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A qualitative study of LiDAR technologies and their application areas

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Abstract

In this work, the most relevant 3D LiDAR technologies and their applications in 2022 were investigated. For this purpose, applications of LiDAR systems were classified into the typical application areas "3D modeling", "smart city", "robotics", "smart automotive" and "consumer goods".

The investigation has shown that neither "mechanical" LiDAR technologies, nor so-called solid-state LiDAR technologies, nor "hybrid" LiDAR technologies can be evaluated as optimal for the typical application areas. In none of the application areas could all of the elaborated requirements be met. However, the "hybrid" LiDAR technologies such as sequential MEMS LiDAR technology and sequential flash LiDAR technology proved to be among the most suitable for most typical application areas. However, other technologies also tended to be suitable for individual typical application areas. Finally, it was found that several of the LiDAR technologies investigated are currently equally suitable for some typical application areas. To evaluate the suitability, concrete LiDAR systems - of different technologies and properties - were compared with the specific requirements of exemplary applications of an application area. The results of the investigation provide an orientation as to which LiDAR technology is promising for which application area. [1, p. I]

1. Introduction

LiDAR" (acronym for "Light Detection And Ranging") is nowadays generally understood to mean a system with which the environment can be recorded and mapped in three dimensions. [2, p. 33] The operating principle is based on that of RaDAR technology ("Radio Detection And Ranging") developed several decades earlier and LASER technology. [3, p. 70] Instead of microwave beams as in RaDAR technology, however, laser beams are emitted in the visible, ultraviolet or infrared range and their reflections are received. [4, p. 318, 5, p. 42] The corresponding LiDAR technology can be used to determine not only the distances but also other properties of the illuminated objects or even of the medium passed by the laser beams.

Since the first presentation of LiDAR technology in the early 1960s, the technology has been further developed and adapted for a variety of applications in different fields. On the one hand, technological development is driven by specific requirements in the various application areas. On the other hand, advances in LiDAR technology enable its useful application in specific fields in the first place. Due to this interplay, technological development has gained momentum especially in the last decade. [6, p. 745] This development concerned not only individual components of a LiDAR system and their interaction, but also the measurement techniques for obtaining information about the scanned objects and the procedures for scanning a section of the environment, as well as signal and data processing. In addition, advances have been made in the performance, cost-effectiveness, and reliability of LiDAR technology. [7, p. 1]

1.1 Research question

Against the background that currently different LiDAR technologies are competing for the application in the same fields, this work will address the question which LiDAR technologies are suitable for which fields of application. [8, p. 409].

The focus of the work is on the so-called 3D-LiDAR technology. An exhaustive treatment of the 3D-LiDAR technologies and their applications is not possible within the scope of this work, neither in depth, nor in breadth.

1.2 Structure of this work

This discursive work is divided into two main parts. In the first main part, the essential characteristics of LiDAR technologies are first elaborated, on the basis of which they are then classified. In the second main part, the LiDAR technologies are discussed with respect to their suitability for typical application areas. As a result of the investigation, suitable LiDAR technologies are finally assigned to the typical application areas in a tabular overview. Due to the continuous and dynamic development of LiDAR technologies, however, the results can only be preliminary and partial.

2. Foundations

In this part of the paper, essential characteristics of LiDAR technologies are described, which are finally used to differentiate and order LiDAR technologies.

2.1 Characteristics of LiDAR technologies

In order to differentiate and classify LiDAR technologies, it is first necessary to determine characteristic features. Such characteristics are firstly the so-called critical parameters, which can be used to evaluate the performance of a LiDAR system. [9, p. 7] A second feature is the measurement technology used to obtain the distances and, if necessary, other information about the target points. A third feature is the method used to scan the environment in a field of view. A fourth feature is the so-called key components of LiDAR systems.

2.1.1 Critical parameters of LiDAR systems

LiDAR systems are characterized by their specific properties. The comparability of the properties of different systems is ensured by assigning them to specific parameters. Some parameters, the so-called critical parameters, are of particular importance: they can be used to determine whether or not a particular LiDAR system is suitable for an application with its specific requirements. [9, p. 4] The main critical parameters are wavelength, laser class, field of view, range, angular resolution, geometric resolution, depth resolution, data rate, frame rate and reliability.

2.1.2 Measurement techniques

LiDAR technologies generate distance values from the travel time of laser light signals. [5, p. 42, 10, p. 17] The time of flight can be determined either directly or indirectly. [11, p. 25945] In the first measurement technique, which is considered the standard technology, usually only the intensity of the received light pulses is measured. [11, p. 25945] Indirect measurement techniques - such as FMCW or RMCW - usually emit coherent, uninterrupted, modulated light waves. [12, p. 1384] In such full waveform techniques, the properties of the light wave - such as its shape and amplitude - can be used to infer the geometric and physical properties of the target - e.g. its relative velocity. [13, pp. 62-63] Corresponding LiDAR technologies are also referred to as 4D LiDAR.

2.1.3 Procedures for scanning a field of view

A distinction can be made between sequential, parallel and hybrid methods for the complete scanning of all target points in a field of view. The conventional scanning method is sequential scanning of the target points at a specific angular distance with a single laser beam, the so-called "single beam". [8, p. 409, 14, p. 3561, 15, p. 4] Only one detector element is required to detect the reflected laser signals. In parallel processes, the field of view is scanned with several laser beams emitted simultaneously. The reflected light signals are detected simultaneously by a matrix of detectors. [8, p. 408] In hybrid scanning methods, too, several laser beams are emitted simultaneously. Unlike parallel methods, however, only a partial area of the field of view is scanned at the same time, so that several measurements must be performed sequentially in order to scan the field of view completely. LiDAR systems that emit multiple laser signals simultaneously are also referred to as multi-beam LiDAR systems. [16, p. 1, 16, p. 2]

2.1.4 Components of LiDAR systems

All LiDAR systems work according to the same basic principle: laser beams with specific properties are generated, modified and emitted onto the target points. The light signal reflected from the target is received, conditioned and finally processed. [17, p. 2, 18, p. 3] Each of these steps requires specific components. The key components of LiDAR technology are the emitters and detectors. [19, p. 102]. An emitter generates the laser beams that are emitted onto the target point. Emitters are usually low-cost, controllable laser diodes, i.e. semiconductor lasers. The most important emitters are currently fiber lasers, surface emitters (e.g. VCSEL emitters) and edge-emitting laser diodes. [20] The reflected light signals are received by photodetectors, usually photodiodes or so-called CMOS sensors, and converted into electrical signals. In LiDAR technology, variants of the "Avalanche Photon Diode" (APD) are often used. [3, p. 75]. Photodiodes can be combined to form larger modules, whereby each photodiode usually corresponds to a two-dimensional pixel. [5, p. 44]

Mirrors, prisms, lenses or so-called MEMS (Micro-Electro-Mechanical Systems) mirrors are used to direct light signals to the target points. MEMS mirrors are attached to two axles and are aligned within a few milliseconds either piezoelectrically, electrostatically, electro-magnetically or electrothermally. [21, p. 8, 21, p. 112] Lenses are also used to control the collimation of the emitted laser beam, amplify the received light signals and influence the size of the field of view. [2, p. 37] If several targets within a field of view are to be scanned in parallel with a single laser source, this can be split into a large number of partial laser beams of lower energy using so-called optical diffusers, usually diffusion lenses. In conventional LiDAR technologies, a rotating prism is often used to direct the laser beam to the target at a constant wavelength. Another possibility is to irradiate a static prism with a laser beam of variable wavelength. This takes advantage of the fact that light of different wavelengths is broken to different degrees in a prism. The latter technique is also known as "wavelength steering". Other important components are the signal and data processing components, but also the clock system and the system control. [22, p. 32] The performance of the corresponding LiDAR system is influenced by the signal processing component's ability to convert the prefiltered and amplified analog signals into digital signals. [7, p. 2, 22, p. 45]

2.2 Classification of LiDAR technologies

In this section, the current LiDAR technologies are defined, differentiated and classified on the basis of their characteristic features.

Basically, "mechanical" and so-called solid-state LiDAR technologies are to be distinguished from each other. The latter are characterized by the fact that they do not use moving components to scan the field of view. [9, p. 2] LiDAR technologies that do not use motors or the like to move the platform or components, but still use moving components such as MEMS, are classified in the literature as hybrid LiDAR technologies. However, in many sources, especially those of the manufacturers of corresponding LiDAR systems themselves, they are classified as a solid-state LiDAR technology.

2.2.1 Mechanical LiDAR technologies

So-called mechanical LiDAR technologies are characterized by the fact that the alignment of laser beams to the target points is performed with mechanically moved components or the movement of the entire platform. [23, p. 121] In mechanical multi-beam LiDAR systems, the entire LiDAR system or platform, including the emitters and detectors working in parallel, is usually rotated or pivoted mechanically. [14, p. 3561] The vertical resolution is determined by the angular separation of the parallel emitted laser beams. So-called single-beam LiDAR systems, which work with only a single laser beam, generally use mirrors or prisms moved by motors for the vertical alignment of the laser beam. [24, p. 167]

So-called "mechanical" LiDAR systems achieve a large range, a very wide field of view of up to 360° and a high scanning accuracy. [9, p. 3, 23, p. 121] However, they are not considered particularly energy-efficient, shock-resistant and robust. [9, p. 3] In addition, the mechanical components result in greater overall weight and volume. [3, p. 73, 17] These drawbacks have driven the development of alternative LiDAR technologies with no or fewer mechanically moving components.

2.2.2 Solid-state LiDAR technologies

So-called solid-state LiDAR technologies are characterized by the fact that, unlike "mechanical" or "hybrid" LiDAR technologies, they do not have any physically moving components. [25, p. 180, 26, p. 171] Sie nutzen die Halbleitertechnik für die optoelektrischen Schlüsselkomponenten. [23, p. 121, 27, p. 4091, 28, p. 1] As a result, they not only achieve the highest level of compactness and robustness, but are also particularly suitable for cost-efficient mass production, especially for so-called CMOS production techniques. [26, p. 171, 27, p. 4091]

There are solid-state LiDAR technologies with sequential and parallel scanning methods. The most important solid-state LiDAR technologies are optical phased array LiDAR technology and flash LiDAR technology. Another technology in which at least the deflection takes place on one axis without moving components is the so-called spectrum scan LiDAR technology.

2.2.2.1 Optical-Phased-Array-LiDAR-Technology

In optical phased array LiDAR technology, the field of view can be scanned sequentially without moving components. For this purpose, not a single laser source is used, but a matrix of several low-power laser diodes whose beam angle is constant, but whose phases can be individually controlled. [3, p. 77] Targeted phase shifts create interference between the laser beams, which determines the shape, intensity and, above all, the beam direction of the resulting laser beam. [3, p. 77, 8, p. 409, 9, pp. 2-3] Optical phased array LiDAR systems are characterized primarily by high robustness, vibration resilience and energy efficiency. [9, p. 2] They achieve a depth resolution in the centimeter range. [27, p. 4094]

2.2.2.2 Flash-LiDAR-Technology

In flash LiDAR technology, the field of view is scanned simultaneously with a large number of laser beams - like a flash. [9, p. 2] Flash LiDAR systems use either a single laser source (single-beam flash LiDAR) with comparatively high peak power, whose laser beam - usually with a so-called diffuser lens - is fanned out to all target points in the field of view. [9, p. 2, 27, p. 4091] Or a matrix with a large number of lower-power laser sources - e.g. VCSEL components - is used (multi-beam flash LiDAR). The reflected light beams are detected by a matrix of photodetectors. The individual photodetectors of the matrix correspond to two-dimensional pixels to which distance values generated from the respective measurement signals are assigned. [10, p. 29, 29, p. 148] The geometric resolution thus depends on the number of photodetectors. The range of such a LiDAR system, on the other hand, is determined primarily by its sensitivity and the intensity of the emitted laser beams. [2, p. 36, 2, p. 38]

Flash LiDAR technology is characterized by very high frame rates. Due to the lack of moving components and their comparatively simple design, they are also considered to be robust, compact and cost-effective. [8, p. 408, 14, p. 3562, 16, p. 2, 29, p. 148]

2.2.3 Hybrid LiDAR technologies

In this paper, hybrid technologies are defined as technologies that have characteristics of both solid-state technologies and "mechanical" technologies. In contrast to solid-state LiDAR technologies, there are still, for example, electro-mechanically or piezo-electrically moved components. [9, p. 3] In some cases, technologies that use hybrid scanning methods are also classified as hybrid, for example the so-called sequential flash LiDAR technology.

The most important hybrid LiDAR technology is the so-called MEMS LiDAR technology, which uses controllable MEMS mirrors. By eliminating the need for motors to control the laser beams, the entire LiDAR-MEMS-LiDAR system is more compact, lighter and more robust than mechanical systems. [21, p. 62, 30, p. 4631, 30, p. 4631, 31, 31, p. 4] In MEMS LiDAR technology, which uses a single laser source, the laser beam is usually fanned out in a vertical line with a diffuser lens. [23, p. 122] Multiple laser sources can also be used, with their laser beams hitting the MEMS mirror at different angles to simultaneously detect different target points. [3, p. 73, 9, p. 12] By panning the MEMS mirror, all target points in the field of view are acquired using a hybrid scanning method. Sequential scanning methods can also be realized: For this, one MEMS mirror is used to deflect the laser beam in the horizontal axis and one in the vertical axis. The light signals reflected from the target points in the field of view are also detected by photo detectors, which are usually combined into modules.

