1D MEMS Micro-Scanning LiDAR

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***Abstract*—Light Detection and Ranging (LiDAR) sensor technology will be the major enabler for automated transportation. As all major OEMs in transportation outline, only by fusing the sensor data of LiDAR, Radar, and cameras, a holistic and robust environment perception can be achieved. However, most of today's available long-range LiDAR solutions are complex and costly, which impedes a broad integration into affordable vehicles and robots. This work details the recently emerged and currently most promising technology towards a low-cost, long-range, robust, and automotive certified LiDAR system: the micro-scanning 1D MEMS-mirror LiDAR. In this work, we depict not only a proposed future 1D LiDAR system design and involved ASIC concepts, we also showcase a very first realized LiDAR prototype which will pave the way towards the future >200m and <200$ LiDAR perception system.**

***Keywords*—LiDAR; direct Time-of-Flight; 1D MEMS mirror; micro-scanning**

I. INTRODUCTION

Highly automated transportation will usher in a major paradigm shift in transportation. It will not only enable radically new use-cases and applications, but will also significantly increase safety for passengers and road users in general. In order to achieve the future goal of highly automated vehicles, various redundant and diverse sensor types are required in order to enable robust environment perception during all possible weather conditions. According to industry and academia, the Light Detection and Ranging (LiDAR) technology will be the key enabler, in conjunction with Radar and cameras, for robust and holistic environment perception (see also [1] and [2]). Figure 1 depicts the basic building blocks of a LiDAR system realizing the direct Time-of-Flight sensing principle: a central system controller triggers the emission of a laser pulse. This laser pulse is reflected by the scenery and is eventually received by a photo diode. The laser pulse's Time-of-Flight, which is measured with the help of fast running counters, directly correlates with the distance between scenery and sensor, thus enabling three-dimensional environment perception.

Today, there are several automotive qualified LiDAR technologies available targeting, e.g., the short-range use-case of emergency breaking. However, when it comes to the long-range (>200m) and low-cost (<200$) automotive use-case, there is still a major gap in technology. So far, there has not been any suitable technology identified that will cover these two essential requirements at the same time. Thanks to the latest technological and manufacturing advances in the field of

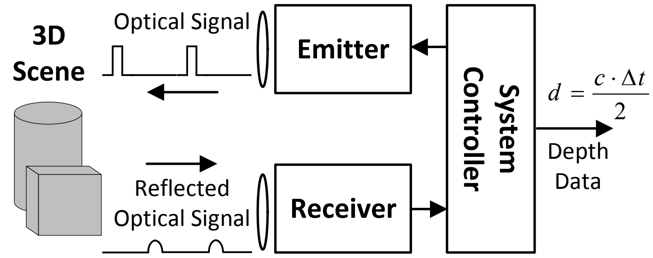

Figure 1. Basic principle of the LiDAR environment perception technology.

Micro-Electro-Mechanical Systems (MEMS), promising new LiDAR concepts based on MEMS mirrors are emerging. These very small mirrors of, e.g., 2x2mm size are employed to deflect the LiDAR system's laser beam into the scenery. Thus, a robust near-solid-state approach is given that enables not only highly accurate and optical-/power-efficient laser deflection, but also enables cost-efficient LiDAR system solutions.

This work presents in detail the 1D micro-scanning MEMS-based LiDAR solution and therefore makes the following fundamental contributions:

- It presents from semiconductor point of view the latest conceptual and technological advances in automotive 1D MEMS micro-scanning LiDAR.
- It showcases a first highly-integrated LiDAR prototype based on the 1D MEMS micro-scanning approach.
- It provides a clear vision towards the future long-range (>200m) and low-cost (<200$) LiDAR system for automotive and robotic applications.

This paper is structured as follows. Section II gives a short introduction into the related work covering the topic of the latest LiDAR technologies. In Section III, our vision of a 1D micro-scanning LiDAR is presented. Section IV depicts a very first working 1D micro-scanning LiDAR prototype. Finally, our results are concluded and some details about our future work are given in Section V.

