Monitor for Safety-Critical Mirror Drivers of MEMS Micro-Scanning LiDAR Systems

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***Abstract*—In future, more and more cars will be equipped with Advanced Driver-Assistance Systems (ADAS) like Adaptive Cruise Control (ACC), Collision Avoidance System and many more. Currently, the driver is responsible by law to perceive the environment and take over control if it is required. But in foreseeable future highly automated vehicles or even fully automated vehicles will appear on the road; where the vehicle is responsible for perceiving the environment, operating the vehicle and intervening in hazardous situations. At the latest then it will be necessary that systems shall not fail unnoticed. Therefore, it is mandatory to monitor safety relevant components. For instance, also Light Detection and Ranging (LiDAR) Systems like the 1D Micro-Electro-Mechanical System (MEMS) Micro-Scanning LiDAR, which will be part of intelligent sensor fusion in ADAS. Due to the fact that highly automated vehicles often have various safety monitors installed, our novel Monitor for the Safety-Critical MEMS Driver is an alternative approach to the well-known Built-In Self-Test (BIST). In this publication, we introduce a novel system architecture that is able to verify the correct functionality of internal control systems in MEMS-based LiDAR systems. To evaluate the effectiveness of our novel monitoring approach, we have implemented the procedure on a 1D MEMS Micro-Scanning LiDAR prototype platform.**

Keywords*–*ADAS; LiDAR; Signal Monitor; 1D MEMS Mirror; Safety Monitor

I. INTRODUCTION

Fully automated driving is gaining more and more attention. Therefore, industry and academia put a lot of effort into researching in the field of sensor fusion and functional safety for sensors in the automotive domain. Key enablers of highly automated vehicles will be robust Radio Detection and Ranging (RADAR) and Light Detection and Ranging (LiDAR) solutions with additional support from vision cameras. By fusion of sensor data and control functions it is intended to enable safe automated driving as well in rural as also in urban environments. In the project PRogrammable sYSTems for INtelligence in automobilEs (PRYSTINE) the consortium aims for a Fail-operational Urban Surround perceptION (FUSION) [1]. For years, various Advanced Driver-Assistance Systems (ADAS), such as Electronic Stability Control (ESC) and Anti-lock Braking System (ABS), have been mandatory in new cars in the European Union [2]. ESC and ABS are ADAS, which are active safety components in contrast to passive safety components, such as seat belts and airbags [3]. For highly automated vehicles, it is indispensable that ADAS

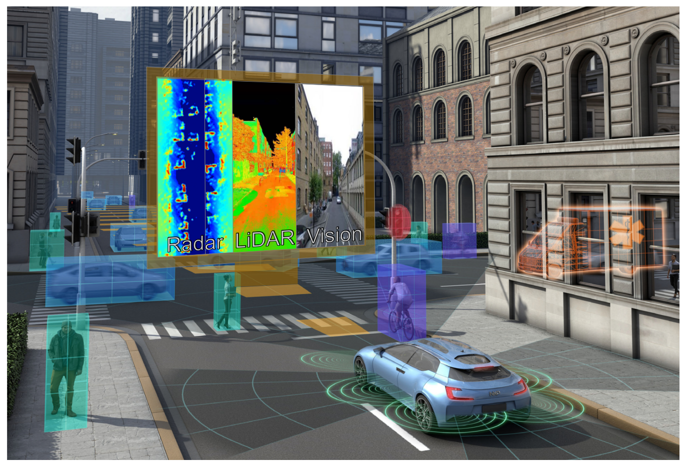

Figure 1. PRYSTINE's concept view of a Fail-operational Urban Surround perceptION (FUSION) [1].

