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**Bewertungsmethodik für LiDAR-Sensoren in Kraftfahrzeugen;
Text Englisch**

Assessment methodology for automotive LiDAR sensors;
Text in English

Méthodologie d'évaluation des capteurs LiDAR automobiles;
Texte en anglais

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Foreword

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Introduction

Automotive Light Detection And Ranging sensors (LiDAR) use the reflection of transmitted electromagnetic waves, in wavelengths ranging from 850 nm to 1 600 nm, for the measurement of distances (ranging). LiDAR is based on laser technology. These sensors offer high potential due to their precise distance sensing and point cloud image generation. Different technological approaches are leading to a variety of sensors based on the LiDAR principle. Although all of these sensors are referred to as "LiDAR", the differences in the components and technology makes a comparison of the specifications and performance difficult. A standardised LiDAR sensor assessment methodology does not exist up to now.

This document provides an assessment methodology by means of common sensor specification and characterization guidelines and a common and application-relevant evaluation framework. The use cases are related to environmental sensing and not in-cabin sensing.

The targets of this document are:

- have a clear and generally accepted framework for specification and testing of automotive LiDAR sensors;
- create an objective understanding of automotive LiDAR sensors for consumer groups and other stakeholders;
- build a trusted basis for OEMs for creating RFQs and introduction of the right product;
- make the selection and specification of Lidar sensors simpler and more efficient for OEMs;
- make development, testing and specification easier for suppliers;
- make the automotive LiDAR market more transparent, profitable, safe and efficient;
- make LiDAR sensors comparable with other technologies.

This document also has some **limitations** related to the content. It does not change existing regulations, e.g. for eye safety of LiDAR sensors.

1 Scope

This document establishes an assessment methodology for LiDAR sensors independent of the design of the sensor and the technological approach. This document is applicable to car manufacturers and sensor suppliers to allow a defined assessment of the sensor performance on a point cloud level, e.g., the accuracy, precision, and robustness of the measurements. This document helps correlate specifications and testing. This document does not seek to establish functional safety requirements. This document is intended for R&D personnel, sensor hardware and software developers, test track operators, testing organizations and manufacturers of automated vehicles and ADAS/AD functions.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

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- DIN-TERMinologieportal: available at <https://www.din.de/go/din-term>
- DKE-IEV: available at <http://www.dke.de/DKE-IEV>

3.1

radial accuracy

range accuracy

deviation of the mean (μ) of a set of radial measurements compared to the true value (τ)

3.2

radial precision

range precision

spread of a set of radial measurements around the mean (μ) of the data set

3.3

point cloud

set of detections in one-, two-, or three-dimensional coordinate space

3.4

Field of View

angular area for which the LiDAR sensor is able to perform measurements

3.5

angular accuracy

deviation of the mean (μ) of a set of angular measurements compared to the true value (τ)

3.6

angular precision

spread of a set of angular measurements around the mean (μ) of the data set

3.7

signal

single distance information at a certain azimuth and elevation which may as well contain intensity, width, noise floor and other parameters

3.8

detection

measured signal of the LiDAR sensor, whether representing ground-truth or artifacts or just noise

Note 1 to entry: Detection can also be replaced by the term measurement.

3.9

rejection zone

rectangular subset in azimuth and elevation which covers detections possibly coming from objects near the target (such as target mounts)

Note 1 to entry: Rejection zone for given target mount in azimuth and elevation is depicted in Figure 1.

3.10

control volume

measurement corridor shaped as a rectangular cuboid with length of the individual maximum measurement distance (longitudinal) or at least up to 3 m background free space behind the target vicinity, width of at least 6 m (lateral) and no vertical restriction in the upward direction

Note 1 to entry: Control volume is parallel to the sensor's Cartesian coordinate system and is restricted in vertical direction by the lower edge of the ground-truth of the target surface.

Note 2 to entry: An illustration of control volume is shown in Figure 1.

3.11

target vicinity

target bounding box

relative bounding box around the ground-truth of the target surface

Note 1 to entry: Conditions for detections to belong to the target vicinity are:

- a) radial error between the detection and the plane of the target surface is below Δr , which is proportional to the radial distance between the target and the sensor;
- b) azimuth and elevation of the detection lie within the extent of the target, having additional tolerance:
 - 1) in elevation direction only in positive direction by Δel ;
 - 2) in azimuth direction in both directions by Δaz .

Note 2 to entry: Target vicinity tolerances Δaz , Δel and Δr have different grade to take different angular precision levels of sensors into account:

- a) Grade 0: $\Delta az, \Delta el = 0^\circ$, $\Delta r = 10 \% \times r$;
- b) Grade A: $\Delta az, \Delta el = 0,2^\circ$, $\Delta r = 2 \% \times r$;
- c) Grade B: $\Delta az, \Delta el = 0,5^\circ$, $\Delta r = 5 \% \times r$;
- d) Grade C: $\Delta az, \Delta el = 1^\circ$, $\Delta r = 10 \% \times r$.