II. RELATED WORK

LiDAR technologies, which are currently explored by industry and academia, can be fundamentally categorized as depicted in Figure 2. The most important conceptual difference concerns the scanning or staring way of perceiving the environment [3]. Staring-based solutions are available in the market and proved to be robust and mature. Although staring-based solutions can be manufactured in a cost-efficient way, they are constrained in terms of field-of-view and maximum measurement range (up to approximately 60m) due to eye- and skin-safety regulations. Flash LiDAR sensors are commercially available through companies like Continental or LeddarTech [4]. Flash LiDARs illuminate the whole scenery at once and employ a detector array or matrix for receiving the reflected light [5]. They are commonly used for short-range use-cases, such as blind spot detection or emergency breaking. Similar to the flash LiDARs, the multi-beam approaches [6] are used for short-range applications.

In contrast to the staring principle, the scan-based approaches divert a collimated laser beam to the target and thus illuminate a small fraction of the scenery at once. By moving the beam position, a 3D surround image of the entire scenery can be generated. Because the whole laser energy is focused in a point or a line instead of the whole field-of-view, better signal-to-noise ratio (SNR) and thus longer measurement distances are achievable. Velodyne, a pioneer in the field of rotating LiDAR scanners, came up with a very first solution for the DARPA Robotic Car Races [7] in 2007. This system achieved a measurement range of up to 120m, 20 frames per second, and a horizontal field-of-view of 360°. Since then, spinning

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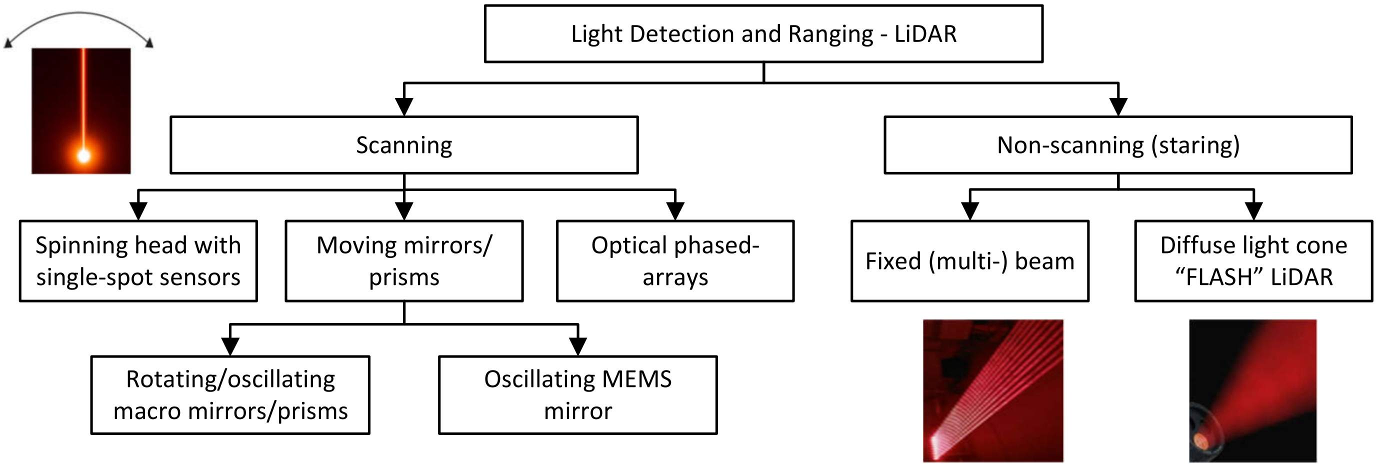

Figure 2. Fundamental classification of various LiDAR concepts.

heads and rotating/oscillating macro mirrors/prisms solutions have further improved in terms of performance, resolution, and robustness. For example, LiDAR systems from Velodyne achieve measurement ranges of 200m with a horizontal field-of-view of 360°. However, their main drawbacks are high costs and moving macro components that degrade the form factor and that hinder a lean car integration.