3. Discussion of LiDAR technologies

In this part of the paper, the LiDAR technologies presented are discussed with respect to their suitability for typical application areas. The goal is to give an orientation for the use of current LiDAR technologies in typical application areas. Finally, the result of the discussion is illustrated as an overview table.

In a first step, the diverse applications of LiDAR systems are grouped into application areas.

In the second step, common requirement parameters are developed for all application areas. This makes it possible to compare the requirement areas with each other and with the specific properties of LiDAR systems.

In a third step, the technology-independent, specific requirements are developed and weighted for each application area.

In a fourth step, the properties of a sufficient number of concrete LiDAR systems are researched using data sheets and other sources. In addition, each of these LiDAR systems will be assigned to either the "mechanical", the "hybrid" or the so-called solid-state LiDAR technologies. In addition, each LiDAR system will be assigned to a specific technology, such as MEMS LiDAR technology, Flash LiDAR technology, or Optical Phased Array LiDAR technology.

In the fifth step, the individual, weighted requirements of the exemplary applications are compared with the corresponding properties of the concrete LiDAR systems.

In the sixth step, the suitability of the concrete LiDAR systems for an application area is evaluated.

Finally, the technologies on which the best evaluated LiDAR systems are based are investigated. As a result of the evaluation, the suitable LiDAR technologies will be assigned to the application areas. [1]

3.1 Determination of requirement parameters for the application of LiDAR systems.

LiDAR systems are used for different purposes and in different environments. The application purpose and the application environment significantly determine the specific requirements, which can be subsumed under requirements for performance, safety and economic efficiency. [9, p. 4, 29, p. 151, 32, p. 2] The requirement parameters include, but are not limited to, the critical parameters.

3.2 Determination of the areas of application

The number of applications for LiDAR systems is steadily increasing. LiDAR systems are already being used to create maps, for urban and traffic planning, for navigation and control of mobile robots and vehicles, in research, in forestry and agriculture, and in entertainment. [9, p. 1, 32, p. 1, 33, p. 2, 34, p. 1] However, there is no uniform classification of the diverse applications into application areas.

The environment in which a LiDAR system is used and its application purpose were used to determine application areas.

The following application areas were developed: 3D modeling (3D mapping), smart city, robotics, smart automotive, and consumer goods. [35, p. 6]

3.2.1 3D Modeling

3D modeling refers to the creation of three-dimensional representations from the point cloud data of a sampled area. These representations are usually three-dimensional geographic maps or models of buildings, objects, etc. of different scales. ([33, p. 3], [36], [37, p. 9]

3.2.2 Smart City

In a so-called smart city, different modes of transport, infrastructure and road users are coordinated with each other. This coordination requires the networking of sensors and control systems of various local - but also regional - systems. [38, p. 11] LiDAR systems are used in this field to measure and analyze the movements of traffic carriers and participants (general objects). This requires additional data processing steps such as segmentation, grouping and modeling of the point cloud data as well as classification, recognition and identification of objects and tracking and prediction of their movements.

3.2.3 Robotic

LiDAR systems are already widely used in the field of robotics. [39, p. 745] They not only help mobile robots to navigate independently, situationally adapted, reliably and safely to a given goal. They also support the safe interaction of robots with humans, animals and objects. [38, p. 8]

3.2.4 Smart Automotive

The application area that has triggered enormous momentum in the development and commercial application of LiDAR technologies is the automotive sector. There, LiDAR technology is regarded as a key technology for so-called autonomous driving. However, LiDAR systems have already been used in the automotive sector for quite some time: for driver assistance systems and automatics systems. The increasing use of these systems has also led to a reduction in their production costs. [22, p. 26] As vehicle automation increases, so do the demands on the reliability and performance of the subsystems involved, such as the LiDAR systems.

3.2.5 Consumer goods

In the meantime, very small and inexpensive LiDAR systems have also become available, which can be used for various purposes in the so-called consumer goods sector. The most relevant consumer goods currently being equipped with LiDAR systems are tablets and smartphones. [22, p. 24]

3.3 Specific requirements for LiDAR systems in the typical application areas

For each of the presented application areas, the corresponding requirements for performance, safety and economic efficiency are worked out from their typical application environment and their application purposes. In addition, the individual requirement parameters of an application area are weighted relatively in terms of their relevance. The results are finally summarized in a table. In the case of clear differences in the environment or the purpose of applications in an area - as in the case of 3D modeling and robotics - an exemplary application was selected and analyzed.

Table 1: Overview of specific requirements for LiDAR systems in application areas and their weighting

Specific requirements for LiDAR systems in application areas and their weighting										
	3D-Mapping Exemplary application: a professional flying drone for cost-effective 3D modeling of a building complex. A flight altitude of up to 100 m was assumed.		Smart City Exemplary application: A ground-based, static LiDAR system for flow control of people in train stations or in airport terminals. An installation height of between 3 and 60 meters with a constant energy supply is assumed.		Robotic Exemplary application: A ground-based, mobile LiDAR system for "last-mile delivery" in urban environ-ments. In part with specific values from Robert Bosch GmbH (Robert Bosch GmbH 2019, p. 6)		mart Automotiv A ground-based, mobile LiDAR system. In part with specific values from Robert Bosch GmbH and others. (Robert Bosch GmbH 2019, p. 6; Spies and Spies 2006, p. 102; Kernhof et al. 2018, p. 35).		Consumer Exemplary application: Smartphones and tablets, in part with specific values from Robert Bosch GmbH (Robert Bosch GmbH 2019, p. 6, 2019, 2019, p. 7).	
parameter	require-ment	weight	require-ment	weight	require-ment	weight	require-ment	weight	require-ment	weight
min. detection distance[m]	2	1	2	13	0,01	21	0,2	20	0,3	16
max. detection distance [m]	125	24	90	22	200	20	200	22	10	6
min. range resolution [°]	1	18	0,05	18	0,05	18	0,1	19	0,02	17
min. hor. field of view [°]	90	17	90	17	360	22	120	17	45	12
min. vert. field of view [°]	30	16	90	16	45	14	30	4	45	13
min. hor. geometric resolution [m]	1	20	0,3	20	0,2	19	1	21	0,05	14
min. vert. geometric resolution [m]	1	19	0,3	19	0,2	16	1	16	0,05	15
min. hor. angular resolution [°]	0,45	15	0,13	15	0,06	15	0,45	14	0,3	11
min. vert. angular resolution [°]	0,45	14	0,13	14	0,06	13	0,45	13	0,3	10
min. datarate	-	13	-	12	-	7	-	6	-	5
min. imagerate [Hz]	10	9	10	11	10	10	10	10	10	9
additional attributes		10	lectance	10	velocity	2	velocity	5	lectance	1
laser safety classification	2	22	1	24	1	24	1	24	1	24
min. wavelegth [nm]	800	23	800	23	800	23	800	23	800	22
min. working temprature [°C]	-25	6	-30	8	-30	8	-25	2	-25	3
max. working temprature [°C]	50	7	60	9	50	9	50	9	45	4
min. vibration resilience	medium	8	low	2	high	12	medium	12	medium	8
min. ambient light resilience	high	21	high	21	high	17	medium	18	medium	7
min. resilience to atmospheric distu	medium	11	medium	7	high	11	medium	11	low	2
max. Price	high	3	high	6	medium	5	medium	15	low	20
max. energy consumption	low	5	high	1	low	6	low	3	low	19
max. weight	low	12	high	3	low	3	high	1	low	21
max. volume	medium	4	high	5	low	4	high	7	low	23
min. production process	custom	2	custom	4	mass pr	1	custom	8	mass pr	18

3.4 Properties of current LiDAR systems

Finally, the specific requirements of LiDAR systems for typical application areas will be compared with the technical and economic properties of concrete LiDAR systems of different technologies. For this purpose, their technology class, the scanning method, the measurement technology and the properties of the selected LiDAR systems are first determined discursively (see appendix A, Table 8). The assignment of the concrete LiDAR systems to a certain technology class is partly associated with a certain uncertainty, because the companies have often only made vague or marketing-oriented statements about their product. The same applies to the scanning methods and the pricing information. If the data sheet for a LiDAR system contains several data for a single pair of meters, the best value was selected. The data for some parameters, e.g. range, can only be compared with each other to a limited extent, since different test procedures and evaluation criteria were used in some cases.

3.5 Evaluation of LiDAR technologies with regard to application areas

To answer the research question of which LiDAR technologies are suitable for which application areas, we now evaluate how the selected LiDAR systems of specific technologies fulfill the specific requirements of the application areas. For this purpose, points were assigned for each fulfilled requirement in each of the application areas according to their relative weighting (values between 1 and 24) (see appendix A, tables 13-17). Relative requirements such as low, medium, high were related to the spectrum of corresponding characteristics of all LiDAR systems studied. Then, LiDAR systems were ranked in descending order according to the mean value of their scores. The mean values are not only used for relative ordering of the LiDAR systems, but their absolute values also express the degree to which the requirements of a range could be met. If all requirements were met, the mean value is 12.5. It was determined by the author that LiDAR systems with a mean value lower than 9 are not considered suitable for the respective requirement area. Based on the order, the absolute points and the distribution of the LiDAR technologies, the evaluation was finally made.

3.5.1 Evaluation of LiDAR technologies in the 3D modeling application area

In the application area "3D modeling", which was represented by an airborne application (flying drone), the order of the LiDAR systems according to their achieved mean values shows that technologies of all three technology classes tend to be assessed as suitable. Systems of all three technology classes are placed among the first ranks and furthermore show almost the maximum mean value. Accordingly, they meet almost all requirements. The best rated system uses a so-called hybrid technology with a hybrid scanning method in which the field of view is expanded by mechanical movements. The upper half of the table shows an accumulation of so-called flash LiDAR technologies. Only the LiDAR systems with the lowest mean values show a larger difference to the neighboring values. Only the so-called optical phased array LiDAR technology has been classified exclusively in the middle field and is therefore to be assessed as less suitable for the application area "3D modeling".

Table 2: Order of technologies of selected LiDAR systems according to the mean value of relative weights of matching properties with the requirements for airborne 3D modeling with a flying drone as an exemplary application.

Evaluation of exemplary LiDAR systems for the application area 3D modeling

Rank	Company	Productname	Technology class	Procedures for scanning a field of view	Measure-ment technique	Avg. value
1	**Innoviz Technologies**	**INNOVIZ360**	**hybrid**	**MEMS und rotatingr Spiegel**	**ToF**	**12,3**
2	**Velodyne**	**Alpha Prime**	**mechanical**	**128 Laser, macromechanical scanning**	**ToF**	**12,1**
3	**Ibeo Automotive Systems**	**IbeoNEXT**	**solid-state**	**VCSEL, 128x80 Laser sequential Flash ("Pure-electronic s**	**ToF**	**11,8**
4	Velodyne LiDAR	Velarray H800	solid-state	micro-lidar array (Multibeam-Flash)	-	11,3
5	Quanergy Systems	M8-Plus	mechanical	-	ToF	11,3
6	Quanergy Systems	M8-Ultra	mechanical	-	ToF	11,3
7	Ouster	OS0	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	11,3
8	Ouster	OS1	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	11,3
9	Baraja	Spectrum Off-Road	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	11,0
10	Aeva Technologies	Aeries I	solid-state	multiple beam (Flash)	FMCW	10,9
11	Samsung	ISOCELL Vizion 33D	solid-state	Flash (VCSEL)	ToF	10,9
12	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	10,8
13	Aeva Technologies	Aeries II	solid-state	multiple beam (Flash)	FMCW	10,7
14	Velodyne LiDAR Inc.	Velarray M1600	solid-state	micro-lidar array (Multibeam-Flash)	-	10,7
15	Ouster	OS2	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	10,6
16	Quanergy Systems	M8-PoE	mechanical	-	ToF	10,6
17	Baraja	Spectrum HD	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	10,5
18	Faro	Focus Premium 350	mechanical	-	ToF	10,5
19	Quanergy Systems	S3-2WSO-S00	solid-state	optical phased array	ToF	10,5
20	Quanergy Systems	M8-Core	mechanical	-	ToF	10,3
21	Velodyne LiDAR Inc.	Puck VLP-16	mechanical	16 Laser	ToF	10,1
22	Velodyn LiDAR	Puck LITE	mechanical	16 Laser	ToF	10,1
23	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechanical	32 Laser	ToF	10,0
24	Luminar Technologies	Hydra	mechanical	2-Axen-Spiegel-Scanner	ToF	10,0
25	Blickfeld	Cube1	hybrid	MEMS	-	10,0
26	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	10,0
27	Quanergy Systems	S3-2NSI-S00	solid-state	optical phased array	ToF	9,7
28	Quanergy Systems	S3-2NSO-S00	solid-state	optical phased array	ToF	9,7
29	Blickfeld	Cube Range 1	hybrid	MEMS	-	9,3
30	Neuvition	Titan S2-120	hybrid	MEMS	ToF	9,2
31	Ibeo Automotive Systems	Ibeo LUX 4L	mechanical	multi-layer	ToF	8,9
32	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	8,9
33	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	8,9
34	Neuvition	Titan M1-R	hybrid	MEMS	ToF	8,9
35	XenomatiX	XenoLidar-Xpert	solid-state	Flash (15000 Laser rays)	ToF	8,8
36	AEye	4SIGHT M	hybrid	MEMS	ToF	8,5
37	Velodyne LiDAR Inc.	HDL-32E	mechanical	32 Laser	ToF	8,5
38	XenomatiX	XenoLidar-Xact	solid-state	Flash (15000 Laser rays)	ToF	7,7
39	LeddarTech Inc.	Leddar Pixell	solid-state	Flash (Full Waveform)	-	6,0

3.5.2 Evaluation of LiDAR technologies in the Smart City application area

In the "smart city" application area, which was represented by a hypothetical application for controlling the flow of people in public spaces, only "hybrid" technologies with hybrid sensing methods were ranked in the top four. The first ten ranks also include five purely "mechanical" technologies. They achieved mean values almost as high as those of the three top-ranked LiDAR systems. The lowest ranks - with significantly lower mean values than those in the top ranks - are again occupied by solid-state technologies. Accordingly, both "hybrid" and "mechanical" LiDAR technologies - but fewer so-called solid-state LiDAR technologies, with the exception of the so-called spectrum-scan LiDAR technology - currently tend to be suitable for use in the "smart city" sector.