Note 3 to entry: An illustration of target vicinity is shown in Figure 1.

3.12

true-positive detection

detection within the target vicinity excluding the rejection zone

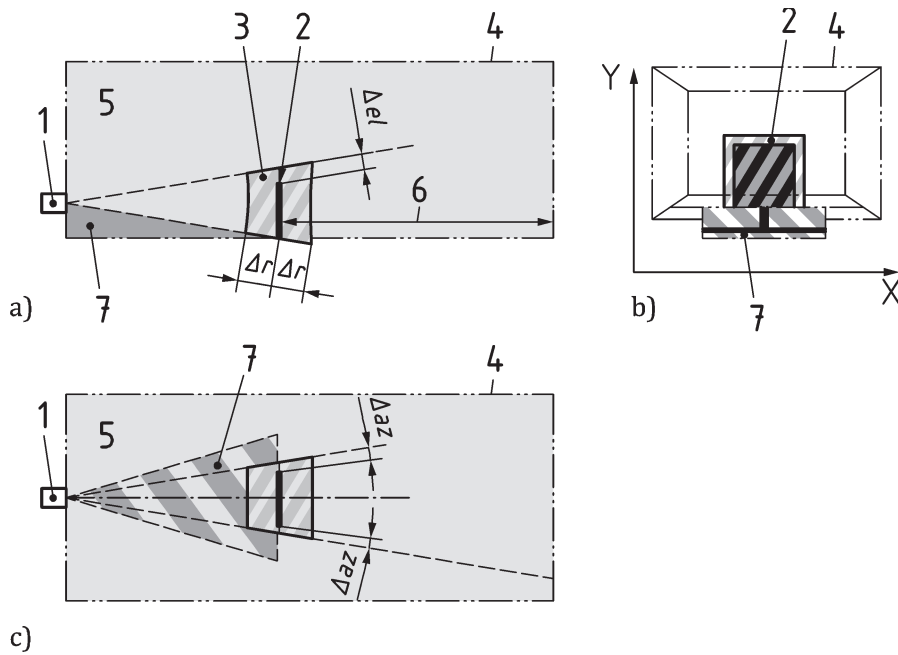
Note 1 to entry: The target vicinity and rejection zone are shown in Figure 1.

3.13

false-positive detection

detection within the control volume but outside the target vicinity

Note 1 to entry: A false-positive space is shown in Figure 1.



Key

- | | |
|-----------------------|-------------------------|
| a) side perspective | 4 control volume |
| b) sensor view | 5 false-positive space |
| c) top perspective | 6 background free space |
| 1 SuT | 7 rejection zone |
| 2 target | X azimuth |
| 3 true-positive space | Y elevation |

Figure 1 — True-positive and false-positive space

3.14

measurement frame

periodical scan of the whole FoV

3.15

frame frequency

rate at which measurement frames are completed

3.16

cluster

group of detections bound by a circle with fixed centre and of fixed radius in angular plane (in azimuth and elevation) over multiple measurement frames

3.17
clustering

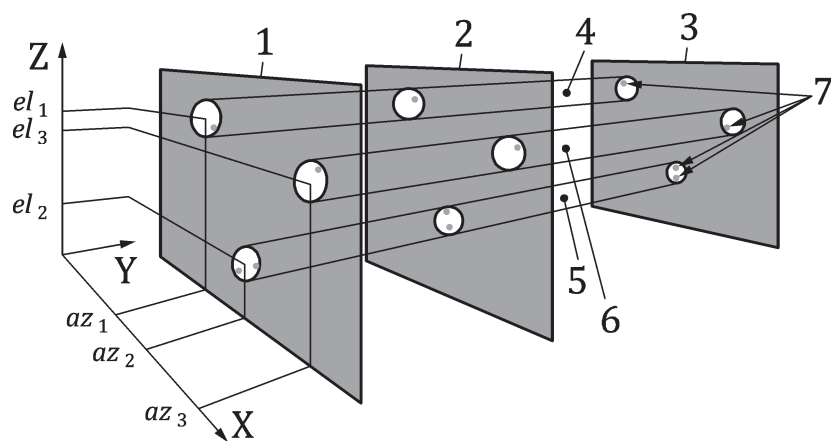
grouping of detections over multiple measurement frames into mutually exclusive subsets, where each subset is bound by a circle with fixed centre in azimuth and elevation and of fixed radius (cluster radius) in angular plane (azimuth and elevation)

Note 1 to entry: Clustering takes slight variances, e.g., a drift in azimuth, taking the sampling pattern into account, to enable comparison between multiple measurement frames. The cluster radius parameter needs to be sized individually for each sensor under test, so that each cluster contains optimally one detection for each measurement frame. In case clusters feature multiple detections per measurement frame, the clusters need to have a mapping from cluster to number of detections per measurement frame. All detections need to fit in corresponding clusters.