A novel concept which is currently explored by academia and industry is optical phased arrays [8]. The major advantage of this novel approach is the possibility for electronic laser beam forming (similar to phased array antennas in Radar), thus omitting the integration of any moving or rotating mechanical parts required for deflecting of beams in a traditional way. However, preliminary research results show that there is still a critical technological gap concerning the efficiency of the photonic integrated circuits. This efficiency degradation, which is in the range of a high double digit percentage, represents a major limitation for long-range LiDAR applications.

The currently most promising concept towards a realizable low-cost (<200$), long-range (>200m), robust, automotive qualified LiDAR environment perception is the micro-scanning MEMS mirror concept. As summarized by Holmstrom et al. [9], there are various types of MEMS-scanner concepts. A crucial differentiating factor is whether one moving axis (as depicted by Krastev et al. [10]) or two moving axes (such as [11] or [12]) are implemented. While the 1D approach typically deflects a vertical laser beam line into the scenery and performs a horizontal scanning (see also Figure 3), the 2D concept deflects a laser point or narrow line and performs vertically as well as horizontally scanning. Furthermore, there are mirrors which are driven in resonance (robust against shocks and vibration, instantaneous measurement of the position for all angles is not required) or without resonance (prone to shocks and vibrations, difficult to control due to the inevitable ringing which needs to be suppressed by a control loop). This work focuses on the resonant 1D MEMS mirror, because this specific setup enables higher scanning frequencies compared to 2D approach and provides high robustness against external perturbations (such as shocks and vibrations which are given in transportation).

Summarizing, even though the LiDAR research community is highly active, there is still a huge gap concerning a realizable long-range and low-cost solution. Therefore, this paper provides a highly relevant and important contribution to the ongoing discussion in this important field of research.

III. 1D MEMS-BASED AUTOMOTIVE LIDAR

Currently, the most promising approach towards a long-range, low-cost, robust, and automotive qualified LiDAR system is enabled through the micro-scanning 1D MEMS mirror concept. In the following, this solution (as depicted in Figure 3) is detailed.

A. *Requirements*

Requirements for a long-range LiDAR sensor are, from OEM and Tier 1 perspective, still in a dynamic development process and differ a lot. Thus, some partly representative requirements can be summarized as follows:

- 120° horizontal field-of-view and 16° vertical field-of-view
- 20cm distance resolution, 0.1° horizontal and 0.5° vertical resolution
- 200m measurement range
- 20 frames per second of field-of-view’s point cloud
- 200$ system costs
- ASIL-C and laser class 1 guaranteeing functional-, eye-, and skin-safety
- High robustness against shocks and vibrations

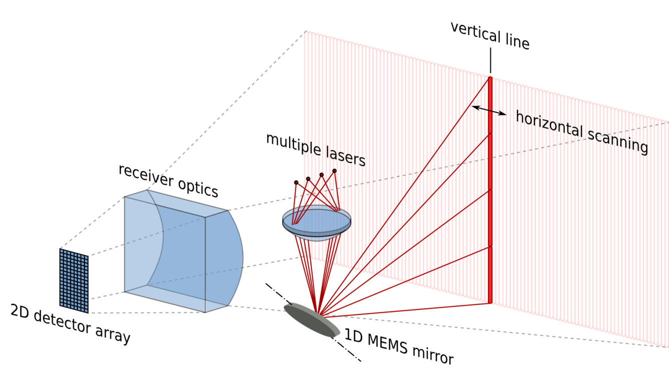

Figure 3. 1D micro-scanning LiDAR illuminating the scenery with a vertical laser beam line and scanning horizontally.