are reliable and therefore to ensure the safety for the driver, passengers and all other road users. Due to quantity and reliability of such ADAS and integrated systems the Society of Automotive Engineers (SAE) has introduced six levels of driving automation. The higher the SAE level, the higher ranked is the driving automation of the vehicle. Due to the competences that the systems take over in the vehicle, it is possible to declare the SAE level of the vehicle [4]. No matter whether a vehicle, according to the manufacturer, would support higher automation levels, it is currently necessary in many countries that the driver continues to observe the environment and in an emergency can take over control [5]. For example, according to Article 8 of the Vienna Convention on Road Traffic, the driver must be able to control the vehicle continuously. The Vienna Convention on Road Traffic was ratified by the majority of EU member countries and several others. Large countries, such as the USA, China or England, are not among the signatories [6]. Due to legal and technical barriers, driving automation levels of vehicles are currently not beyond SAE level 2. In order to introduce vehicles with SAE Level 3 and higher in the future, it is imperative to adapt the law from a legal point of view and to develop ADAS with a higher level of safety, reliability and availability. In projects like PRYSTINE, it is the goal to develop components and systems for high reliable and safe ADAS [1]. To ensure the proper functionality of systems it is mandatory to monitor

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the system especially safety critical parts of it. In case of a malfunction the system has to be degraded and in worst case suspended. Hence, these safety monitors are essential for ADAS in vehicles of SAE level 3 and above. Misbehaviour of a system is only detectable if the system is monitored. Therefore, we have been engaged in monitoring the critical signals of a 1D MEMS Micro-Scanning LiDAR System.

With our paper contribution we:

- create a novel test opportunity for control loops,
- ensure the detection of malfunction during test run and
- enhance safety due to this diverse monitoring approach.

The remainder of the paper is structured as follows. The overview on related work of MEMS-based LiDAR systems is given in Section II. The architecture of a novel safety monitor for safety-critical signals in a MEMS-based LiDAR System will be presented in detail in Section III and the achieved results including a short discussion will be provided in Section IV. A summary and short discussion of the findings will conclude this paper in Section V.

II. Related Work

LiDAR technologies, which are currently available in the market are very bulky and cost intensive like the Velodyne HDL-64E [7]. Therefore, industry and academia put a lot of effort into the research of automotive qualified, long-range and low-cost LiDARs. Druml et al. have introduced a 1D MEMS Micro-Scanning LiDAR, which is able to perceive the environment up to 200m, shall cost less than 200$ and is qualified for automotive applications due to its robustness [8]. The functional principle of the 1D MEMS-based LiDAR by Druml et al. is depicted in Figure 3. Several lasers are shot on the 1D MEMS mirror. A vertical laser beam is deflected by the mirror into the scenery. This vertical line is moved horizontally across the Field-of-View(FoV) by oscillation of the mirror and the reflected light of the obstacle is captured by a stationary detector.

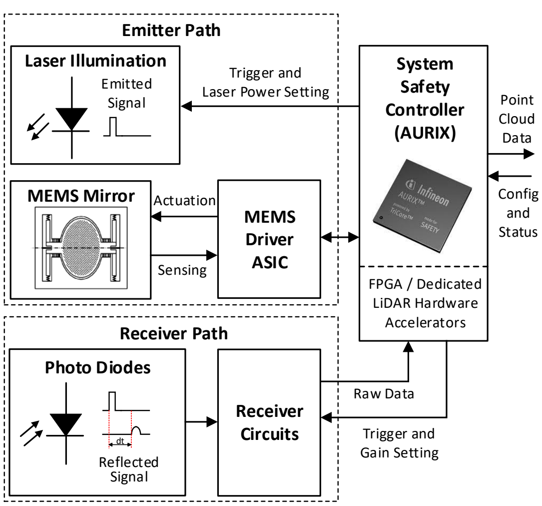

Figure 2. System concept of a 1D MEMS-based automotive LiDAR system by Druml et al. [8].