Table 3: Ordering of technologies of selected LiDAR systems according to the mean value of relative weights of matching properties with the requirements for flow control in public spaces such as railroad stations or airports as an exemplary application in the field of "smart city".

Evaluation of exemplary LiDAR systems for the application area Smart City

Rank	Company	Product name	Technologie class	Procedures for scanning a field of view	Measure-ment technique	Avg. value
1	**Ouster**	**OS1**	**hybrid**	**sequential Multibeam-Flash (128 rotating VCSEL Laser A**	**-**	**11,9**
2	**Ouster**	**OS0**	**hybrid**	**sequential Multibeam-Flash (128 rotating VCSEL Laser A**	**-**	**11,6**
3	**Innoviz Technologies**	**INNOVIZ360**	**hybrid**	**MEMS und rotatingr Spiegel**	**ToF**	**11,6**
4	Ouster	OS2	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	11,5
5	Baraja	Spectrum HD	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	11,5
6	Faro	Focus Premium 350	mechanical	-	ToF	11,5
7	Quanergy Systems	M8-Core	mechanical	-	ToF	11,5
8	Quanergy Systems	M8-Plus	mechanical	-	ToF	11,5
9	Quanergy Systems	M8-Ultra	mechanical	-	ToF	11,5
10	Quanergy Systems	M8-PoE	mechanical	-	ToF	11,5
11	Baraja	Spectrum Off-Road	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	11,1
12	Aeva Technologies	Aeries II	solid-state	multiple beam (Flash)	FMCW	10,4
13	Neuvition	Titan M1-R	hybrid	MEMS	ToF	10,0
14	Velodyne LiDAR Inc.	Puck VLP-16	mechanical	16 Laser	ToF	9,9
15	Velodyn LiDAR	Puck LITE	mechanical	16 Laser	ToF	9,9
16	Velodyne	Alpha Prime	mechanical	128 Laser, macromechanical scanning	ToF	9,8
17	Aeva Technologies	Aeries I	solid-state	multiple beam (Flash)	FMCW	9,7
18	Samsung	ISOCELL Vizion 33D	solid-state	Flash (VCSEL)	ToF	9,6
19	Velodyne LiDAR Inc.	Velarray M1600	solid-state	micro-lidar array (Multibeam-Flash)	-	9,6
20	Ibeo Automotive Systems	IbeoNEXT	solid-state	VCSEL, 128x80 Laser sequential Flash ("Pure-electronic se	ToF	9,6
21	Neuvition	Titan S2-120	hybrid	MEMS	ToF	9,5
22	Quanergy Systems	S3-2WSO-S00	solid-state	optical phased array	ToF	9,4
23	Luminar Technologies	Hydra	mechanical	2-Axen-Spiegel-Scanner	ToF	9,4
24	Velodyne LiDAR Inc.	HDL-32E	mechanical	32 Laser	ToF	9,0
25	Velodyne LiDAR	Velarray H800	solid-state	micro-lidar array (Multibeam-Flash)	-	8,8
26	Quanergy Systems	S3-2NSO-S00	solid-state	optical phased array	ToF	8,6
27	Quanergy Systems	S3-2NSI-S00	solid-state	optical phased array	ToF	8,5
28	AEye	4SIGHT M	hybrid	MEMS	ToF	8,2
29	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechanical	32 Laser	ToF	8,2
30	Blickfeld	Cube Range 1	hybrid	MEMS	-	8,1
31	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	7,9
32	Blickfeld	Cube1	hybrid	MEMS	-	7,8
33	Ibeo Automotive Systems	Ibeo LUX 4L	mechanical	multi-layer	ToF	7,6
34	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	7,6
35	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	7,6
36	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	6,7
37	LeddarTech Inc.	Leddar Pixell	solid-state	Flash (Full Waveform)	-	6,6
38	XenomatiX	XenoLidar-Xact	solid-state	Flash (15000 Laser rays)	ToF	6,4
39	XenomatiX	XenoLidar-Xpert	solid-state	Flash (15000 Laser rays)	ToF	5,7

3.5.3 Evaluation of LiDAR technologies in the field of robotics

In the "robotics" application area, which was represented by a hypothetical application for so-called last-mile delivery, hybrid technologies are rated as the most suitable. Corresponding systems are ranked in the top three. Their mean values stand out clearly from the values of other technologies and are the only ones to exceed the critical mean value of 9. However, the mean values achieved in the area of robotics are characterized by their overall lower absolute values compared to the previous results. Accordingly, several requirements were not met.

Table 4: Ordering of technologies of exemplary LiDAR systems according to the mean value of relative weights of matching properties with the requirements for "last-mile delivery" as an exemplary application in the field of "robotics"

Evaluation of exemplary LiDAR systems for the application area for robotics						
Rank	Company	Product name	Technology class	Procedure for scanning a field of view	Measure-ment technique	Avg. value
1	**Ouster**	**OS2**	**hybrid**	**sequential Multibeam-Flash (128 rotating VCSEL Laser A**	**-**	**9,5**
2	**Ouster**	**OS0**	**hybrid**	**sequential Multibeam-Flash (128 rotating VCSEL Laser A**	**-**	**9,5**
3	**Ouster**	**OS1**	**hybrid**	**sequential Multibeam-Flash (128 rotating VCSEL Laser A**	**-**	**9,5**
4	Quanergy Systems	M8-Ultra	mechanical	-	ToF	8,9
5	Baraja	Spectrum HD	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	8,6
6	Baraja	Spectrum Off-Road	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	8,5
7	Quanergy Systems	M8-Core	mechanical	-	ToF	8,5
8	Quanergy Systems	M8-Plus	mechanical	-	ToF	8,3
9	Innoviz Technologies	INNOVIZ360	hybrid	MEMS und rotatingr Spiegel	ToF	8,3
10	Quanergy Systems	M8-PoE	mechanical	-	ToF	8,2
11	Faro	Focus Premium 350	mechanical	-	ToF	8,1
12	Velodyn LiDAR	Puck LITE	mechanical	16 Laser	ToF	7,7
13	Velodyne LiDAR Inc.	Puck VLP-16	mechanical	16 Laser	ToF	7,6
14	Ibeo Automotive Systems	IbeoNEXT	solid-state	VCSEL, 128x80 Laser sequential Flash ("Pure-electronic se	ToF	7,5
15	Velodyne LiDAR Inc.	Velarray M1600	solid-state	micro-lidar array (Multibeam-Flash)	-	7,1
16	Samsung	ISOCELL Vizion 33D	solid-state	Flash (VCSEL)	ToF	7,0
17	Velodyne LiDAR	Velarray H800	solid-state	micro-lidar array (Multibeam-Flash)	-	6,7
18	Neuvition	Titan M1-R	hybrid	MEMS	ToF	6,7
19	Quanergy Systems	S3-2NSI-S00	solid-state	optical phased array	ToF	6,5
20	Neuvition	Titan S2-120	hybrid	MEMS	ToF	6,2
21	Velodyne	Alpha Prime	mechanical	128 Laser, macromechanical scanning	ToF	6,0
22	Quanergy Systems	S3-2NSO-S00	solid-state	optical phased array	ToF	6,0
23	Quanergy Systems	S3-2WSO-S00	solid-state	optical phased array	ToF	6,0
24	Blickfeld	Cube Range 1	hybrid	MEMS	-	6,0
25	Aeva Technologies	Aeries I	solid-state	multiple beam (Flash)	FMCW	6,0
26	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechanical	32 Laser	ToF	5,9
27	AEye	4SIGHT M	hybrid	MEMS	ToF	5,9
28	Aeva Technologies	Aeries II	solid-state	multiple beam (Flash)	FMCW	5,7
29	Velodyne LiDAR Inc.	HDL-32E	mechanical	32 Laser	ToF	5,7
30	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	5,4
31	Blickfeld	Cube1	hybrid	MEMS	-	5,2
32	LeddarTech Inc.	Leddar Pixell	solid-state	Flash (Full Waveform)	-	5,0
33	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	4,9
34	Luminar Technologies	Hydra	mechanical	2-Axen-Spiegel-Scanner	ToF	4,8
35	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	4,8
36	Ibeo Automotive Systems	Ibeo LUX 4L	mechanical	multi-layer	ToF	4,1
37	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	4,1
38	XenomatiX	XenoLidar-Xpert	solid-state	Flash (15000 Laser rays)	ToF	3,6
39	XenomatiX	XenoLidar-Xact	solid-state	Flash (15000 Laser rays)	ToF	3,6

3.5.4 Evaluation of LiDAR technologies in the field of Smart Automotive

The order of the LiDAR systems according to their achieved mean values indicates relatively clearly in the application area "intelligent motor vehicles" that solid-state LiDAR technologies, in particular the so-called flash LiDAR technology and the so-called spectrum scan technology, are best suited here. Moreover, of all the LiDAR systems investigated, the top six rankings are precisely those that use uninterrupted, modulated laser beams for indirect measurement of the time of flight. The mean values of the best-ranked LiDAR systems of "hybrid" technologies, especially those that use movements of the platform to extend the field of view, are not significantly different from those of the best-ranked systems. Therefore, so-called hybrid technologies are also to be assessed as having a tendency to be suitable. Since systems based on "mechanical" technologies are listed in the middle and lower ranges of the table, with only a few exceptions, the "mechanical" technology class tends not to be suitable for the application area "intelligent vehicles".

Table 5: Order of technologies of selected LiDAR systems according to the mean value of relative weights of matching properties with the requirements for the application area "intelligent motor vehicles".

Evaluation of exemplary LiDAR systems for the application area Smart Automotive						
Rank	Company	Product name	Technology class	Procedure for scanning a field of view	Measure-ment technique	Avg. value
1	**Velodyne LiDAR**	**Velarray H800**	**solid-state**	**micro-lidar array (Multibeam-Flash)**	**-**	**11,4**
2	**Baraja**	**Spectrum Off-Road**	**solid-state**	**Wavelengh steering/ "Spectrum Scan", RMCW (Random**	**RMCW**	**11,0**
3	**Velodyne LiDAR Inc.**	**Velarray M1600**	**solid-state**	**micro-lidar array (Multibeam-Flash)**	**-**	**10,6**
4	Baraja	Spectrum HD	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	10,5
5	Aeva Technologies	Aeries II	solid-state	multiple beam (Flash)	FMCW	10,4
6	Aeva Technologies	Aeries I	solid-state	multiple beam (Flash)	FMCW	10,3
7	Velodyne	Alpha Prime	mechanical	128 Laser, macromechanical scanning	ToF	10,3
8	Innoviz Technologies	INNOVIZ360	hybrid	MEMS und rotatingr Spiegel	ToF	10,2
9	Ouster	OS2	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	10,2
10	Ibeo Automotive Systems	IbeoNEXT	solid-state	VCSEL, 128x80 Laser sequential Flash ("Pure-electronic se	ToF	10,1
11	Samsung	ISOCELL Vizion 33D	solid-state	Flash (VCSEL)	ToF	9,9
12	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechanical	32 Laser	ToF	9,8
13	Faro	Focus Premium 350	mechanical	-	ToF	9,5
14	Quanergy Systems	M8-Ultra	mechanical	-	ToF	9,4
15	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	9,4
16	Luminar Technologies	Hydra	mechanical	2-Axen-Spiegel-Scanner	ToF	9,2
17	Ouster	OS0	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	9,2
18	Ouster	OS1	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	9,2
19	Quanergy Systems	M8-Plus	mechanical	-	ToF	9,2
20	Quanergy Systems	M8-PoE	mechanical	-	ToF	9,2
21	Velodyne LiDAR Inc.	Puck VLP-16	mechanical	16 Laser	ToF	9,0
22	Quanergy Systems	M8-Core	mechanical	-	ToF	8,9
23	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	8,8
24	Velodyn LiDAR	Puck LITE	mechanical	16 Laser	ToF	8,7
25	Neuvition	Titan M1-R	hybrid	MEMS	ToF	8,5
26	AEye	4SIGHT M	hybrid	MEMS	ToF	8,4
27	Velodyne LiDAR Inc.	HDL-32E	mechanical	32 Laser	ToF	8,0
28	Quanergy Systems	S3-2NSI-S00	solid-state	optical phased array	ToF	7,9
29	Blickfeld	Cube Range 1	hybrid	MEMS	-	7,9
30	Quanergy Systems	S3-2NSO-S00	solid-state	optical phased array	ToF	7,8
31	Quanergy Systems	S3-2WSO-S00	solid-state	optical phased array	ToF	7,8
32	Blickfeld	Cube1	hybrid	MEMS	-	7,8
33	XenomatiX	XenoLidar-Xact	solid-state	Flash (15000 Laser rays)	ToF	7,7
34	Ibeo Automotive Systems	Ibeo LUX 4L	mechanical	multi-layer	ToF	7,5
35	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	7,5
36	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	7,5
37	Neuvition	Titan S2-120	hybrid	MEMS	ToF	7,5
38	XenomatiX	XenoLidar-Xpert	solid-state	Flash (15000 Laser rays)	ToF	7,3
39	LeddarTech Inc.	Leddar Pixell	solid-state	Flash (Full Waveform)	-	6,9

3.5.5 Evaluation of LiDAR technologies in the consumer goods sector

In the consumer goods sector, which was re-presented by smartphone and tablet applications, the LiDAR systems ranked according to their mean values show relatively clearly that solid-state LiDAR technologies are to be rated as the most suitable. Only LiDAR systems of such technologies occupy the first four ranks and even exceed the critical mean value of 9. However, they achieve at most 80 percent of the maximum mean value. Several requirements were therefore not met. The best-ranked solid-state technologies are flash LiDAR technology based on VCSEL emitters and optical phased array LiDAR technology. Hybrid technologies, like "mechanical" technologies, which for the most part occupy the last ranks, are not considered suitable for applications in the so-called consumer goods sector.