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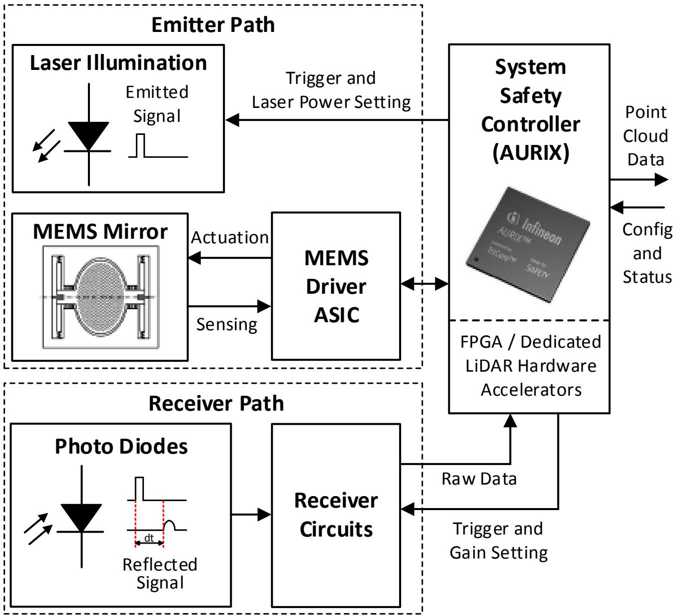

Figure 4. System concept of a potential future 1D MEMS-based automotive LiDAR system.

B. Design Space Considerations

Given these requirements, the design space of MEMS mirrors considerable favors the 1D scanning approach over a 2D scanning approach. By deflecting a vertical laser beam line horizontally, a sweet spot in terms of signal-to-noise ratio and sampling rates is achieved compared to 2D mirrors (slower line-by-line sampling) and Flash LiDARs (degraded signal-to-noise values at long ranges due to eye-safety limitations). This is of special importance when considering the maximum possible laser pulse repetition rates of affordable laser sources, which is in the range of 100kHz. Given a modest field-of-view of, e.g., 400 x 80 pixel, a 2D scanning solution requires a laser pulse-repetition-frequency of 640kHz in order to achieve 20fps (without taking signal averaging for improved SNR into account). When taking into account also the flight time of light (e.g., $2\mu s$ for 300m), 2D scanning is regarded as an unfavorable approach in order to meet the automotive frame-rate and SNR requirements. In contrast, the 1D approach, which scans with each laser beam trigger one complete vertical line, enables the integration of affordable 100kHz pulse-repetition-frequency lasers, and thus making the <200$ vision feasible. The achieved high frame-rates can then be exploited for scene oversampling in order to further improve the signal quality. In addition to pulse repetition frequency and SNR considerations, an automotive LiDAR system has to be robust against shocks and vibrations. Here, oscillating scanning solutions provide more robustness compared to non-oscillating approach. In particular, the 1D oscillating scanning solution provides highest robustness by design. Summarizing, based on currently available technologies, 2D micro-scanning and Flash LiDARs hardly fulfill the requirements for robust, long-range, and low-cost LiDAR systems.

C. Overall System Concept and Chipset

Figure 4 depicts the system concept of a potential future 1D MEMS-based automotive LiDAR system. This chipset is composed of the oscillating 1D MEMS mirror and its MEMS Driver ASIC, a System Safety Controller, a laser illumination unit, an (1D or 2D) array of photo diodes (such as avalanche photo diodes (APDs) or single-photon avalanche diodes (SPADs)), and Receiver Circuits. The main purpose of MEMS Driver ASIC is to sense, actuate, and control the oscillating MEMS mirror. Furthermore, it implements crucial functional safety features and provides an essential MEMS phase clock that is used to synchronize the whole system to the movement of the mirror. The MEMS Driver ASIC's phase clock and safety signals are provided to the central System Safety Controller. This System Safety Controller synchronizes with the MEMS phase clock and triggers the laser illumination unit according to a laser-shoot-pattern. At the same time, the System Safety Controller triggers the Receiver Circuits in order to capture the laser beam reflections. The Receiver Circuits samples and digitizes the reflected laser light. The Receiver Circuits' output data is then forwarded to the System Safety Controller. Finally, the System Safety Controller performs the final signal processing (e.g., calculation of the point cloud), which may be carried out hardware accelerated either with an FPGA or dedicated hardware units, and sends the data to a central ADAS ECU or sensor fusion box.

Figure 5. Fabricated and packaged 1D MEMS Mirror.