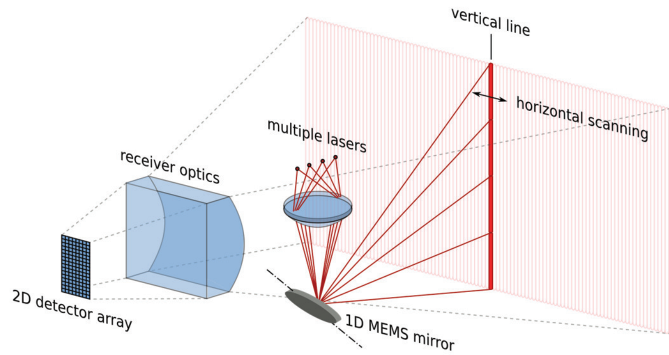

Figure 3. Functional principle of a 1D micro-scanning LiDAR [8].

A. *1D MEMS Micro-Scanning LiDAR*

In this section, the 1D MEMS-based LiDAR System by Druml et al. is presented. The system concept of the MEMS-based LiDAR is depicted in Figure 2. Druml et al.'s system consists in general of an emitter path, a receiver path and the System Safety Controller (AURIX). In the emitter path are included a laser illumination unit, the MEMS mirror and the actuation and sensing unit of the mirror, the MEMS Driver ASIC. Within the receiver path are an array of photo diodes and the receiver circuits. The System Safety Controller is the central unit, which is responsible ,e.g., for monitoring, controlling and signal processing. According to the signal processing part, the task of the System Safety Controller is to compute and provide a 3D point cloud for dedicated ADAS [8]. Due to the dependence of correct position, direction and verification signals of the mirror, the Driver ASIC, which is responsible for the actuation and sensing of the MEMS mirror, is described in particular. The MEMS Driver is providing crucial signals to the System Safety Controller and therefore it is mandatory that the delivered information is reliable. By reference to the correctness of these crucial signals, the System Safety Controller will create with the raw data from the receiver circuits a plausible 3D point cloud. If the crucial signals were corrupted the 3D point cloud would be useless due to wrong assumptions of the reflected laser origin.

In Figure 4, the crucial signals are illustrated, which are provided by the MEMS Driver ASIC. These signals are needed to monitor during operation the current status of the MEMS mirror. The POSITION_L represents whether the mirror is

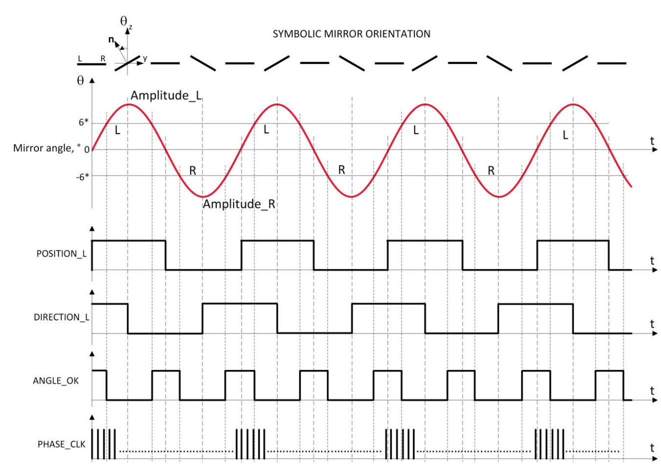

Figure 4. Crucial signals of the MEMS Driver ASIC from Druml et al.'s LiDAR system [8].

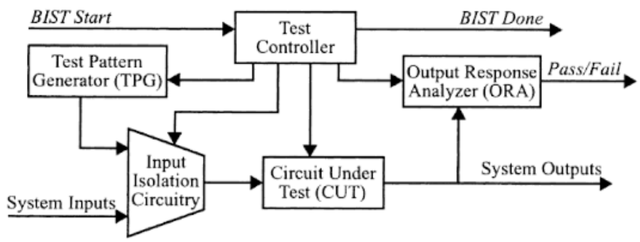

Figure 5. A basic Built-In Self-Test Architecture [9].

aligned to the left or to the right side; logical high means an alignment to the left and logical low to the right. DIRECTION_L indicates in which direction the movement is located; logical high means moving to left and logical low to the right. Precise and high-frequent phase information of the current mirror position is provided by a PHASE_CLK signal that counts from 0 to n_{max} in equal time steps during one mirror oscillation. Furthermore, an ANGLE_OK signal is available besides the tracking signals. This ANGLE_OK signal notifies to the System Safety Controller if the Driver ASIC operates according to the programmed specification (e.g., angle setpoint is reached). To be able to ensure functional-, eye-, and skin-safety this notification is mandatory: MEMS mirror's current position and MEMS Driver ASIC's internal position information must match to allow a laser shooting [8].