Table 6: Order of technologies of selected LiDAR systems according to the mean value of relative weights of matching properties and requirements for the so-called consumer goods sector, represented by the application in smartphones and tablets.

Rank	Company	Product name	Technology class	Procedure for scanning a field of view	Measure-ment	Avg. value
Evaluation of exemplary LiDAR systems for the consumer goods sector						
1	**Samsung**	**ISOCELL Vizion 33D**	**solid-state**	**Flash (VCSEL)**	**ToF**	**10,2**
2	**Quanergy Systems**	**S3-2WSO-S00**	**solid-state**	**optical phased array**	**ToF**	**9,8**
3	**Quanergy Systems**	**S3-2NSI-S00**	**solid-state**	**optical phased array**	**ToF**	**9,4**
4	Quanergy Systems	S3-2NSO-S00	solid-state	optical phased array	ToF	**9,4**
5	Ouster	OS0	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	**8,8**
6	Ouster	OS1	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	**8,8**
7	Innoviz Technologies	INNOVIZ360	hybrid	MEMS und rotatingr Spiegel	ToF	**8,7**
8	Velodyne LiDAR	Velarray H800	solid-state	micro-lidar array (Multibeam-Flash)	-	**8,6**
9	Neuvition	Titan S2-120	hybrid	MEMS	ToF	**8,3**
10	XenomatiX	XenoLidar-Xact	solid-state	Flash (15000 Laser rays)	ToF	**8,2**
11	Ibeo Automotive Systems	IbeoNEXT	solid-state	VCSEL, 128x80 Laser sequential Flash ("Pure-electronic se	ToF	**8,0**
12	XenomatiX	XenoLidar-Xpert	solid-state	Flash (15000 Laser rays)	ToF	**7,6**
13	Blickfeld	Cube Range 1	hybrid	MEMS	-	**7,5**
14	Velodyn LiDAR	Puck LITE	mechanical	16 Laser	ToF	**7,3**
15	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechanical	32 Laser	ToF	**7,2**
16	Blickfeld	Cube1	hybrid	MEMS	-	**7,2**
17	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	**7,2**
18	Velodyne LiDAR Inc.	Velarray M1600	solid-state	micro-lidar array (Multibeam-Flash)	-	**7,0**
19	Velodyne LiDAR Inc.	Puck VLP-16	mechanical	16 Laser	ToF	**7,0**
20	Baraja	Spectrum Off-Road	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	**6,8**
21	Aeva Technologies	Aeries II	solid-state	multiple beam (Flash)	FMCW	**6,5**
22	AEye	4SIGHT M	hybrid	MEMS	ToF	**6,5**
23	Aeva Technologies	Aeries I	solid-state	multiple beam (Flash)	FMCW	**6,4**
24	Baraja	Spectrum HD	solid-state	Wavelengh steering/ "Spectrum Scan", RMCW (Random	RMCW	**6,4**
25	Ouster	OS2	hybrid	sequential Multibeam-Flash (128 rotating VCSEL Laser Ar	-	**6,0**
26	Velodyne LiDAR Inc.	HDL-32E	mechanical	32 Laser	ToF	**6,0**
27	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	**5,8**
28	Luminar Technologies	Hydra	mechanical	2-Axen-Spiegel-Scanner	ToF	**5,8**
29	Faro	Focus Premium 350	mechanical	-	ToF	**5,7**
30	Quanergy Systems	M8-Core	mechanical	-	ToF	**5,5**
31	Velodyne	Alpha Prime	mechanical	128 Laser, macromechanical scanning	ToF	**5,4**
32	Quanergy Systems	M8-Plus	mechanical	-	ToF	**5,3**
33	Quanergy Systems	M8-Ultra	mechanical	-	ToF	**5,3**
34	Ibeo Automotive Systems	Ibeo LUX 4L	mechanical	multi-layer	ToF	**5,1**
35	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	**5,1**
36	Ibeo Automotive Systems	Ibeo LUX	mechanical	multi-layer	ToF	**5,1**
37	Neuvition	Titan M1-R	hybrid	MEMS	ToF	**4,6**
38	Quanergy Systems	M8-PoE	mechanical	-	ToF	**4,5**
39	LeddarTech Inc.	Leddar Pixell	solid-state	Flash (Full Waveform)	-	**3,9**

3.6 Conclusion

Having evaluated the suitability of LiDAR technologies for each of the typical application areas, the individual results are now summarized in a table.

Table 7: Evaluation of the suitability of the different LiDAR technologies for typical application areas (green tick - tends to be suitable, red cross - not suitable).

LiDAR-Technology		Application area: 3D-modeling	Smart City	Robotic	Smart Automotiv	Consumer goods
mechanical	rotating	✓	✓	✗	✗	✗
hybrid	MEMS	✗	✗	✗	✗	✗
	seq. MEMS	✓	✓	✓	✓	✗
	seq. Flash	✓	✓	✓	✓	✗
solid-state	Flash	✓	✗	✗	✓	✓
	OPA	✗	✗	✗	✗	✓
	other	✓	✓	✗	✓	✗

The results show which current technologies tend to be suitable for an area. In all the application areas considered - with the exception of the so-called consumer goods and robotics areas - several current technologies can be considered equally suitable. In the "robotics" and "consumer goods" application areas, a single LiDAR technology class is currently considered to be suitable in each case: In the "robotics" sector - especially for applications with mobile, autonomous robots - these are "hybrid" technologies. In the consumer goods sector, on the other hand, especially for compact mobile devices, only solid-state technologies have proven to be suitable. On the other hand, special "hybrid" technologies, which are characterized by hybrid scanning processes, have proven to be suitable for all typical applications - except for the so-called consumer goods sector.

The influence of error sources on the results was not quantified in this work. One potential source of error is the methodological approach to the evaluation of the LiDAR technologies: On the one hand, a selection of concrete LiDAR systems of different technologies had to be made to represent the characteristics of the respective technology. A larger selection of LiDAR systems of different technologies could improve the robustness of the results. On the other hand, the requirements of the typical application areas were also determined on the basis of exemplary applications. A different selection of exemplary applications, different requirements and weightings, would lead to different results. Another source of error is missing or erroneous data from the LiDAR systems. In addition, many specifications, e.g., the range of a LiDAR system, are not standardized. Another potential source of error is the assignment of LiDAR systems to one technology. Manufacturers have tended to assign their own LiDAR systems to so-called solid-state technologies. At the same time, meaningful descriptions of the technology were often avoided or the product data withheld in order to protect the manufacturers' intellectual property.

4. Summary

This work investigated which 3D LiDAR technologies are suitable for which application areas. The areas of "3D modeling", "intelligent city", "robotics", "intelligent vehicles" and "consumer goods" were determined as typical application areas. In order to evaluate the suitability of LiDAR technologies for typical application areas, exemplary applications were identified for each area - with the exception of the relatively homogeneous application area "intelligent vehicles" - and their specific requirements for performance, safety and cost-effectiveness were worked out and weighted relatively. The methodological approach of the study is based on the assumption that, on the one hand, these exemplary applications represent their entire field of application and, on the other hand, that concrete LiDAR systems represent a specific LiDAR technology.

Based on their essential characteristics, three LiDAR technology classes were determined: "mechanical" LiDAR technologies, so-called solid-state LiDAR technologies, and "hybrid" LiDAR technologies. The components used, the scanning method, and the measurement technique were identified as important characteristics of the LiDAR technologies. The scanning methods can be divided into sequential, parallel, and hybrid methods. The investigation of current LiDAR systems has shown that most of the distance measurement is done by direct time-of-flight measurement using laser light pulses. Few of the LiDAR systems considered use indirect techniques such as the so-called FMCW or RMCW technique, in which modulated uninterrupted laser light is emitted. LiDAR systems with indirect measurement techniques have proven to be particularly suitable for the application area of "intelligent vehicles".

This study indicates that technologies from all three technology classes are suitable for the areas of "3D modeling" and "smart city". In contrast, only "hybrid" technologies were assessed as suitable for the "robotics" application area, and only solid-state LiDAR technologies were assessed as suitable for the "consumer goods" application area. For the application area "intelligent vehicles", only mechanical technologies were assessed as tending to be unsuitable.

In addition, it was shown that current "hybrid" technologies tend to be suitable for almost all application areas - except for the so-called consumer goods area. The so-called flash LiDAR technology has proven to be the most significant solid-state LiDAR technology at present. However, it has also been shown that the so-called spectrum scan LiDAR technology is promising. [1]

5. Outlook

In this work, the current state of the technologies was examined in terms of their suitability for typical applications. The various LiDAR technologies show different potential in terms of increasing performance while reducing cost, size, weight, and power consumption. To meet a wide range of requirements, multiple LiDAR systems could be used, possibly networked together. Another approach to cover a wide range of requirements is the development of so-called intelligent LiDAR systems whose performance characteristics - for example, the resolution of a part of the field of view or the so-called frame rate - can be controlled. Hybrid MEMS-LiDAR technologies are considered particularly suitable for this purpose. It is predicted that, analogous to the development of photo and video cameras, semiconductor-based flash LiDAR technology based on VCSEL emitters and CMOS detectors will eventually prevail. [40] So-called mechanical LiDAR technologies could continue to play a role for such applications in the future, when performance characteristics are clearly more important than cost and physical characteristics. Finally, the most suitable technology for a specific application could be selected and customized to achieve optimal performance, taking into account safety and economic requirements. [35, p. 4]

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Appendix A

Table 8: Overview of the technology and properties of LiDAR systems from different manufacturers.