D. MEMS Mirror

The central element of the whole LiDAR system design is given by the 1D oscillating MEMS mirror and its MEMS Driver ASIC. The MEMS mirror, as it is depicted in Figure 5, implements an electrostatic comb drive approach [13] with a very high Q factor of approximately 150. By applying a voltage of, e.g., 100V to the comb fingers, an electric force is applied by the capacitance structure that pulls the rotor towards its zero position. Switching off this high-voltage after the rotor crossed the zero position, let's the mirror swing towards its maximum deviation. When reaching the maximum deviation, high-voltage is again switched on. Figure 6 depicts the very concise response curve if the frequency of the high voltage actuation is changed. Starting with an actuation frequency f_{start} and reducing it, let's the operation point move on the lower resonance curve. While being on the lower resonance curve the phase relation between actuation voltage and mirror is positive, which means that the mirror and its zero crossing follow the actuation voltage. If the actuation frequency is further reduced until it reaches f_{jump}, a jump in the phase relation and in the mirror's deviation angle is observable. At the top resonance curve, the phase relation between actuation voltage and mirror is now negative, which implies that the actuation voltage follows the mirror and its zero crossing. If the actuation frequency is now increased, also the mirror's deviation angle increases. Finally, when surpassing a maximum stable frequency, the working point drops back to the lower resonance curve. Therefore, the response

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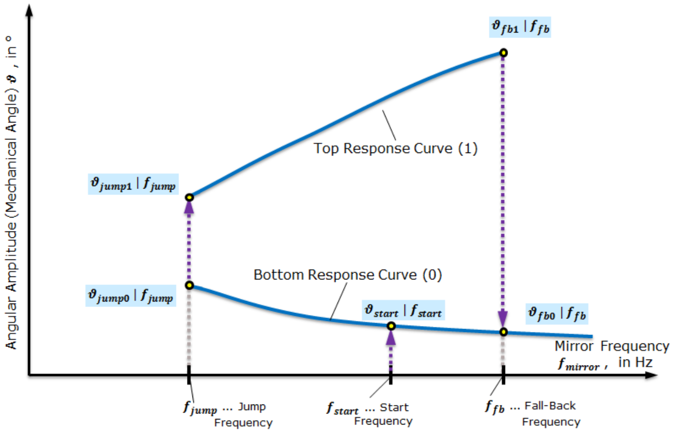

Figure 6. MEMS mirror response curve. Changing the actuation frequency results in a non-linear change in mirror' oscillation angle.

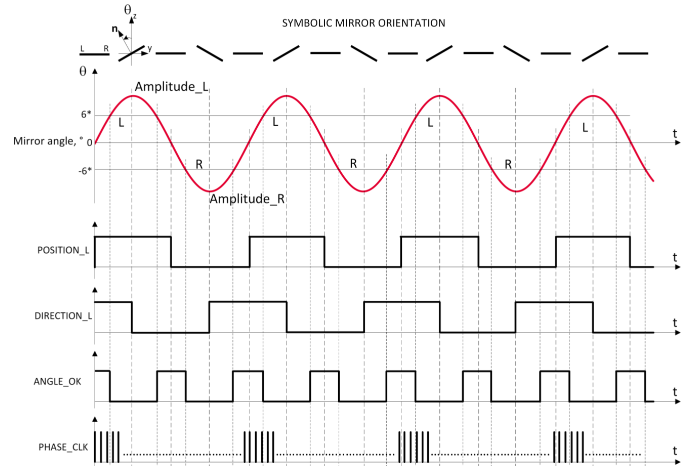

Figure 7. MEMS position and safety signaling of the MEMS Driver ASIC.

curve describes the mechanical behavior of the MEMS mirror as a non-linear harmonic oscillator.

Depending on the mirror design (mechanical design, leaf springs, comb drive structure, etc.), deviation angles of more than +/-15°are achievable. Thanks to the mirror's high Q factor, its oscillator design, and the one-dimensional rotation axis, a laser beam deflection solution is given that provides high robustness against external perturbations (such as shocks or car vibrations). Furthermore, thanks to its conventional mirror design, the laser beam can be deflected almost losslessly and with high pulse-repetition frequencies (which is an essential enabler for oversampling of the environment).