B. Test Facilities

One of the major objectives of the automobile industry is to evolve the individual traffic. The coexistence of partial automated, highly automated and fully automated cars will be the reality in the near future. In conventionally equipped vehicles, the driver is responsible for environment perception, operation of the vehicle and intervention in hazardous situations. In prospective automated cars more and more competences will move from the driver to the car. Based on information, which is obtained from ADAS, the vehicle will make decisions. Therefore, it is apparently necessary that this information is reliable. To ensure safe and reliable operation of ADAS and their embedded components like LiDAR, it is mandatory to test the behaviour for correctness. BISTs and a wide variety of safety monitors can be used for this purpose.

1) Built-In Self-Test:
A Built-In Self-Test (BIST) is thought to run simultaneously to the circuit and is monitoring or checking the output of a circuit to check its validity. The BIST needs a strategy for generating input signals for the circuit and has to know how to evaluate the correlated output. The circuit or device which is tested is called the Circuit Under Test (CUT). A basic BIST architecture is shown in Figure 5. A realization of a BIST fundamentally needs to implement four new functions to the existing system. First of all, there is the Test Pattern Generator (TPG), which is responsible for generating the input signals and for the test. The test pattern consists of multiple sets of test cases, which theoretically simulates all possible combinations of input signals. The complement to the TPG is the Output Response Analyzer (ORA). Its task is to know every correct output response of the CUT and decides whether the current output is faulty or valid. To create a meaningful and valid test it is important to isolate the test from any other input. Therefore, the Input Isolation Circuitry (IIC) is implemented. Its task is to decouple all input signals, which are commonly provided to the CUT and replace them with test-signal coming from the TPG. Last but not least, to synchronize the behaviour of the TPG, ORA and IIC the Test Controller is implemented. It first initializes a specific test then decouples the System Inputs and finally activates the ORA which then outputs a Fail or Passed signal [9][10].

2) Safety Monitor Approaches:
Besides BISTs, there are also other monitors, which verify the behaviour of circuits and overall systems. Schuldt et al. [11], for example, are strive to test and validate ADAS efficiently by reference to systematically generated virtual test scenarios. The idea hereby is to identify the factors, which are affecting the assistance system. Hence, the test scenarios will be generated. By reference to the test scenarios a test will be executed and due to a variety of scenarios a evaluation of the results can be done. Another approach to monitor ADAS is presented by Mauritz et al. [12]. With this approach results obtained from simulations are transferred to the road. They ensure a consistently behaviour of the ADAS in both worlds due to a simulation of realistic driving conditions and by utilization of a set of runtime monitors. Furthermore, Meany [13] elucidated that in all modern safety-critical systems the Integrated Circuits (IC) are the root. According to Meany, besides redundant and diverse development, it is necessary to monitor the ICs to be fault-tolerant. There are several ways to monitor the IC during operation. Meany addresses in his paper several opportunities of IC diagnostics.

III. Core Concept and Architecture

In this section, we present our concept and architecture for a novel safety monitor of MEMS-based LiDAR systems. The reliability of the Driver is a sensitive topic, therefore it is indispensable to monitor and test the Driver extensively and diverse. Due to that we have introduced this novel procedure to be able to test and monitor the Driver in a new way. At first, the architecture modifications are highlighted and described. Furthermore, we go through the process flow of the monitoring and test period. With this new monitor there is another possibility to detect faults in the Driver module at an early stage and to take appropriate measures. Due to the diversity of the testing module it should be possible to prevent undetected faults even better.