Properties of selected LiDAR systems

	Producer	Productname	Datasheet	Technology class/ Architectur	Proc. for scanning a field of view	Measurement technique	min. detection distance in m	max. detection distance in m	Range resolution in m	max. hor. Field of View in °	max. vert. Field of View in °	min. hor. geometric resolution	min. vert. geometric resolution	hor. angular resolution in °	vert. angular resulution in °	data rate in mill. points/s	max. frame rate in Hz	additional attributes	laser safety classification	wavelength in nm	min. working temperature in °C	max. working temperature in °C	vibration resilience	ambient light resilience	resilience to atmospheric disturbances	max. price in thous. USD	energy consumption in W	max. weight in kg	volume (WxHxD) in dm³	production process
1	Luminar Technologies	Hydra		mechani	2-Axen	ToF	2,00	500	0,01	120	30	0,61	0,26	0,070	0,030		30	Ref	1	1550	-10	40	SAE J1211, IEC 60068				55	4,500	4,41	suita
2	AEye	4SIGHT M	x	hybrid	MEMS	ToF		1000	0,03	60	30	1,75	1,75	0,100	0,100	4,00	100		1	1550	-40	70	IEC60068		Rain,	0,40	40	3,000	2,60	suita
3	Aeva Technologies	Aeries I	x	solid-stat	multipl	FMCW		300	0,02	120	30	0,16	0,52	0,030	0,100		20	Ges	1		0	45	ISO	immune		0,50		5,500	4,50	suita
4	Aeva Technologies	Aeries II	x	solid-stat	multipl	FMCW		500	0,02	120	30	0,22	0,22	0,025	0,025		20	Ges	1		-40	85	ISO 16750			0,50		1,800	1,26	suita
5	Innoviz Technologies	INNOVIZ360	x	hybrid	MEMS	ToF	0,30	300		360	64	0,26	0,26	0,050	0,050		25		1	905	-40	85		imm	Rain,	1,00	25	0,700	0,84	aime
6	Innoviz Technologies	INNOVIZPRO	x	hybrid	MEMS	ToF	2,10	135	0,05	72	19	0,42	0,94	0,180	0,400	2,00	16		1	905	-10	50	relia	resili	resili	1,00	40	0,950	0,79	aime
7	Ouster	OS0	x	hybrid	sequen	-	0,30	45	0,03	360	90	0,01	0,01	0,010	0,010	2,62	20		1	865	-40	60	IEC6	imm	all co	10,86	20	0,377	0,53	
8	Ouster	OS1	x	hybrid	sequen	-	0,30	100	0,03	360	45	0,02	0,02	0,010	0,010	2,62	20		1	865	-40	60	IEC6	imm	all co	19,30	20	0,377	0,53	
9	Ouster	OS2	x	hybrid	sequen	-	1,00	210	0,03	360	23	0,04	0,04	0,010	0,010	2,62	20		1	865	-20	60	IEC6	imm	all conditio		24	1,100	1,41	
10	Velodyne LiDAR Inc.	Velarray M1600	x	solid-stat	micro-l	-	0,10	30	0,05	120	32	0,10	0,10	0,200	0,200		25		1	905	-40	85	ISO	imm	all co	1,00	15	1,000	0,80	suita
11	Velodyne LiDAR	Velarray H800	x	solid-stat	micro-l	-	0,10	200	0,05	120	16	0,91	0,70	0,260	0,200		25		1	905	-40	85	ISO	day/	indoo	0,50	13	1,000	0,75	well-
12	Velodyne LiDAR Inc.	Puck VLP-16	x	mechani	16 Lase	ToF		100	0,03	360	30	0,17	3,49	0,10	2,000	0,60	20		1	903	-10	60	high	high	highl	3,47	8	0,830	0,77	
13	Velodyne LiDAR Inc.	Ultra Puck VLP-3	x	mechani	32 Lase	ToF	0,10	200	0,03	360	40	0,35	1,15	0,100	0,330	1,20	20		1	903	-20	60			almo	9,99	10	0,925	0,92	suita
14	Velodyn LiDAR	Puck LITE	x	mechani	16 Lase	ToF		100	0,03	360	30	0,17	3,49	0,100	2,000		20		1	903	-10	60	wid	wide	wide envirc		8	0,590	0,77	
15	Velodyne LiDAR Inc.	HDL-32E	x	mechani	32 Lase	ToF		100	0,02	360	41	0,14	2,32	0,080	1,330	1,39	20		1	905	-10	60					12	1,000	1,05	
16	Velodyne	Alpha Prime	x	mechani	128 Las	ToF		300	0,03	360	40	0,52	0,58	0,100	0,110	4,60	20		1	905	-20	60		Little susc		75,00	23	3,500	3,87	mult
17	Quanergy Systems	S3-2NSI-S00	x	solid-stat	optical	ToF	0,50	20	0,15	50	4	0,03	0,03	0,100	0,100		25		1	905	-10	50	true	indo	indoor		9	0,671	0,53	Cost
18	Quanergy Systems	S3-2NSO-S00	x	solid-stat	optical	ToF	0,50	10	0,15	50	4	0,02	0,02	0,100	0,100		25		1	905	-10	50	true	80000 Lux			9	0,671	0,53	Cost
19	Quanergy Systems	S3-2WSO-S00	x	solid-stat	optical	ToF	0,25	8	0,15	100	4	0,01	0,01	0,100	0,100		25		1	905	-10	50	true	80000 Lux			9	0,671	0,53	Cost
20	Quanergy Systems	M8-Core	x	mechani	-	ToF	0,50	100	0,03	360	20	0,06	0,06	0,033	0,033	1,30	20	Ref	1	905	-20	60	ETSI	imm	harsh envir		16	0,900	0,92	
21	Quanergy Systems	M8-Plus	x	mechani	-	ToF	0,50	150	0,03	360	20	0,09	0,09	0,033	0,033	1,30	20	Ref	1	905	-20	60	ETSI	imm	harsh	3,79	16	0,900	0,92	
22	Quanergy Systems	M8-Ultra	x	mechani	-	ToF	0,50	200	0,03	360	20	0,12	0,12	0,033	0,033	1,30	20	Ref	1	905	-20	60	ETSI	imm	harsh	4,48	16	0,900	0,92	
23	Quanergy Systems	M8-PoE	x	mechani	-	ToF	0,50	150	0,03	360	20	0,09	0,09	0,033	0,033	1,30	20	Ref	1	905	-20	60	ETSI	imm	harsh	4,13	18	1,360	2,06	
24	Blickfeld	Cube Range 1	x	hybrid	MEMS	-	5,00	250	0,02	18	12	1,05	0,26	0,240	0,060		50	Ref	1	905	-30	60			85% Humid		9	0,385	0,42	
25	Blickfeld	Cube1	x	hybrid	MEMS	-	1,50	250	0,02	70	30	1,75	0,33	0,400	0,075		50	Ref	1	905	-30	60			85%	4,16	9	0,275	0,25	
26	Ibeo Automotive Systems	IbeoNEXT	x	solid-stat	128x8	ToF		250		120	60	0,17	0,31	0,040	0,070		25	Ref	1	885	-40	85	robust ur		zuver	1,00	7	0,650	0,96	in lar
27	Ibeo Automotive Systems	Ibeo LUX 4L	x	mechani	multi-la	ToF		50	0,04	110	3	0,22	0,70	0,250	0,800		25		1	905	-40	85				9,00	9	1,000	1,35	
28	Ibeo Automotive Systems	Ibeo LUX	x	mechani	multi-la	ToF		50	0,04	110	6	0,22	0,70	0,250	0,800		25		1	905	-40	85				9,00	9	1,000	1,35	
29	Ibeo Automotive Systems	Ibeo LUX	x	mechani	multi-la	ToF		30	0,04	110	3	0,13	0,42	0,250	0,800		25		1	905	-40	85				9,00	9	1,000	1,35	
30	Baraja	Spectrum HD	x	solid-stat	Wavele	RMCW	0,01	250	0,05	120	25	0,05	0,17	0,013	0,040		30	Ges	1		-40	105	ISO	immuneit		1,00	20		0,30	mass
31	Baraja	Spectrum Off-Ro	x	solid-stat	Wavele	RMCW	0,00	240		120	30	0,21	0,08	0,050	0,020	0,66	40	Ges	1	1530	-40	50	ISO	imm	tough	1,00	5	2,200	3,46	mass
32	LeddarTech Inc.	Leddar Pixell	x	solid-stat	Flash (F	-		56	0,03	178	16	1,86	1,95	1,900	2,000		20		1	905	-30	65	IEC 6006		harsh	2,40	20	2,100	2,74	
33	XenomatiX	XenoLidar-Xpert	X	solid-stat	Flash (1	ToF	0,20	150	1,50	30	10	0,39	0,39	0,150	0,150	0,30	20	Ref	1	940	-10	40	true solic		10-90	10,00	12	0,550	0,55	prep
34	XenomatiX	XenoLidar-Xact	X	solid-stat	Flash (1	ToF	0,20	50	0,50	60	20	0,26	0,26	0,300	0,300	0,30	20	Ref	1	940	-10	40	true solic		10-90	10,00	13	0,550	0,55	prep
35	Robosense	RS-LiDAR-M1	x	hybrid	MEMS	-	0,70	200	0,05	120	25	0,70	0,70	0,200	0,200	1,50	10		1	905	-40	85				10,20	18	0,730	0,53	desg
36	Neuvition	Titan M1-R	x	hybrid	MEMS	ToF	1,00	300	0,02	15	8	0,05	0,05	0,010	0,010	1,00	30		1	1550	-20	65				10,00	25	1,520	1,58	
37	Neuvition	Titan S2-120	x	hybrid	MEMS	ToF	0,30	18	0,02	220	128	0,16	0,16	0,500	0,500		10		1	940	-40	65				10,00	9	0,620	0,72	
38	Samsung	ISOCELL Vizion 3	x	solid-stat	Flash (V	ToF	0,20	5	0,05	78	78	0,01	0,01	0,122	0,163		120		1	940	-30	70		indoor/ou		0,30	0	0,010	0,00	
39	Faro	Focus Premium	x	mechani	-	ToF	0,50	350	0,00	360	300	0,05	0,05	0,009	0,009	2,00	97		1	1554	-20	55				39,50	32	4,400	4,34	
Average							0,71	143	0,14	160	37	0,34	0,31	0,22	0,27	1,41	32		1	994	-26	65				8,75	17	1,321	1,35	
Median							0,50	150	0,03	120	25	0,17	0,26	0,10	0,10	1,30	20		1	905	-20	60				4,14	13	0,913	0,92	

Table 9: Comparison of the specific requirements of an exemplary airborne application in the application area "3D modeling" with the properties of concrete LiDAR systems and the evaluation as the mean value of the weighted points.

Comparison of the properties of selected LiDAR systems with the requirements for 3D modeling.

					Requirement parameter	min. detection distance in m	max. detection distance in m	min. range resolution in m	min. horiz. Field of View in °	min. vert. Field of View in °	min. hor. geom. resolution in m	min. vert. geom. resolution in m	min. horiz. angular resolution in °	min. vert. angular resolution in °	data rate in points/s	min. frame rate in Hz	data point attributes	min. laser safety classification	min. wavelength in nm	min. working temprature in °C	max. working temprature in °C	min. vibration resilience	min. ambient light resilience	min. resilience to atmospheric disturbances	max. price	max. energy consumotion	max. weight in kg	max. volume	production process	Average (only values)
					relative weighting	1	24	18	17	16	20	19	15	14	13	9	10	22	23	6	7	8	21	11	3	5	12	4	2	
	Producer	Productname	Tech. Cla	Proc. fc	Measu	2,00	125	1,00	90	30	1,00	1,00	0,45	0,45		10	Ref	2	800	-25	50	ediu	high	ediur	high	low	low	medium	single-unit c	
1	Luminar Technologies	Hydra	mechani	2-Axen	ToF	1	24	18	17	16	20	19	15	14	-	9	10	22	23	0	0	8	0	-	3	0	0	0	2	10,0
2	AEye	4SIGHT M	hybrid	MEMS	ToF	-	24	18	0	16	0	0	15	14	-	9	-	22	23	6	7	8	0	11	3	0	0	0	2	8,5
3	Aeva Technologies	Aeries I	solid-stat	multipl	FMCW	-	24	18	17	16	20	19	15	14	-	9	0	22	-	0	0	8	21	-	3	-	0	0	2	10,9
4	Aeva Technologies	Aeries II	solid-stat	multipl	FMCW	-	24	18	17	16	20	19	15	14	-	9	0	22	-	6	7	8	0	-	3	-	0	4	2	10,7
5	Innoviz Technologies	INNOVIZ360	hybrid	MEMS	ToF	1	24	-	17	16	20	19	15	14	-	9	-	22	23	6	7	-	21	11	3	0	12	4	2	12,3
6	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	0	24	18	0	0	20	19	15	14	-	9	-	22	23	0	7	8	21	11	3	0	0	4	2	10,0
7	Ouster	OS0	hybrid	sequen	-	1	0	18	17	16	20	19	15	14	-	9	-	22	23	6	7	8	21	11	3	0	12	4	2	11,3
8	Ouster	OS1	hybrid	sequen	-	1	0	18	17	16	20	19	15	14	-	9	-	22	23	6	7	8	21	11	3	0	12	4	2	11,3
9	Ouster	OS2	hybrid	sequen	-	1	24	18	17	0	20	19	15	14	-	9	-	22	23	0	7	8	21	11	3	0	0	0	2	10,6
10	Velodyne LiDAR Inc.	Velarray M1600	solid-stat	micro-l	-	1	0	18	17	16	20	19	15	14	-	9	-	22	23	6	7	8	21	11	3	0	0	4	2	10,7
11	Velodyne LiDAR	Velarray H800	solid-stat	micro-l	-	1	24	18	17	0	20	19	15	14	-	9	-	22	23	6	7	8	21	11	3	5	0	4	2	11,3
12	Velodyne LiDAR Inc.	Puck VLP-16	mechani	16 Lase	ToF	-	0	18	17	16	20	0	15	0	-	9	-	22	23	0	7	8	21	11	3	5	12	4	2	10,1
13	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechani	32 Lase	ToF	1	24	18	17	16	20	0	15	14	-	9	-	22	23	0	7	-	0	11	3	5	0	4	2	10,0
14	Velodyn LiDAR	Puck LITE	mechani	16 Lase	ToF	-	0	18	17	16	20	0	15	0	-	9	-	22	23	0	7	8	21	11	3	5	12	4	2	10,1
15	Velodyne LiDAR Inc.	HDL-32E	mechani	32 Lase	ToF	-	0	18	17	16	20	0	15	0	-	9	-	22	23	0	7	-	0	-	3	5	0	4	2	8,5
16	Velodyne	Alpha Prime	mechani	128 Las	ToF	-	24	18	17	16	20	19	15	14	-	9	-	22	23	0	7	-	21	-	3	0	0	0	2	12,1
17	Quanergy Systems	S3-2NSI-S00	solid-stat	optical	ToF	1	0	18	0	0	20	19	15	14	-	9	-	22	23	0	7	8	21	11	3	5	12	4	2	9,7
18	Quanergy Systems	S3-2NSO-S00	solid-stat	optical	ToF	1	0	18	0	0	20	19	15	14	-	9	-	22	23	0	7	8	21	-	3	5	12	4	2	9,7
19	Quanergy Systems	S3-2WSO-S00	solid-stat	optical	ToF	1	0	18	17	0	20	19	15	14	-	9	-	22	23	0	7	8	21	-	3	5	12	4	2	10,5
20	Quanergy Systems	M8-Core	mechani	-	ToF	1	0	18	17	0	20	19	15	14	-	9	10	22	23	0	7	8	21	11	3	0	12	4	2	10,3
21	Quanergy Systems	M8-Plus	mechani	-	ToF	1	24	18	17	0	20	19	15	14	-	9	10	22	23	0	7	8	21	11	3	0	12	4	2	11,3
22	Quanergy Systems	M8-Ultra	mechani	-	ToF	1	24	18	17	0	20	19	15	14	-	9	10	22	23	0	7	8	21	11	3	0	12	4	2	11,3
23	Quanergy Systems	M8-PoE	mechani	-	ToF	1	24	18	17	0	20	19	15	14	-	9	10	22	23	0	7	8	21	11	3	0	0	0	2	10,6
24	Blickfeld	Cube Range 1	hybrid	MEMS	-	0	24	18	0	0	0	19	15	14	-	9	10	22	23	6	7	-	0	11	3	5	12	4	2	9,3
25	Blickfeld	Cube1	hybrid	MEMS	-	1	24	18	0	16	0	19	15	14	-	9	10	22	23	6	7	-	0	11	3	5	12	4	2	10,0
26	Ibeo Automotive Systems	IbeoNEXT	solid-stat	VCSEL,	ToF	-	24	-	17	16	20	19	15	14	-	9	10	22	23	6	7	8	0	11	3	5	12	4	2	11,8
27	Ibeo Automotive Systems	Ibeo LUX 4L	mechani	multi-la	ToF	-	0	18	17	0	20	19	15	0	-	9	-	22	23	6	7	-	0	-	3	5	0	4	2	8,9
28	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	18	17	0	20	19	15	0	-	9	-	22	23	6	7	-	0	-	3	5	0	4	2	8,9
29	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	18	17	0	20	19	15	0	-	9	-	22	23	6	7	-	0	-	3	5	0	4	2	8,9
30	Baraja	Spectrum HD	solid-stat	Wavele	RMCW	1	24	18	17	0	20	19	15	14	-	9	0	22	-	6	7	8	21	-	3	0	-	4	2	10,5
31	Baraja	Spectrum Off-Road	solid-stat	Wavele	RMCW	1	24	-	17	16	20	19	15	14	-	9	0	22	23	6	7	8	21	11	3	5	0	0	2	11,0
32	LeddarTech Inc.	Leddar Pixell	solid-stat	Flash (F	-	-	0	18	17	0	0	0	0	0	-	9	-	22	23	6	7	8	0	11	3	0	0	0	2	6,0
33	XenomatiX	XenoLidar-Xpert	solid-stat	Flash (1	ToF	1	24	0	0	0	20	19	15	14	-	9	10	22	23	0	0	8	0	11	3	5	12	4	2	8,8
34	XenomatiX	XenoLidar-Xact	solid-stat	Flash (1	ToF	1	0	0	0	0	20	19	15	14	-	9	10	22	23	0	0	8	0	11	3	5	12	4	2	7,7
35	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	1	24	18	17	0	20	19	15	14	-	9	-	22	23	6	7	-	0	-	3	0	12	4	2	10,8
36	Neuvition	Titan M1-R	hybrid	MEMS	ToF	1	24	18	0	0	20	19	15	14	-	9	-	22	23	0	7	-	0	-	3	0	0	0	2	8,9
37	Neuvition	Titan S2-120	hybrid	MEMS	ToF	1	0	18	17	16	20	19	0	0	-	9	-	22	23	6	7	-	0	-	3	5	12	4	2	9,2
38	Samsung	ISOCELL Vizion 33D	solid-stat	Flash (V	ToF	1	0	18	0	16	20	19	15	14	-	9	-	22	23	6	7	-	21	-	3	5	12	4	2	10,9
39	Faro	Focus Premium 350	mechani	-	ToF	1	24	18	17	16	20	19	15	14	-	9	-	22	23	0	7	-	0	-	3	0	0	0	2	10,5