E. MEMS Driver ASIC

The crucial task of the MEMS Driver ASIC is to sense, actuate, and control the movement of the MEMS mirror. Actuation of the mirror is carried out by simply switching on / off the mirror's high-voltage at the right point in time. However, in order to perform this high-voltage switching on / off properly, precisely sensing of the mirror position is essential. Since the mirror's comb fingers form a capacitance that varies with the mirror's position, position sensing is carried out by measuring this position dependent capacitance. Such kind of capacitance sensing can be performed with various measurement principles. One feasible measurement principle is the usage of trans-impedance converters in order to convert the capacitor's current flows into voltages levels. These voltage levels can then be analog-to-digital converted and can be processed by digital analysis and control circuits.

In general, the MEMS mirror can be operated either in open control-loop or closed control-loop, cf. [14]. While the open control-loop mode actuates the mirror with a defined frequency without taking advantage of any control strategies, the closed control-loop mode implements two important control strategies:

- A phased-locked loop precisely follows the movement (phase) of the oscillating MEMS mirror.
- An amplitude control loop ensures that the maximum deflection angle of the MEMS mirror stays constant.

With the help of these two control loops, a robust scan shape can be guaranteed. In order to signal the central System Safety Controller (which triggers the laser beam firing) the momentary position of the MEMS mirror, the following important signals are provided: *POSITION_L* (mirror is either on the left or right side) and *DIRECTION_L* signals (mirror moves either towards the left or right side) provide precise information of the mirror's momentary position, as illustrated in Figure 7. When the mirror crosses its zero position, the position signal changes. When the mirror is at its maximum deflection angle, the direction signal changes. A *PHASE_CLK* signal, which counts in equi-temporal steps from 0 to n_{max} during one mirror swing, provides a precise and high-frequent phase information of the momentary mirror position. These three signals are not only crucial for the system controller in order to decide at which mirror position to trigger the laser beam firing, but also to enable an efficient way to track the MEMS mirror. As a consequence, the precision of these signals directly influences the whole LiDAR system's measurement accuracy. In addition to these tracking signals, an *ANGLE_OK* signal is provided by the MEMS Driver ASIC in order to notify the system controller whether the angle setpoint is reached or not. This notification is crucial for ensuring functional-, eye-, and skin-safety: if and only if both the MEMS mirror and the MEMS Driver ASIC operate properly within their specified set of parameters, then laser shooting is permitted.

F. Photo Diodes and Receiver Circuits

The LiDAR system's receiving part (which is primarily defined through an 1D or 2D array of photo diodes, Receiver Circuits, and hardware-accelerated signal processing) is absolutely crucial in order to achieve the required SNR and maximum distance requirements. The number of implemented photo diodes defines vertical resolution, which is not constrained by our system architecture. In the shown receiver signal chain, the Receiver Circuits' main purpose is to amplify the received electrical current from the array of photo diodes with the help of high-performance amplifiers. This amplification circuit has to implement not only a high dynamic range (in order to detect targets in near vicinity and far away), but shall also support adjustable gain settings, short recovery times (in order to detect a weak pulse directly after a strong pulse), and low electrical/optical cross-talk between channels. After amplification of the sensed analog signals, a high-speed conversion to the digital domain is required. At this point, the LiDAR system's design space critically expands by selecting the ADCs' resolution and sampling rate: more than 1-Bit ADC resolution is required for signal amplitude analyses (in order to detect for example lane markings), high sampling rates are required for more accurate range resolutions (e.g., 1.5 GHz for 10cm range resolution). Given a modest laser pulse-repetition rate of, e.g., 100kHz

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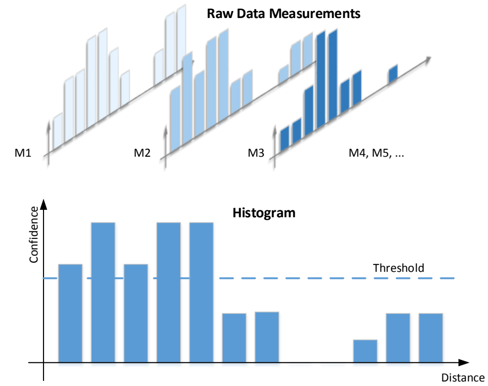