In Figure 6, the modified block diagram is illustrated. In principle, it is a common phase-locked loop (PLL), which is essential for the MEMS mirror actuation, the System Safety Controller, the MEMS mirror and our novel Safety-Critical Mirror Driver Monitor (SCMDM). The HV(On/Off) signal sets the points in time in the internal schedule at which the High Voltage (HV) is switched on or off. This internal schedule is administrated by the Mirror Subtiming block. How fast or slow this schedule is processed is dependable from the PLL and thus, we aimed to test the PLL on its functionality. Due to this we have designed a SCMDM and also adapted the existing architecture and integrate our novel monitor into it. The core of the SCMDM is consisting of a mirror simulation part and a decision part. The decision part is responsible to decide when the test run is conducted and for notification to the System Safety Controller. With the start of the test run and the accompanying monitoring of the system, it is also necessary to decouple the Driver from the physical MEMS mirror. Hence, there were switches for the

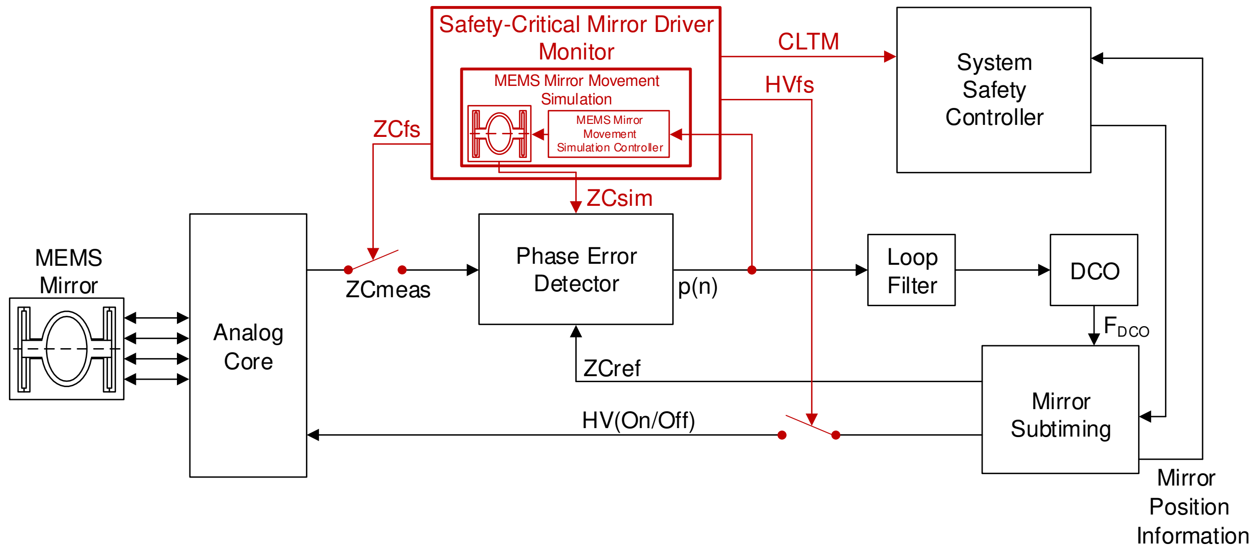

Figure 6. Block diagram of a PLL architecture with the novel adaptions to include a Safety-Critical Mirror Driver Monitor module in the system.

Zero-Crossing measured (ZCmeas) and High Voltage On/Off (HV(On/Off)) signals implemented. In case of test run started the SCMDM block disables the switch for ZCmeas signal by Zero-Crossing forwarding stop (ZCfs) signal and the switch for HV(On/Off) signal by High Voltage forwarding stop (HVfs) signal. Furthermore, the SCMDM notifies the System Safety Controller about a test run by the Control Loop Test Mode (CLTM) signal.

