser, in which the laser sends multiple beams to measure the environment. During snow flurries, individual laser beams have a greater potential of passing snow crystals, so that a greater distance can be measured. Hence, the observed measured individual distance is greater. When measuring the average distance with the laser, the effect of snow crystals showed significant decrease in visibility ranges.

Moreover, in the case of fog, the maximum measured distance by the laser decreases significantly, as was demonstrated in laboratory tests described in [11], since fog is denser and more effectively prevents the penetration of laser scanner beams. As a result, the tests have shown that the sensor allows for identification of reduced visibility through fog or snow flurries.

For commercial fog detection systems, accuracy of the laser scanner can be lowered to detect slow movements of fog formations. For this reason, a lower cost, but equivalent range capacity scanner (up to 200 meters) can be more appropriate for use in a roadside unit.

VIII. DISCUSSION

The shape of the measured absorbance curves is in-line with findings made by Naboulsi et al. [8] for communication devices, even if the calculated absolute attenuation is different. The main reason for this is the different coefficients used in the calculation. However, this is not so important, since the main target is to find the optimal wavelength for automotive applications, for driving in various outdoor weather conditions. Stabilizing all possible conditions is too cumbersome for any practical outdoor application where ambient illumination, fog density, snow, etc. are a reality.

There are two major development steps planned to increase the robustness of the LIDAR system in automotive use in order to increase the level of autonomous driving in all weather conditions [12]:

- *Improve the laser scanner hardware by investigating the optimal wavelengths, possible power ranges and optimizing optical and electronic components.*
- *Develop a software module, which continuously assesses the performance level of the laser scanner according to the obvious changes in detection capability.*

LIDAR is one of the key components in automated driving. The current cameras and radar cover the area 40 m in front of the car. The problem becomes obvious when considering highway automation, where the detection range needs to be 100 – 300 m ahead of the vehicle. At this range, object detection, without any optical measurement unit, is challenging. The development targets are conducted from the requirements given by automotive industry in RobustSENSE project for development has been shown in Table 1.

TABLE I. TABLE 1. REQUIREMENTS FOR THE ADVANCED WEATHER ROBUST LASER SCANNER

TITLE	REQUIREMENTS	RELEVANCE	TYPE OF REQUIREMENT
Laser scanner interface	The system shall provide an interface to read data from laserscanner. The device may provide whether object or tracking data as an output.	Must	Non-functional
LIDAR performance assessment	The system is able to assess confidence for the LIDAR object detection	Significant	Functional
Laserscanner installation	The laserscanners shall be mounted to the front bumper of the vehicle. The lidar have at least 100 degrees horizontal view angle.	Significant	Non-functional
Sensing distance	LIDAR have a sensing range of 250 m in clear visibility and at least 30 m in dense fog or heavy rain.	Significant	Functional
Costs	LIDAR component costs needs to be reasonable (< 1000 € for passenger car use in 10 years time frame).	Good to have	Non-functional

The same laser scanner unit is also installed on the Fiat 500L research vehicle for support of autonomous driving (Figure 2). In autonomous or semi-autonomous vehicles, the visibility range for detection may differ, due to environmental conditions i.e. fog, rain or snowfall. To detect different environmental conditions that can affect sensor visibility, the same fog detection algorithm can be used with a laser scanner, as with a roadside unit. If visibility can be measured in real time, the reliability index (detection reliability for each sensor) can be updated, based on environment conditions. In vehicle installation, detection accuracy can be increased since the road surface can be detected more accurately than in a roadside unit installed as a reference.

One important aspect when considering autonomous driving, is that the car must know the performance level of the

environment perception system. Therefore, the RobustSENSE project focuses on developing a performance assessment component to enable the vehicle to adapt its speed and braking distances according to the sensing system's visibility range. The system checks if the scanner detection range for long distances is degraded, compared to ideal conditions, where no rain or fog exist in the atmosphere. Therefore, the software will estimate two value maximums and averages in order to estimate performance as compared to ideal conditions (see Figure 9).

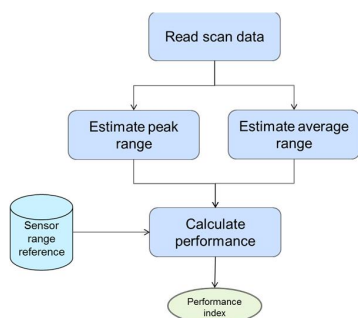


Figure 9. The laser scanner performance calculation routine.

IX. CONCLUSION

To summarize, the preliminary tests have been carried out in airport outdoor conditions. The aim of these tests is to discover and create test rigs for optimizing wavelengths in foggy conditions. These are, naturally, still far from real outdoor conditions, but are the first step towards new laser scanner systems for harsh outdoor weather conditions in automotive applications.

Hardware and software development for increasing the performance of the sensing principle, performance assessment to enable appropriate adjust of vehicle controls, is also vitally important. Performance assessment is based on information on how much sensor performance is degraded in foggy and rainy weather conditions. The major challenge is to enable automated and autonomous cars to be able to adapt their surveillance capabilities in harsh weather conditions.

The results indicate that even the current laser scanner is able to detect fog with very good accuracy (> 90%) which is highly comparable to the other existing environment perception devices. This allows for the assumption that the results can be used for development of a performance assessment module to evaluate the performance of a long range environment perception system. Even if the tests have been conducted on the roadside instead of on vehicles, they prove that there is a potential for improving laser scanner performance in harsh weather conditions, when considering the whole object recognition chain: laser scanner sensor => object detection software => sensor data fusion. One major unanswered question remains: would changing from a 902 nm band to a 1550 nm be expedient? However, in practical terms, this is not

so straightforward due to the need of more expensive components such as electronics, laser chips and optical paths. However, cost limitations are a demand in the passenger car industry and, therefore, development work is still needed.

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