Figure 8. Increasing confidence by oversampling and histogram evaluation.

and 32 vertical pixels, results according to (1) in several GBit/s of raw data.

$$RawData = PRF \cdot VPixels \cdot ADC_{Res} \cdot ADC_{Rate} \quad (1)$$

After acquisition of the raw sensor data, a lot of effort (in terms of computational resources and power dissipation) has to be spent in order to compute a robust 3D point cloud. Such a signal processing chain can include various types of computations, e.g., averaging of several measurements, evaluation of histograms, usage of matched filtering, etc. The aim of these signal processing steps is not only on improving the LiDAR system's SNR and on mitigating interferences from sunlight and other LiDARs, but also on reducing the final data rate towards the System Safety Controller or a central sensor fusion box. Figure 8 highlights the benefits of signal averaging and histogram evaluations: SNR and confidence increase, while data rates decrease at the same time by factors. These fundamental LiDAR signal processing steps define a very active research arena impacted by both academia and industry. Moreover, further important research questions arise when aiming for an optimized system partitioning: what kind of signal processing shall be integrated into Receiver Circuits, a potential FPGA, the System ASIC, and a central sensor fusion box in order to minimize data rates while maintaining as much data- and algorithm-flexibility as possible.

G. System Safety Controller

Infineon Technologies' AURIX can be employed as the central System Safety Controller. AURIX is a 32-Bit System-on-Chip, compliant to various standards, such as IEC 61508, ISO 26262, and ISO 25119, and is used in particular in automotive and industrial domains as a *Safety Element out of Context* (SEooC) for applications such as electric power steering, airbag control, etc. In the given 1D MEMS micro-scanning LiDAR system, AURIX is not only employed to monitor the integrity of the MEMS mirror, MEMS Driver, and Receiver Circuits, but also to monitor power supply, control signals, and the LiDAR data stream. Apart from functional safety features, the AURIX also implements hardware and software for controlling and signal processing. In particular the laser scan pattern is controlled by the AURIX by triggering lasers and the Receiver Circuits at well defined points in time. With regards to signal processing, the task of AURIX is to compute and provide 3D point cloud data for dedicated ADAS and sensor fusion ECUs. Depending on the OEMs' / Tier1s' requirements, not only the pre-processed LiDAR point cloud data is provided, but for example also each pixel's most relevant multi-hit targets. As highlighted in Figure 4, the next generation AURIX safety controllers will also support dedicated LiDAR hardware accelerators that will further enhance and speed-up LiDAR signal processing.

IV. PROTOTYPE

Based on the presented 1D MEMS micro-scanning LiDAR concept and the proposed system partitioning (see Figure 4), we realized a very first working prototype. Please note that due to disclosure policies, currently only some overview results can be provided. Figure 9 and Figure 10 showcase the assembled and opened prototype. Only thanks to the miniaturizing of emitter path (MEMS mirror, MEMS Driver ASIC) and receiver path (photo diodes, Receiver Circuits, signal processing FPGA, AURIX Safety Controller), such a small form factor is achievable. Moreover, the LiDAR prototype implements advanced hardware-accelerated signal processing techniques, which makes its sensing capabilities unaffected by interferences from other LiDAR systems, which is a crucial requirement for a broad adoption in transportation. The output of this LiDAR prototype is a 3D point cloud with more than 20 frame per seconds. Due to the

Figure 9. 1D MEMS mirror based LiDAR prototype.