Table 10: Comparison of the specific requirements of an exemplary application in the application area "smart city" with the characteristics of concrete LiDAR systems and the evaluation as the mean value of the weighted points.

Comparison of the properties of selected LiDAR systems with the requirements for the Smart City sector

					Requirement parameter	min. detection distance in m	max. detection distance in m	min. range resolution in m	min. horiz. Field of View in °	min. vert. Field of View in °	min. hor. geom. resolution in m	min. vert. geom. resolution in m	min. horiz. angular resolution in °	min. vert. angular resolution in °	data rate in points/s	min. frame rate in Hz	data point attributes	min. laser safety classification	min. wavelength in nm	min. working temprature in °C	max. working temprature in °C	min. vibration resilience	min. ambient light resilience	min. resilience to atmospheric disturbances	max. price	max. energy consumotion	max. weight in kg	max. volume	production process	Average (only values)
					relative weighting	13	22	18	17	16	20	19	15	14	12	11	10	24	23	8	9	2	21	7	6	1	3	5	4	
	Producer	Productname	Tech. Cla	Proc. fc	Measu	2,00	90	0,05	90	90	0,30	0,30	0,13	0,13		10	Ref	1	800	-30	60	low	high	mediu	high	high	high	high	singl	
1	Luminar Technologies	Hydra	mechani	2-Axen	ToF	13	22	18	17	0	0	19	15	14	-	11	10	24	23	0	0	2	0	-	6	1	3	5	4	9,4
2	AEye	4SIGHT M	hybrid	MEMS	ToF	-	22	18	0	0	0	0	15	14	-	11	-	24	23	8	9	2	0	7	6	1	3	5	4	8,2
3	Aeva Technologies	Aeries I	solid-stat	multipl	FMCW	-	22	18	17	0	20	0	15	14	-	11	10	24	-	0	0	2	21	-	6	1	3	5	4	9,7
4	Aeva Technologies	Aeries II	solid-stat	multipl	FMCW	-	22	18	17	0	20	19	15	14	-	11	10	24	-	8	9	2	0	-	6	1	3	5	4	10,4
5	Innoviz Technologies	INNOVIZ360	hybrid	MEMS	ToF	13	22	-	17	0	20	19	15	14	-	11	-	24	23	8	9	2	21	7	6	1	3	5	4	11,6
6	Innoviz	INNOVIZPRO	hybrid	MEMS	ToF	0	22	18	0	0	0	0	0	0	-	11	-	24	23	0	0	2	21	7	6	1	3	5	4	6,7
7	Ouster	OS0	hybrid	sequen	-	13	0	18	17	16	20	19	15	14	-	11	-	24	23	8	9	2	21	7	6	1	3	5	4	11,6
8	Ouster	OS1	hybrid	sequen	-	13	22	18	17	0	20	19	15	14	-	11	-	24	23	8	9	2	21	7	6	1	3	5	4	11,9
9	Ouster	OS2	hybrid	sequen	-	13	22	18	17	0	20	19	15	14	-	11	-	24	23	0	9	2	21	7	6	1	3	5	4	11,5
10	Velodyne LiDAR Inc.	Velarray M1600	solid-stat	micro-l	-	13	0	18	17	0	20	19	0	0	-	11	-	24	23	8	9	2	21	7	6	1	3	5	4	9,6
11	Velodyne LiDAR	Velarray H800	solid-stat	micro-l	-	13	22	18	17	0	0	0	0	0	-	11	-	24	23	8	9	2	21	7	6	1	3	5	4	8,8
12	Velodyne LiDAR Inc.	Puck VLP-16	mechani	16 Lase	ToF	-	22	18	17	0	20	0	15	0	-	11	-	24	23	0	9	2	21	7	6	1	3	5	4	9,9
13	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechani	32 Lase	ToF	13	22	18	17	0	0	0	15	0	-	11	-	24	23	0	9	2	0	7	6	1	3	5	4	8,2
14	Velodyn LiDAR	Puck LITE	mechani	16 Lase	ToF	-	22	18	17	0	20	0	15	0	-	11	-	24	23	0	9	2	21	7	6	1	3	5	4	9,9
15	Velodyne LiDAR Inc.	HDL-32E	mechani	32 Lase	ToF	-	22	18	17	0	20	0	15	0	-	11	-	24	23	0	9	2	0	-	6	1	3	5	4	9,0
16	Velodyne	Alpha Prime	mechani	128 Las	ToF	-	22	18	17	0	0	0	15	14	-	11	-	24	23	0	9	2	21	-	6	1	3	5	4	9,8
17	Quanergy Systems	S3-2NSI-S00	solid-stat	optical	ToF	13	0	0	0	0	20	19	15	14	-	11	-	24	23	0	0	2	21	7	6	1	3	5	4	8,5
18	Quanergy Systems	S3-2NSO-S00	solid-stat	optical	ToF	13	0	0	0	0	20	19	15	14	-	11	-	24	23	0	0	2	21	-	6	1	3	5	4	8,6
19	Quanergy Systems	S3-2WSO-S00	solid-stat	optical	ToF	13	0	0	17	0	20	19	15	14	-	11	-	24	23	0	0	2	21	-	6	1	3	5	4	9,4
20	Quanergy Systems	M8-Core	mechani	-	ToF	13	22	18	17	0	20	19	15	14	-	11	10	24	23	0	9	2	21	7	6	1	3	5	4	11,5
21	Quanergy Systems	M8-Plus	mechani	-	ToF	13	22	18	17	0	20	19	15	14	-	11	10	24	23	0	9	2	21	7	6	1	3	5	4	11,5
22	Quanergy Systems	M8-Ultra	mechani	-	ToF	13	22	18	17	0	20	19	15	14	-	11	10	24	23	0	9	2	21	7	6	1	3	5	4	11,5
23	Quanergy Systems	M8-PoE	mechani	-	ToF	13	22	18	17	0	20	19	15	14	-	11	10	24	23	0	9	2	21	7	6	1	3	5	4	11,5
24	Blickfeld	Cube Range 1	hybrid	MEMS	-	0	22	18	0	0	0	19	0	14	-	11	10	24	23	8	9	2	0	7	6	1	3	5	4	8,1
25	Blickfeld	Cube1	hybrid	MEMS	-	13	22	18	0	0	0	0	0	14	-	11	10	24	23	8	9	2	0	7	6	1	3	5	4	7,8
26	Ibeo Automotive Systems	IbeoNEXT	solid-stat	VCSEL,	ToF	-	22	-	17	0	20	0	15	14	-	11	10	24	23	8	9	2	0	7	6	1	3	5	4	9,6
27	Ibeo Automotive Systems	Ibeo LUX 4L	mechani	multi-la	ToF	-	0	18	17	0	20	0	0	0	-	11	-	24	23	8	9	2	0	-	6	1	3	5	4	7,6
28	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	18	17	0	20	0	0	0	-	11	-	24	23	8	9	2	0	-	6	1	3	5	4	7,6
29	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	18	17	0	20	0	0	0	-	11	-	24	23	8	9	2	0	-	6	1	3	5	4	7,6
30	Baraja	Spectrum HD	solid-stat	Wavele	RMCW	13	22	18	17	0	20	19	15	14	-	11	10	24	-	8	9	2	21	-	6	1	3	5	4	11,5
31	Baraja	Spectrum Off-Road	solid-stat	Wavele	RMCW	13	22	-	17	0	20	19	15	14	-	11	10	24	23	8	0	2	21	7	6	1	3	5	4	11,1
32	LeddarTech Inc.	Leddar Pixell	solid-stat	Flash (F	-	-	0	18	17	0	0	0	0	0	-	11	-	24	23	8	9	2	0	7	6	1	3	5	4	6,6
33	XenomatiX	XenoLidar-Xpert	solid-stat	Flash (1	ToF	13	22	0	0	0	0	0	0	0	-	11	10	24	23	0	0	2	0	7	6	1	3	5	4	5,7
34	XenomatiX	XenoLidar-Xact	solid-stat	Flash (1	ToF	13	0	0	0	0	20	19	0	0	-	11	10	24	23	0	0	2	0	7	6	1	3	5	4	6,4
35	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	13	22	18	17	0	0	0	0	0	-	11	-	24	23	8	9	2	0	-	6	1	3	5	4	7,9
36	Neuvition	Titan M1-R	hybrid	MEMS	ToF	13	22	18	0	0	20	19	15	14	-	11	-	24	23	0	9	2	0	-	6	1	3	5	4	10,0
37	Neuvition	Titan S2-120	hybrid	MEMS	ToF	13	0	18	17	16	20	19	0	0	-	11	-	24	23	8	9	2	0	-	6	1	3	5	4	9,5
38	Samsung	ISOCELL Vizion 33D	solid-stat	Flash (V	ToF	13	0	18	0	0	20	19	15	0	-	11	-	24	23	8	9	2	21	-	6	1	3	5	4	9,6
39	Faro	Focus Premium 350	mechani	-	ToF	13	22	18	17	16	20	19	15	14	-	11	-	24	23	0	9	2	0	-	6	1	3	5	4	11,5

Table 11: Comparison of the specific requirements of an exemplary application in the field of robotics with the properties of concrete LiDAR systems and the evaluation as the mean value of the weighted points.

Comparison of the properties of selected LiDAR systems with the requirements for the field of robotics.