After a test run is started (can be started at at a vehicle start or when stopping in front of a traffic light) the Zero-Crossing simulated (ZCsim) signal is instead of the ZCmeas forwarded to the Phase Error Detector (PD) block. In case of a vehicle start, the frequency of the simulated MEMS mirror movement is set to a random but plausible frequency. Otherwise, the frequency is set to a different frequency than the actual mirror swing to test and monitor the behaviour of the MEMS Driver during control operation. To be able to adapt the simulated frequency of the Zero-Crossing (ZC) a MEMS Mirror Movement Simulation Controller (MMMSC) is implemented in the simulation part of the SCMDM. By reference to the PLL error this controller is adapting the simulated MEMS mirror frequency and works contrary to the PLL. Due to the characteristics of the MEMS mirror concerning acceleration and deceleration, the control loop of the simulation must take these into account. This is necessary to be able to emulate the physical MEMS mirror's behaviour after frequency increase respectively decrease. The acceleration of the mirror requires more energy effort than its deceleration. Thus, the integrator values have to be chosen accordingly to that fact. How the flow of this procedure looks alike is depicted in Figure 7. The test cycle and monitoring procedure is divided in the following steps:

1) **Checking for Driving Cycle**
In the background, it is continuously checked whether the vehicle is in the driving state or not. A stopped driving cycle is, for example, a vehicle stop before a traffic light or a vehicle start. A test cycle with subsequent mirror restart usually lasts much shorter than 1s. In both cases, traffic light stop and vehicle start, there is at least 1s time to perform the test and monitoring cycle. Hence, the SCMDM is started after a stop of the driving cycle is detected.

2) **Safety-Critical Mirror Driver Monitor Enable**
After the driving cycle check gives green light for the SCMDM the SCMDM is enabled and notifies the System Safety Controller via the CLTM signal about the test cycle. Next step is to adjust the frequency for the simulated mirror.

3) **Frequency Adjustment**
On the basis of a simulated mirror movement the adequate and orderly function of the MEMS Driver

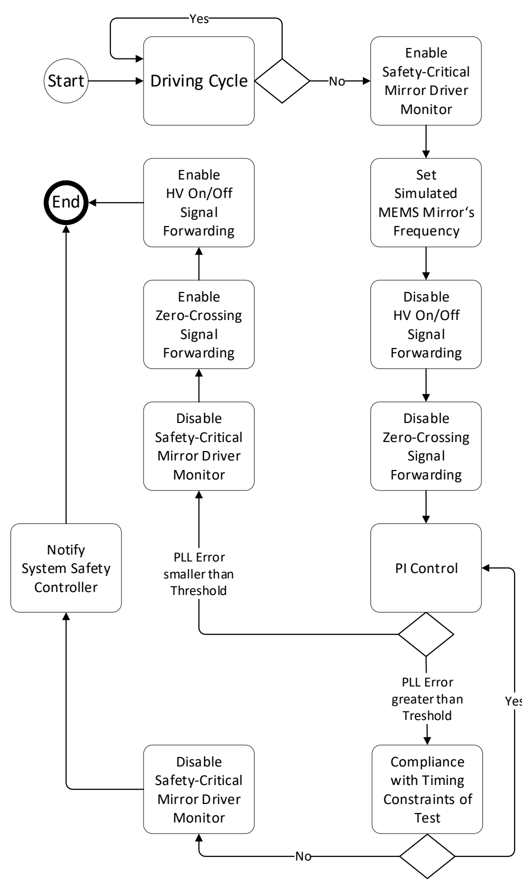

Figure 7. Process flow of the Safety-Critical Mirror Driver Monitor module.

ASIC's PLL shall be proved. Therefore, it is necessary to set a start frequency for this simulated mirror with a significant difference to the actual frequency of the physical MEMS mirror. In case of a vehicle start it is only necessary to choose a frequency within given limits of the physical MEMS mirror. If the MEMS mirror has already been in operation, the frequency to be set must then be selected within plausible limits and the selected frequency must also be sufficiently different from the actual mirror frequency. After the initial frequency of the mirror simulation is set the system has to be decoupled from the physical MEMS mirror during the test cycle.