Note 2 to entry: The principle of clustering is visualized in Figure 2 and Table 1. It shows that a cluster describes a subset within the azimuth-elevation space and how it can be derived from measurement data by regarding each measurement frame and sorting single detections into clusters. For each cluster the number of possible detections per frame (#det) are counted to take revisits into account. The clustering is complete when all possible detections can be sorted into clusters, no detection belongs to more than one cluster.

Note 3 to entry: Clustering should ideally be performed directly on the measurement data, taking momentary offsets of the sensor into account. If the conditions of the clustering can only be met for measurement durations of 10 s if the cluster radius is larger than 0,1°, then the sampling of the sensor does not suffice the testing conditions.

Note 4 to entry: Annex A (informative) provides further information on the background to clustering.



Key	
1 1st measurement frame	6 third cluster
2 2nd measurement frame	7 detections
3 3rd measurement frame	X azimuth
4 first cluster	Y time
5 second cluster	Z elevation

Figure 2 — Clustering

Table 1 — Clustering map

	az	el	detections per frame (#det)
First cluster	az ₁	el ₁	1
Second cluster	az ₂	el ₂	2
Third cluster	az ₃	el ₃	1

3.18**cluster sample size**

number of detections, which belong to a cluster

3.19**true-positive cluster**

cluster whose centre satisfies the condition of true-positive detections

3.20**false-positive cluster**

cluster whose centre satisfies the condition of false-positive detections

3.21**revisit rate**

mean rate at which sensor scans the same cluster

Note 1 to entry: The revisit rate for a cluster is evaluated as the ratio of the number of detections in a cluster to the duration over all measurements.

Note 2 to entry: Sensors providing multiple distances per measurement direction, so called multiple returns, have their numbers of detection reduced by restricting the number of detections per cluster per frame to one.

3.22**Lambertian surface**

diffusor surface that has the same apparent radiance in all directions of the hemisphere above the surface

3.23**retro-reflector**

device or surface that reflects radiation (usually light) back to its source with minimum scattering and results in a reflectivity that is higher than a 100 % reflective Lambertian surface

3.24**accuracy**

deviation of the mean (μ) of the dataset compared to the true value (τ)

Note 1 to entry: The arithmetic mean of the dataset is to be calculated as:

$$\mu = \frac{1}{N} \sum_{i=1}^N x_i$$

Note 2 to entry: The accuracy of a dataset is depicted in Figure 3.

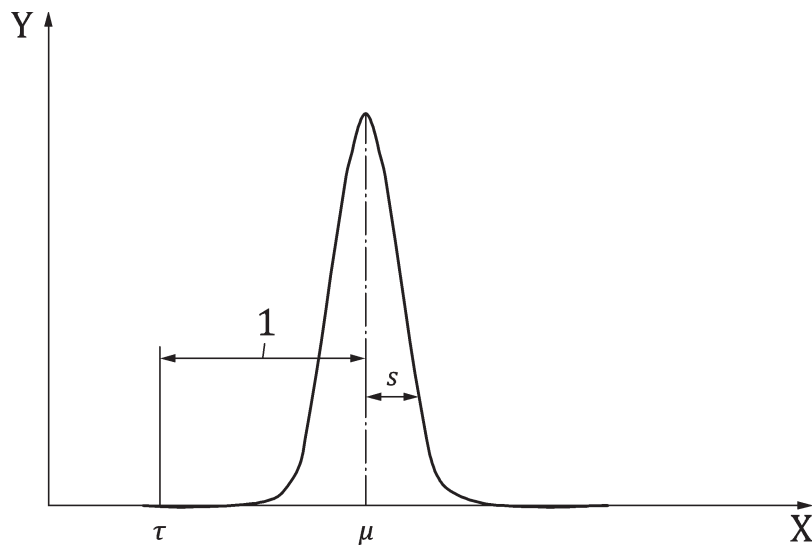
3.25**precision**

standard deviation of the dataset

Note 1 to entry: The standard deviation of the dataset is to be calculated as:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \mu)^2}$$

Note 2 to entry: The precision of a dataset describes the spread of the data around its mean as shown in Figure 3.