					Requirement parameter	min. detection distance in m	max. detection distance in m	min. range resolution in m	min. horiz. Field of View in °	min. vert. Field of View in °	min. hor. geom. resolution in m	min. vert. geom. resolution in m	min. horiz. angular resolution in °	min. vert. angular resolution in °	data rate in points/s	min. frame rate in Hz	data point attributes	min. laser safety classification	min. wavelength in nm	min. working temprature in °C	max. working temprature in °C	min. vibration resilience	min. ambient light resilience	min. resilience to atmospheric disturbances	max. price	max. energy consumotion	max. weight in kg	max. volume	production process	Average (only values)
					relative weighting	21	20	18	22	14	19	16	15	13	7	10	2	24	23	8	9	12	17	11	5	6	3	4	1	
	Producer	Productname	Technolo	Proc. fc	Measu	0,01	200	0,05	360	45	0,20	0,20	0,06	0,06		10	Ges	1	800	-30	50	high	high	high	mediun	low	low	low	Serie	
1	Luminar Technologies	Hydra	mechani	2-Axen	ToF	0	20	18	0	0	0	0	0	13	-	10	0	24	23	0	0	12	0	0	-	0	0	0	1	4,8
2	AEye	4SIGHT M	hybrid	MEMS	ToF	-	20	18	0	0	0	0	0	0	-	10	-	24	23	8	9	12	0	11	5	0	0	0	1	5,9
3	Aeva Technologies	Aeries I	solid-stat	multipl	FMCW	-	20	18	0	0	19	0	15	0	-	10	2	24	0	0	0	12	17	0	5	-	0	0	1	6,0
4	Aeva Technologies	Aeries II	solid-stat	multipl	FMCW	-	20	18	0	0	0	0	15	13	-	10	2	24	0	8	9	12	0	0	5	-	0	0	1	5,7
5	Innoviz Technologies	INNOVIZ360	hybrid	MEMS	ToF	0	20	-	22	14	0	0	15	13	-	10	-	24	23	8	9	0	17	11	5	0	3	4	1	8,3
6	Innoviz Technologies	INNOVIZPRO	hybrid	MEMS	ToF	0	0	18	0	0	0	0	0	0	-	10	-	24	23	0	9	12	17	11	5	0	0	4	1	5,4
7	Ouster	OS0	hybrid	sequen	-	0	0	18	22	14	19	16	15	13	-	10	-	24	23	8	9	12	17	11	0	0	3	4	0	9,5
8	Ouster	OS1	hybrid	sequen	-	0	0	18	22	14	19	16	15	13	-	10	-	24	23	8	9	12	17	11	0	0	3	4	0	9,5
9	Ouster	OS2	hybrid	sequen	-	0	20	18	22	0	19	16	15	13	-	10	-	24	23	0	9	12	17	11	-	0	0	0	0	9,5
10	Velodyne LiDAR Inc.	Velarray M1600	solid-stat	micro-l	-	0	0	18	0	0	19	16	0	0	-	10	-	24	23	8	9	12	17	11	5	0	0	4	1	7,1
11	Velodyne LiDAR	Velarray H800	solid-stat	micro-l	-	0	20	18	0	0	0	0	0	0	-	10	-	24	23	8	9	12	17	11	5	6	0	4	1	6,7
12	Velodyne LiDAR Inc.	Puck VLP-16	mechani	16 Lase	ToF	-	0	18	22	0	19	0	0	0	-	10	-	24	23	0	9	12	17	11	5	6	3	4	0	7,6
13	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechani	32 Lase	ToF	0	20	18	22	0	0	0	0	0	-	10	-	24	23	0	9	0	0	11	0	6	0	4	1	5,9
14	Velodyn LiDAR	Puck LITE	mechani	16 Lase	ToF	-	0	18	22	0	19	0	0	0	-	10	-	24	23	0	9	12	17	11	-	6	3	4	0	7,7
15	Velodyne LiDAR Inc.	HDL-32E	mechani	32 Lase	ToF	-	0	18	22	0	19	0	0	0	-	10	-	24	23	0	9	0	0	0	-	6	0	0	0	5,7
16	Velodyne	Alpha Prime	mechani	128 Las	ToF	-	20	18	22	0	0	0	0	0	-	10	-	24	23	0	9	0	17	0	0	0	0	0	1	6,0
17	Quanergy Systems	S3-2NSI-S00	solid-stat	optical	ToF	0	0	0	0	0	19	16	0	0	-	10	-	24	23	0	9	12	17	11	-	6	3	4	1	6,5
18	Quanergy Systems	S3-2NSO-S00	solid-stat	optical	ToF	0	0	0	0	0	19	16	0	0	-	10	-	24	23	0	9	12	17	0	-	6	3	4	1	6,0
19	Quanergy Systems	S3-2WSO-S00	solid-stat	optical	ToF	0	0	0	0	0	19	16	0	0	-	10	-	24	23	0	9	12	17	0	-	6	3	4	1	6,0
20	Quanergy Systems	M8-Core	mechani	-	ToF	0	0	18	22	0	19	16	15	13	-	10	0	24	23	0	9	12	17	11	-	0	3	0	0	8,5
21	Quanergy Systems	M8-Plus	mechani	-	ToF	0	0	18	22	0	19	16	15	13	-	10	0	24	23	0	9	12	17	11	5	0	3	0	0	8,3
22	Quanergy Systems	M8-Ultra	mechani	-	ToF	0	20	18	22	0	19	16	15	13	-	10	0	24	23	0	9	12	17	11	0	0	3	0	0	8,9
23	Quanergy Systems	M8-PoE	mechani	-	ToF	0	0	18	22	0	19	16	15	13	-	10	0	24	23	0	9	12	17	11	5	0	0	0	0	8,2
24	Blickfeld	Cube Range 1	hybrid	MEMS	-	0	20	18	0	0	0	0	0	13	-	10	0	24	23	8	9	0	0	11	-	6	3	4	0	6,0
25	Blickfeld	Cube1	hybrid	MEMS	-	0	20	18	0	0	0	0	0	0	-	10	0	24	23	8	9	0	0	11	0	6	3	4	0	5,2
26	Ibeo Automotive Systems	IbeoNEXT	solid-stat	VCSEL,	ToF	-	20	-	0	14	19	0	15	0	-	10	0	24	23	8	9	12	0	11	5	6	3	0	1	7,5
27	Ibeo Automotive Systems	Ibeo LUX 4L	mechani	multi-la	ToF	-	0	18	0	0	0	0	0	0	-	10	-	24	23	8	9	0	0	0	0	6	0	0	0	4,1
28	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	18	0	0	0	0	0	0	-	10	-	24	23	8	9	0	0	0	0	6	0	0	0	4,1
29	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	18	0	0	19	0	0	0	-	10	-	24	23	8	9	0	0	0	0	6	0	0	0	4,9
30	Baraja	Spectrum HD	solid-stat	Wavele	RMCW	21	20	18	0	0	19	16	15	13	-	10	2	24	0	8	9	12	17	0	5	0	-	4	1	8,6
31	Baraja	Spectrum Off-Road	solid-stat	Wavele	RMCW	21	20	-	0	0	0	16	15	13	-	10	2	24	23	8	9	12	17	11	5	6	0	0	1	8,5
32	LeddarTech Inc.	Leddar Pixell	solid-stat	Flash (F	-	-	0	18	0	0	0	0	0	0	-	10	-	24	23	8	9	12	0	11	5	0	0	0	0	5,0
33	XenomatiX	XenoLidar-Xpert	solid-stat	Flash (1	ToF	0	0	0	0	0	0	0	0	0	-	10	0	24	23	0	0	12	0	11	0	6	3	4	1	3,6
34	XenomatiX	XenoLidar-Xact	solid-stat	Flash (1	ToF	0	0	0	0	0	0	0	0	0	-	10	0	24	23	0	9	12	0	11	0	6	3	4	1	4,0
35	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	0	20	18	0	0	0	0	0	0	-	10	-	24	23	8	9	0	0	0	0	0	3	4	1	4,8
36	Neuvition	Titan M1-R	hybrid	MEMS	ToF	0	20	18	0	0	19	16	15	13	-	10	-	24	23	0	9	0	0	0	0	0	0	0	0	6,7
37	Neuvition	Titan S2-120	hybrid	MEMS	ToF	0	0	18	0	14	19	16	0	0	-	10	-	24	23	8	9	0	0	0	0	6	3	4	0	6,2
38	Samsung	ISOCELL Vizion 33D	solid-stat	Flash (V	ToF	0	0	18	0	14	19	16	0	0	-	10	-	24	23	8	9	0	17	0	5	6	3	4	0	7,0
39	Faro	Focus Premium 350	mechani	-	ToF	0	20	18	22	14	19	16	15	13	-	10	-	24	23	0	9	0	0	0	0	0	0	0	0	8,1

Table 12: Comparison of the specific requirements in the application area "intelligent motor vehicles" with the properties of concrete LiDAR systems and the evaluation as the mean value of the weighted points.

Comparison of the properties of selected LiDAR systems with the requirements for Smart Automotive.

					Requirement parameter	min. detection distance in m	max. detection distance in m	min. range resolution in m	min. horiz. Field of View in °	min. vert. Field of View in °	min. hor. geom. resolution in m	min. vert. geom. resolution in m	min. horiz. angular resolution in °	min. vert. angular resolution in °	data rate in points/s	min. frame rate in Hz	data point attributes	min. laser safety classification	min. wavelength in nm	min. working temprature in °C	max. working temprature in °C	min. vibration resilience	min. ambient light resilience	min. resilience to atmospheric disturbances	max. price	max. energy consumotion	max. weight in kg	max. volume	production process	Average (only values)
					relative weighting	20	22	19	17	4	21	16	14	13	6	10	5	24	23	2	9	12	18	11	15	3	1	7	8	
	Producer	Productname	Technolo	Proc. fc	Measu	0,20	200	0,10	120	30	1,00	1,00	0,45	0,45		10	Ges	1	800	-25	50	ediu	ediu	ediun	ediun	low	high	high	singl	
1	Luminar Technologies	Hydra	mechani	2-Axen	ToF	0	22	19	17	4	21	16	14	13	-	10	0	24	23	0	0	12	-	-	-	0	1	7	8	**9,2**
2	AEye	4SIGHT M	hybrid	MEMS	ToF	-	22	19	0	4	0	0	14	13	-	10	-	24	23	2	9	12	-	11	15	0	1	7	8	**8,4**
3	Aeva Technologies	Aeries I	solid-stat	multipl	FMCW	-	22	19	17	4	21	16	14	13	-	10	5	24	-	0	0	12	18	-	15	-	1	7	8	**10,3**
4	Aeva Technologies	Aeries II	solid-stat	multipl	FMCW	-	22	19	17	4	21	16	14	13	-	10	5	24	-	2	9	12	-	-	15	-	1	7	8	**10,4**
5	Innoviz Technologies	INNOVIZ360	hybrid	MEMS	ToF	0	22	-	17	4	21	16	14	13	-	10	-	24	23	2	9	-	18	11	15	0	1	7	8	**10,2**
6	Innoviz Technologies	INNOVIZPRO	hybrid	MEMS	ToF	0	0	19	0	0	21	16	14	13	-	10	-	24	23	0	9	12	18	11	15	0	1	7	8	**8,8**
7	Ouster	OS0	hybrid	sequen	-	0	0	19	17	4	21	16	14	13	-	10	-	24	23	2	9	12	18	11	0	0	1	7	8	**9,2**
8	Ouster	OS1	hybrid	sequen	-	0	0	19	17	4	21	16	14	13	-	10	-	24	23	2	9	12	18	11	0	0	1	7	8	**9,2**
9	Ouster	OS2	hybrid	sequen	-	0	22	19	17	0	21	16	14	13	-	10	-	24	23	0	9	12	18	11	-	0	1	7	8	**10,2**
10	Velodyne LiDAR Inc.	Velarray M1600	solid-stat	micro-l	-	20	0	19	17	4	21	16	14	13	-	10	-	24	23	2	9	12	18	11	15	0	1	7	8	**10,6**
11	Velodyne LiDAR	Velarray H800	solid-stat	micro-l	-	20	22	19	17	0	21	16	14	13	-	10	-	24	23	2	9	12	18	11	15	3	1	7	8	**11,4**
12	Velodyne LiDAR Inc.	Puck VLP-16	mechani	16 Lase	ToF	-	0	19	17	4	21	0	14	0	-	10	-	24	23	0	9	12	18	11	15	3	1	7	8	**9,0**
13	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechani	32 Lase	ToF	20	22	19	17	4	21	0	14	13	-	10	-	24	23	0	9	-	-	11	0	3	1	7	8	**9,8**
14	Velodyn LiDAR	Puck LITE	mechani	16 Lase	ToF	-	0	19	17	4	21	0	14	0	-	10	-	24	23	0	9	12	18	11	-	3	1	7	8	**8,7**
15	Velodyne LiDAR Inc.	HDL-32E	mechani	32 Lase	ToF	-	0	19	17	4	21	0	14	0	-	10	-	24	23	0	9	-	-	-	-	3	1	7	8	**8,0**
16	Velodyne	Alpha Prime	mechani	128 Las	ToF	-	22	19	17	4	21	16	14	13	-	10	-	24	23	0	9	-	18	-	0	0	1	7	8	**10,3**
17	Quanergy Systems	S3-2NSI-S00	solid-stat	optical	ToF	0	0	0	0	0	21	16	14	13	-	10	-	24	23	0	9	12	18	11	-	3	1	7	8	**7,9**
18	Quanergy Systems	S3-2NSO-S00	solid-stat	optical	ToF	0	0	0	0	0	21	16	14	13	-	10	-	24	23	0	9	12	18	-	-	3	1	7	8	**7,8**
19	Quanergy Systems	S3-2WSO-S00	solid-stat	optical	ToF	0	0	0	0	0	21	16	14	13	-	10	-	24	23	0	9	12	18	-	-	3	1	7	8	**7,8**
20	Quanergy Systems	M8-Core	mechani	-	ToF	0	0	19	17	0	21	16	14	13	-	10	0	24	23	0	9	12	18	11	-	0	1	7	8	**8,9**
21	Quanergy Systems	M8-Plus	mechani	-	ToF	0	0	19	17	0	21	16	14	13	-	10	0	24	23	0	9	12	18	11	15	0	1	7	8	**9,2**
22	Quanergy Systems	M8-Ultra	mechani	-	ToF	0	22	19	17	0	21	16	14	13	-	10	0	24	23	0	9	12	18	11	0	0	1	7	8	**9,4**
23	Quanergy Systems	M8-PoE	mechani	-	ToF	0	0	19	17	0	21	16	14	13	-	10	0	24	23	0	9	12	18	11	15	0	1	7	8	**9,2**
24	Blickfeld	Cube Range 1	hybrid	MEMS	-	0	22	19	0	0	0	16	14	13	-	10	0	24	23	2	9	-	-	11	-	3	1	7	8	**7,9**
25	Blickfeld	Cube1	hybrid	MEMS	-	0	22	19	0	4	0	16	14	13	-	10	0	24	23	2	9	-	-	11	0	3	1	7	8	**7,8**
26	Ibeo Automotive Systems	IbeoNEXT	solid-stat	VCSEL,	ToF	-	22	-	17	4	21	16	14	13	-	10	0	24	23	2	9	12	-	11	15	3	1	7	8	**10,1**
27	Ibeo Automotive Systems	Ibeo LUX 4L	mechani	multi-la	ToF	-	0	19	0	0	21	16	14	0	-	10	-	24	23	2	9	-	-	-	0	3	1	7	8	**7,5**
28	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	19	0	0	21	16	14	0	-	10	-	24	23	2	9	-	-	-	0	3	1	7	8	**7,5**
29	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	0	19	0	0	21	16	14	0	-	10	-	24	23	2	9	-	-	-	0	3	1	7	8	**7,5**
30	Baraja	Spectrum HD	solid-stat	Wavele	RMCW	20	22	19	17	0	21	16	14	13	-	10	5	24	-	2	9	12	18	-	15	0	1	7	8	**10,5**
31	Baraja	Spectrum Off-Road	solid-stat	Wavele	RMCW	20	22	-	17	4	21	16	14	13	-	10	5	24	23	2	9	12	18	11	15	3	1	7	8	**11,0**
32	LeddarTech Inc.	Leddar Pixell	solid-stat	Flash (F	-	-	0	19	17	0	0	0	0	0	-	10	-	24	23	2	9	12	-	11	15	0	1	7	8	**6,9**
33	XenomatiX	XenoLidar-Xpert	solid-stat	Flash (1	ToF	20	0	0	0	0	21	16	14	13	-	10	0	24	23	0	0	12	-	11	0	3	1	7	8	**7,3**
34	XenomatiX	XenoLidar-Xact	solid-stat	Flash (1	ToF	20	0	0	0	0	21	16	14	13	-	10	0	24	23	0	9	12	-	11	0	3	1	7	8	**7,7**
35	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	0	22	19	17	0	21	16	14	13	-	10	-	24	23	2	9	-	-	-	0	0	1	7	8	**9,4**
36	Neuvition	Titan M1-R	hybrid	MEMS	ToF	0	22	19	0	0	21	16	14	13	-	10	-	24	23	0	9	-	-	-	0	0	1	7	8	**8,5**
37	Neuvition	Titan S2-120	hybrid	MEMS	ToF	0	0	19	17	4	21	16	0	0	-	10	-	24	23	2	9	-	-	-	0	3	1	7	8	**7,5**
38	Samsung	ISOCELL Vizion 33D	solid-stat	Flash (V	ToF	20	0	19	0	4	21	16	14	13	-	10	-	24	23	2	9	-	18	-	15	3	1	7	8	**9,9**
39	Faro	Focus Premium 350	mechani	-	ToF	0	22	19	17	4	21	16	14	13	-	10	-	24	23	0	9	-	-	-	0	0	1	7	8	**9,5**