4) **Decoupling**
Switches have been integrated into the existing architecture to decouple the system from the MEMS mirror. By means of HVfs the HV(On/Off) signal is decoupled from the physical mirror and thus prevents an unwanted mirror actuation. During the test phase, the mirror is actuated in a open loop mode with the HV(On/Off) value, which is configured before the test is started. In order to prevent a disturbance of the control loop in the test mode by the ZC of the physical mirror, the ZCmeas signal is switched off. Thus, only the ZCsim signal is forwarded to the PD block and the PLL is not affected of two different, actual and simulated ZC, signals.

5) **PI Control**
Then the control of the PLL and the simulated mirror frequency begins. The PLL is operating as usual and tries to match the internal adjusted frequency with the simulated mirror frequency. The simulated mirror is also adapting the frequency with respect to the specifics of the acceleration and deceleration of the physical mirror. By reference to the obtained PLL error the MEMS Mirror Movement Simulation (MMMS) part is informed whether an acceleration (frequency increase) or a deceleration (frequency decrease) has to be simulated. It is necessary to know whether the simulated mirror needs to be accelerated or decelerated because the integrator values of acceleration and deceleration are different. This is the case because there is a difference in energy consumption between acceleration and deceleration. This control happens until either the simulated mirror has the desired frequency or a time limit is reached.

6) **End of PI Control**

   a) **Control Success**
   After the control process was successful, the SCMDM is disabled and the physical MEMS mirror is integrated into the control system again instead of the simulated one. To re-integrate the MEMS mirror, the ZCmeas signal is forwarded to the PD block and the HV(On/Off) signal of the Mirror Subtiming block is forwarded to the Analog Core that connects to the physical mirror.

   b) **Control Abort**
   In the case that the control is aborted by reaching the time limit, the SCMDM is also disabled. In contrast to successful control, however, a notification of failure is transmitted to the System Safety Controller. The System Safety Controller is then responsible for what measures are taken. Such measures could possibly be a further test run or a degradation of the system.

7) **Encoupling**
After the test run is finished, the physical mirror is coupled back into the system. This works in principle similar to the start-up procedure. The physical mirror in open loop mode is put back into closed loop mode by activating the PLL. This completes the test run and the system continues to operate as before.

With this novel procedure there is another possibility to check the function of a control loop for MEMS-based LiDAR systems. Especially for safety-critical components in environmental perception systems, it is important that there is not only redundancy of tests and monitors but also diversity. The most important thing is to ensure the correct functioning of the systems that provide information for ADAS and other fusion components. The following section discusses and explains the results of the novel monitor approach.

IV. Results

In this section, we provide the measurement results of our novel monitoring procedure, which has been introduced in Section III.

Figure 8 shows the start of the novel monitor procedure. After 427 mirror half periods, the frequency of the simulated mirror is changed. The Angle_Ok signal can be used as an indicator for a frequency shift between mirror and driver because it indicates whether the angle setpoint is reached or not. At the beginning of the frequency mismatch this is also clearly visible in the ZC measurement. The red signal corresponds to the ZC reference signal of the MEMS mirror Driver and the blue one to the ZCsim signal. After the 427 mirror half period it is clearly visible that the reference and the simulated ZC signal are no longer synchronous. The exemplary course of the mirror is recorded at Mirror Angle. The red curve indicates the course of the mirror at the same frequency and the blue curve looks like the course when the new frequency is set for