**Key**

1 accuracy

X feature value

Y PDF

 s precision (standard deviation) μ mean of a dataset τ true-value of dataset**Figure 3 — Accuracy and precision****3.26****detection probability**

ratio of the number of detections during a measurement and the expected number of detections considering the number of measurement frames

3.27**true-positive detection probability**

mean of the detection probabilities of all clusters whose detections lie within target vicinity at given ground-truth position

3.28**false-positive detection rate**

mean ratio of the number of false-positive detections to the total number of positive detections (false-positives and true-positives)

3.29**maximum detection distance**

maximum radial distance up to which the true-positive detection probability is larger than or equal to 50 % for a target with particular reflectivity and size

3.30**minimum detection distance**

minimum radial distance from which the true-positive detection probability is larger than or equal to 50 % for a target with particular reflectivity and size

3.31**false-positive detection deviation**

mean of angular deviations from false-positive clusters to their nearest target edges along the chosen angular dimension (azimuth and elevation)

3.32

angular cluster density

number of clusters whose centres lie within the target extent in azimuth and elevation divided by the target extent in azimuth (°) and elevation (°)

3.33

separability

minimum distance to be maintained between two targets in order for them to be distinguishable as two separate targets by the sensor

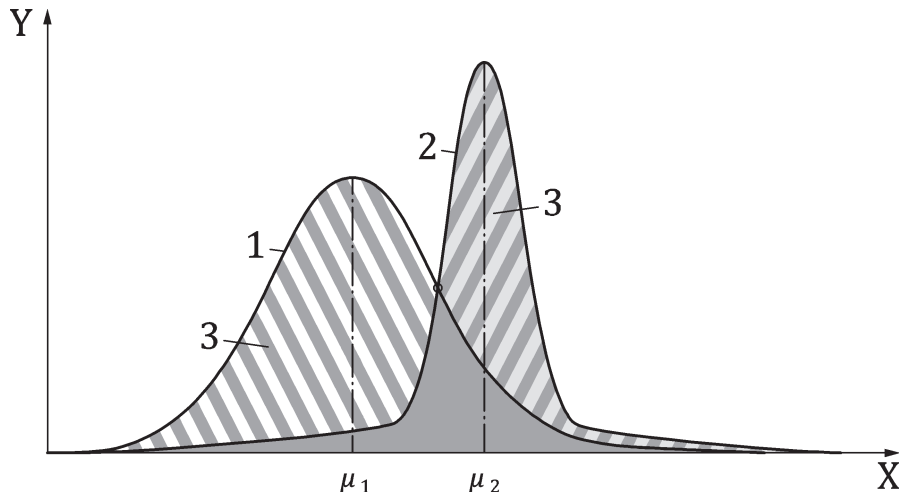
3.34

binary feature separability

probability to correctly classify a feature value given to two different states with given normal distributions, which are to be classified under the condition that their absolute probabilities are equal

Note 1 to entry: Probability of correct classification of a feature is depicted in Figure 4.

Note 2 to entry: States can be different target types, such as Lambertian targets with different reflectivity as 10 % and 80 %. The feature can be an intensity value, that the sensor outputs per each detection. The normal distributions then describe the statistical occurrence of intensity values for both target types.



Key

- | | |
|---|--|
| 1 PDF of normal distribution given first state | X feature value |
| 2 PDF of normal distribution given second state | Y PDF |
| 3 binary feature separability | μ_1 mean of normal distribution given first state |
| | μ_2 mean of normal distribution given second state |

Figure 4 — Binary feature separability

3.35

false alarm

detection made by sensor in the absence of target within the control volume

4 Symbols and abbreviations

The following abbreviations are used in this document:

- | | |
|-----|-------------------------|
| AA | angular accuracy |
| ACD | angular cluster density |

AD	automated driving
ADAS	advanced driver assistance system
AP	angular precision
FAR	false alarm rate
FDD	false-positive detection deviation
FDR	false-positive detection rate
FoV	Field of View
KPI	key performance indicator
LiDAR	Light Detection And Ranging sensor
OEM	original equipment manufacturer
PD	probability of detection
PDF	probability density function
RA	radial accuracy
R&D	research & development
RFQ	request for quotation
RP	radial precision
RR	revisit rate
SuT	Sensor under Test

The following symbols are used in this document:

α_t	slope of the target surface relative to measurement direction
A	area of target extent in angular plane
d	physical distance
h	mounting height above ground
N	number of data points or clusters
N_e	number of clusters within target extent in angular plane
N_{fp}	number of false-positive clusters
r	mean radial distance to the target surface
s	standard deviation of a dataset
R_i	Lambertian reflectivity
az	azimuth
el	elevation
t_i	timestamp of detection in a dataset
t_m	measurement duration over all detections of a given test
x_i	data point in a dataset
Δaz	target detection tolerance in azimuth direction
Δel	target detection tolerance in elevation direction
Δr	target detection tolerance in radial direction
μ	mean of a dataset
τ	true value of dataset

5 Overall methodology

The raw output of LiDAR sensors is in the form of point clouds. Each point cloud is made up of a set of detections made by the LiDAR in the environment surrounding it. In order to use LiDARs for automotive applications,