Table 13: Comparison of the specific requirements of a portable application in the application area "consumer goods" with the characteristics of concrete LiDAR systems and the evaluation as the mean value of the weightings.

Comparison of the properties of selected LiDAR systems with the requirements for the consumer goods sector.

	Requirement parameter / relative weighting					min. detection distance in m	max. detection distance in m	min. range resolution in m	min. horiz. Field of View in °	min. vert. Field of View in °	min. hor. geom. resolution in m	min. vert. geom. resolution in m	min. horiz. angular resolution in °	min. vert. angular resolution in °	data rate in points/s	min. frame rate in Hz	data point attributes	min. laser safety classification	min. wavelength in nm	min. working temprature in °C	max. working temprature in °C	min. vibration resilience	min. ambient light resilience	min. resilience to atmospheric disturbances	max. price	max. energy consumotion	max. weight in kg	max. volume	production process	Average (only values)
						16	6	17	12	13	14	15	11	10	5	9	1	24	22	3	4	8	7	2	20	19	21	23	18	
	Producer	Productname	Technolo	Proc. fc	Measu	0,30	10	0,02	45	45	0,05	0,05	0,3	0,3		10	Ref	1	800	-25	45	ediu	ediu	low	low	low	low	low	Serie	
1	Luminar Technologies	Hydra	mechani	2-Axen	ToF	0	6	17	12	0	0	0	11	10	-	9	1	24	22	0	0	8	-	2	-	0	0	0	18	5,8
2	AEye	4SIGHT M	hybrid	MEMS	ToF	-	6	0	12	0	0	0	11	10	-	9	-	24	22	3	4	8	-	2	20	0	0	0	18	6,5
3	Aeva Technologies	Aeries I	solid-stat	multipl	FMCW	-	6	17	12	0	0	0	11	10	-	9	0	24	-	0	4	8	7	2	20	-	0	0	18	6,4
4	Aeva Technologies	Aeries II	solid-stat	multipl	FMCW	-	6	17	12	0	0	0	11	10	-	9	0	24	-	3	4	8	-	2	20	-	0	0	18	6,5
5	Innoviz Technologies	INNOVIZ360	hybrid	MEMS	ToF	16	6	-	12	13	0	0	11	10	-	9	-	24	22	3	4	-	7	2	0	0	21	23	18	8,7
6	Innoviz Technologies	INNOVIZPRO	hybrid	MEMS	ToF	0	6	0	12	0	0	0	11	0	-	9	-	24	22	0	4	8	7	2	0	0	0	23	18	5,8
7	Ouster	OS0	hybrid	sequen	-	16	6	0	12	13	14	15	11	10	-	9	-	24	22	3	4	8	7	2	0	0	21	23	0	8,8
8	Ouster	OS1	hybrid	sequen	-	16	6	0	12	13	14	15	11	10	-	9	-	24	22	3	4	8	7	2	0	0	21	23	0	8,8
9	Ouster	OS2	hybrid	sequen	-	0	6	0	12	0	14	15	11	10	-	9	-	24	22	0	4	8	7	2	-	0	0	0	0	6,0
10	Velodyne LiDAR Inc.	Velarray M1600	solid-stat	micro-l	-	16	6	0	12	0	0	0	11	10	-	9	-	24	22	3	4	8	7	2	0	0	0	23	18	7,0
11	Velodyne LiDAR	Velarray H800	solid-stat	micro-l	-	16	6	0	12	0	0	0	11	10	-	9	-	24	22	3	4	8	7	2	20	19	0	23	18	8,6
12	Velodyne LiDAR Inc.	Puck VLP-16	mechani	16 Lase	ToF	-	6	0	12	0	0	0	11	0	-	9	-	24	22	0	4	8	7	2	0	19	21	23	0	7,0
13	Velodyne LiDAR Inc.	Ultra Puck VLP-32C	mechani	32 Lase	ToF	16	6	0	12	0	0	0	11	0	-	9	-	24	22	0	4	-	-	2	0	19	0	23	18	7,2
14	Velodyn LiDAR	Puck LITE	mechani	16 Lase	ToF	-	6	0	12	0	0	0	11	0	-	9	-	24	22	0	4	8	7	2	-	19	21	23	0	7,3
15	Velodyne LiDAR Inc.	HDL-32E	mechani	32 Lase	ToF	-	6	17	12	0	0	0	11	0	-	9	-	24	22	0	4	-	-	2	-	19	0	0	0	6,0
16	Velodyne	Alpha Prime	mechani	128 Las	ToF	-	6	0	12	0	0	0	11	10	-	9	-	24	22	0	4	-	7	2	0	0	0	0	18	5,4
17	Quanergy Systems	S3-2NSI-S00	solid-stat	optical	ToF	0	6	0	12	0	14	15	11	10	-	9	-	24	22	0	4	8	7	2	-	19	21	23	18	9,4
18	Quanergy Systems	S3-2NSO-S00	solid-stat	optical	ToF	0	6	0	12	0	14	15	11	10	-	9	-	24	22	0	4	8	7	2	-	19	21	23	18	9,4
19	Quanergy Systems	S3-2WSO-S00	solid-stat	optical	ToF	16	0	0	12	0	14	15	11	10	-	9	-	24	22	0	4	8	7	2	-	19	21	23	18	9,8
20	Quanergy Systems	M8-Core	mechani	-	ToF	0	6	0	12	0	0	0	11	10	-	9	1	24	22	0	4	8	7	2	-	0	21	0	0	5,5
21	Quanergy Systems	M8-Plus	mechani	-	ToF	0	6	0	12	0	0	0	11	10	-	9	1	24	22	0	4	8	7	2	0	0	21	0	0	5,3
22	Quanergy Systems	M8-Ultra	mechani	-	ToF	0	6	0	12	0	0	0	11	10	-	9	1	24	22	0	4	8	7	2	0	0	21	0	0	5,3
23	Quanergy Systems	M8-PoE	mechani	-	ToF	0	6	0	12	0	0	0	11	10	-	9	1	24	22	0	4	8	7	2	0	0	0	0	0	4,5
24	Blickfeld	Cube Range 1	hybrid	MEMS	-	0	6	17	0	0	0	0	11	10	-	9	1	24	22	3	4	-	-	2	-	19	21	23	0	7,5
25	Blickfeld	Cube1	hybrid	MEMS	-	0	6	17	12	0	0	0	0	10	-	9	1	24	22	3	4	-	-	2	0	19	21	23	0	7,2
26	Ibeo Automotive Systems	IbeoNEXT	solid-stat	VCSEL,	ToF	-	6	-	12	13	0	0	11	10	-	9	1	24	22	3	4	8	-	2	0	19	21	0	18	8,0
27	Ibeo Automotive Systems	Ibeo LUX 4L	mechani	multi-la	ToF	-	6	0	12	0	0	0	11	0	-	9	-	24	22	3	4	-	-	2	0	19	0	0	0	5,1
28	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	6	0	12	0	0	0	11	0	-	9	-	24	22	3	4	-	-	2	0	19	0	0	0	5,1
29	Ibeo Automotive Systems	Ibeo LUX	mechani	multi-la	ToF	-	6	0	12	0	0	0	11	0	-	9	-	24	22	3	4	-	-	2	0	19	0	0	0	5,1
30	Baraja	Spectrum HD	solid-stat	Wavele	RMCW	16	6	0	12	0	0	0	11	10	-	9	0	24	-	3	4	8	7	2	0	0	-	23	18	6,4
31	Baraja	Spectrum Off-Road	solid-stat	Wavele	RMCW	16	6	-	12	0	0	0	11	10	-	9	0	24	22	3	4	8	7	2	0	19	0	0	18	6,8
32	LeddarTech Inc.	Leddar Pixell	solid-stat	Flash (F	-	-	6	0	12	0	0	0	0	0	-	9	-	24	22	3	4	8	-	2	0	0	0	0	0	3,9
33	XenomatiX	XenoLidar-Xpert	solid-stat	Flash (1	ToF	16	6	0	0	0	0	0	11	10	-	9	1	24	22	0	0	8	-	2	0	19	21	23	18	7,6
34	XenomatiX	XenoLidar-Xact	solid-stat	Flash (1	ToF	16	6	0	12	0	0	0	11	10	-	9	1	24	22	0	4	8	-	2	0	19	21	23	18	8,2
35	Robosense	RS-LiDAR-M1	hybrid	MEMS	-	0	6	0	12	0	0	0	11	10	-	9	-	24	22	3	4	-	-	2	0	0	21	23	18	7,2
36	Neuvition	Titan M1-R	hybrid	MEMS	ToF	0	6	17	0	0	0	0	11	10	-	9	-	24	22	0	4	-	-	2	0	0	0	0	0	4,6
37	Neuvition	Titan S2-120	hybrid	MEMS	ToF	16	6	17	12	13	0	0	0	0	-	9	-	24	22	3	4	-	-	2	0	19	21	23	0	8,3
38	Samsung	ISOCELL Vizion 33D	solid-stat	Flash (V	ToF	16	0	0	12	13	14	15	11	10	-	9	-	24	22	3	4	-	7	2	20	19	21	23	0	10,2
39	Faro	Focus Premium 350	mechani	-	ToF	0	6	17	12	13	0	0	11	10	-	9	-	24	22	0	4	-	-	2	0	0	0	0	0	5,7