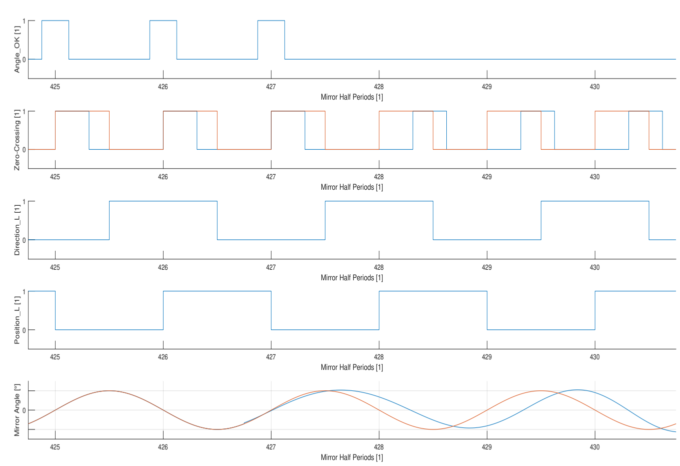

Figure 8. Measurement with the initial frequency adaption of the simulated MEMS mirror.

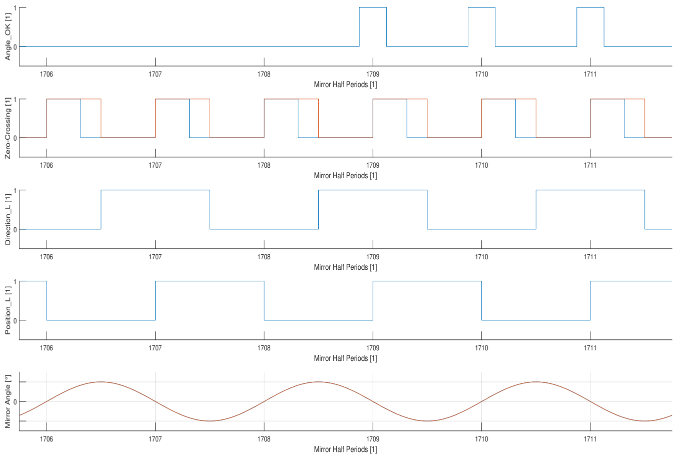

Figure 9. Measurement with the frequency match of the simulated MEMS mirror and the MEMS Driver.

the simulated mirror. Figure 9 shows that the frequency of the mirror has been adjusted again and that the angle setpoint has been reached again from the 1709 mirror half period onwards. Here the Angle_Ok signal is essential for detecting whether the angle setpoint has already been reached again. It looks as if the frequencies of mirror and Driver are equalized before the 1709th mirror half period. The exemplary courses of the mirror overlap almost completely and reference and simulated ZC signal also occur again almost simultaneously. For our measurement, the control required 1282 mirror half periods to adjust the frequencies. That was about 220ms at this frequency. Depending on the frequency difference between mirror and Driver, this control time can be extended or shortened. Finally, the results of the frequency adaption duration are summarised and shown in Table I.

TABLE I. MEASUREMENT RESULTS

	Begin	End	Time in ms
Duration of Frequency Adaption	427	1709	$\sim$ 220

V. CONCLUSION

In our paper, we have introduced a novel architecture for a Safety-Critical Mirror Driver Monitor. With this monitor a new possibility is created to test the control of a MEMS-based LiDAR system and to monitor the functionality of the Driver during the test cycle. The diversity of system monitor options is further increased with this new SCMDM, along with BIST and other diagnostic variants, further reducing the likelihood of malfunctions remaining undetected. With a duration of around 220ms, this test run is also well under 1s. So it is no problem to perform this procedure while the start of the vehicle or a vehicle stop in front of a traffic light. Even if the traffic starts to move again, not even 1s passes until the LiDAR system is operational again. Due to the speed at which the vehicle starts to move (usually a slow start), it is only a few centimetres at the most that the vehicle does not receive any information from the LiDAR. By further optimizing the parameters, the time required for the test run can probably be shortened considerably. Our intention was to show that in principle it is possible to simulate the mirror and thus create a further possibility for MEMS Driver monitoring by means of the novel monitor. Monitors such as these will be even more important in the future for highly automated vehicles than they already are in safety-critical vehicle components. The top priority is to ensure the safety and reliability of the ADAS in the vehicles and also to check whether this is the case.

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