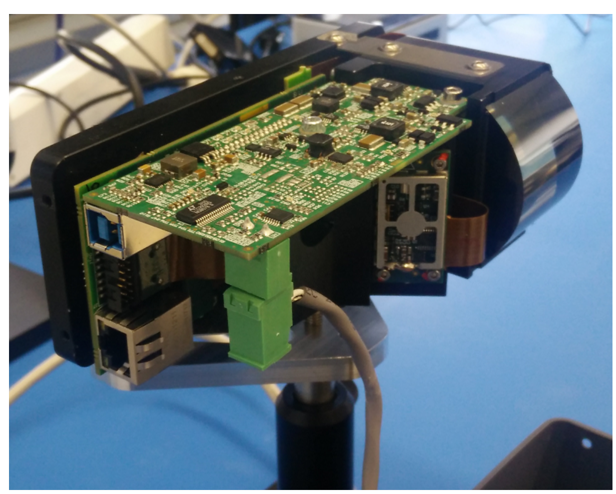

Figure 10. LiDAR prototype implementing optics, lasers, controllers, MEMS mirror, Receiver Circuits, MEMS Driver ASIC, and signal processing.

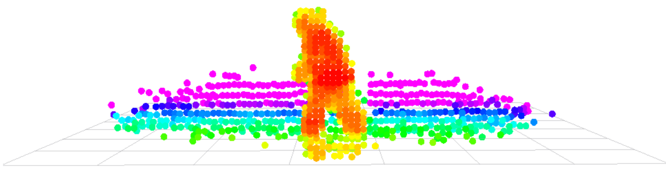

Figure 11. A clearly classifiable pedestrian detected in a few meters distance of the LiDAR system. Visualization is performed with ROS Robot Operating System.

usage of standardized data formats, the 3D point cloud data can be easily visualized with freely available software tools such as ROS Robot Operating System (cf. [15]). Finally, Figure 11 shows the ROS visualization of a pedestrian crossing the LiDAR's field-of-view, and Figure 12 depicts a standard indoor lab scenery and its 3D point cloud representation.

V. Conclusions

Light Detection and Ranging (LiDAR) sensor technology will be the major enabler for automated transportation. Only by fusing the sensor data of LiDAR, Radar, and cameras, a holistic and robust environment perception can be achieved. As outlined, currently there is major gap concerning a realizable long-range and low-cost LiDAR solution.

This work detailed the recently emerged and currently most promising approach towards a low-cost, long-range, robust, and automotive LiDAR system: the micro-scanning 1D MEMS mirror LiDAR. We depicted not only the vision of a potential future system design and its required ASIC concepts, we also showcased a very first realized 1D LiDAR prototype. Given the presented results, a quantum leap towards the future >200m and <200$ LiDAR perception system and the future revolution in transportation was made.

Our future work fully focuses on advancing the semiconductor components of the the micro-scanning 1D MEMS mirror LiDAR in order to make our vision happen.

Acknowledgment

The authors would like to thank the ECSEL Joint Undertaking and the Austrian Federal Ministry for Transport, Innovation and Technology which funded the PRYSTINE project under the grant agreement n° 783190.

Furthermore, the authors would like to thank all LiDAR colleagues from Infineon Technologies in the Netherlands, Germany, and Austria for their valuable contributions.

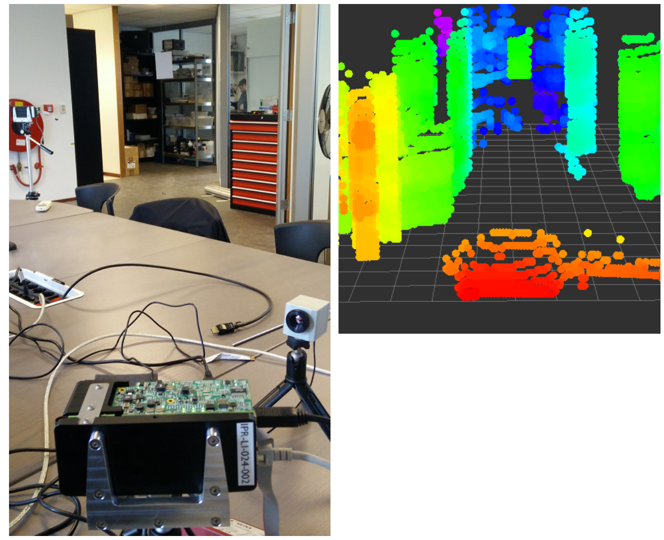

Figure 12. Standard lab scenery and its 3D point cloud visualized with ROS Robot Operating System.

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