Review

Formal Review of several test methodologies, radar and sensor systems articles from the Automotive Industry

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**Abstract:** Background: A short presentation on several scientific articles written on test methodologies radar and sensor systems. Materials and Methods: Reviews are done over a number of twenty different scientific articles.

Results: We formulate an honest opinion over each of the articles described in the reference.

Conclusions: We present our conclusion based on our research done on the scientific articles.

**Keywords:** testing, sensors, automotive

1. Background

The Automotive industry is a flourishing domain, where technological breakthroughs occur very frequently. Today, automobiles incorporate a series of intricately designed electronic and electric components, which collect data from the driving environment via sensors, with the ultimate purpose of ensuring vehicle, driver, passenger and pedestrian safety. In this review, we compiled several testing methodologies for testing sensor-based systems that are found in an automobile, giving you a short overview on them and discussing its components and the benefits and compromises that they induce.

2. Materials and Methods

We will start analyzing the contents of twenty scientific articles from the field of automotive, which contain applications in sensor systems and test methodologies. More specifically, the articles analyzed are referring to the following application domains:

* Effects of rain clutter, fog and ice on automotive sensors[1-5]
* Advanced Automotive Sensors [6,7]
* Testing methods of automotive systems [8-16]
* Target detection for Automotive Radars [17-20]

2.1. Effects of rain clutter, fog and ice on automotive sensors

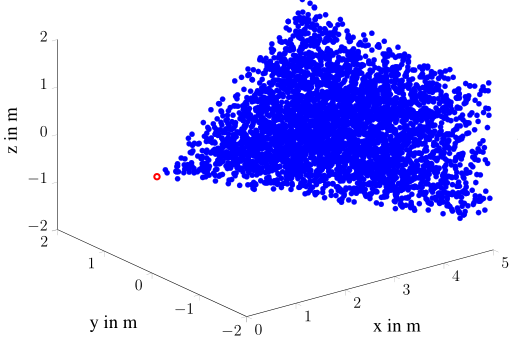
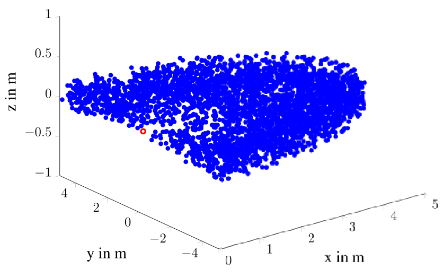
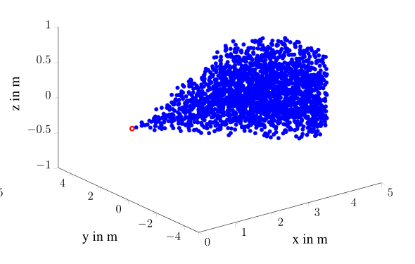
Our first application domain brings us into the field of rain clutter, fog and ice detection using radar and sensor systems and its effects on the road. In their abstract, S. Hasirlioglu and A. Riener[1] offer a solution to test the reliability of rain detection sensors using camera, lidar and radar systems. They explain that small errors in sensor data measurement and interpretation can lead to severe accidents, thus, testing the reliability of sensors and safety systems before market introduction is of high importance. But it is becoming increasingly difficult to test these systems in real-world environments due to their increasing complexity, so they propose a solution to simulate these effects using a model-based approach, straight from the development phase. The wear effect that rain has on automotive sensors also needs to be replicated in these simulation environments. Luckily, Hasirlioglu and Riener offered came up with a solution: they used a mathematical model to simulate raindrops, and ultimately distribute them over the sensor’s field of view, also done in a simulated environment. The mathematical model they used is the three-parameter lognormal distribution:

|  |  |
| --- | --- |
| N(D) = exp(), | (1) |

where is the total drop number per unit volume (m3), is the geometric mean diameter in mm, and σ the standard deviation of *D*. For their experiment, they considered the following approximations for these parameters:

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |
|  | (4) |

where R is the rain intensity in mm/h.



**Figure 1.** FOV of each surround sensor including water drops. The left image represents the FOV of camera sensors, the center image the FOV of lidar sensors, and the image on the right the FOV of radar sensors. The number or drops is reduced by a factor of 10 for better clarity and the diameters of the drops are not considered.

From this, they have generated rain volume by inserting equations 2-4 into 1, and assuming the R = 100 mm/h, they have achieved 1382 drops per cubic meter.

For camera sensors they have generated noise based on the ray tracing technique, which creates a two-dimensional representation of a three-dimensional world. This noise would then ultimately be applied to the camera lens, to replicate rain. A similar method is also applied to the lidar sensors, but with an angle offset on the vertical axis, so multiple beams are distanced by each other to replicate a “curtain” of rain drops.(see figure 2). For the radar sensors, they assumed that each radar beam interacts with each raindrop.

Chart, bar chart

Description automatically generated

**Figure 2.** Resulting noise filters for each sensor type. The left image represents the noise filter for camera sensors with a resolution of 640 x 480 pixels. Adding this mask to a camera output and applying additional adjustments leads to an image including the effects of rain. The center image shows the noise filter for lidar sensors. Each element includes information about ray-drop intersections, which models the effect of rain on every single beam of a scanning sensor. The image on the right represents the radar noise model and shows the radar cross sections of rain within range cells.

To test this, they have created 3 scenarios: first, a vehicle placed at 10 m from the sensors under clear weather conditions, second, a vehicle placed at 10 m under real-life weather conditions, and the third one is the model-based simulation described in their work. The results from the second and third scenarios are strikingly similar.

In a similar fashion, Alexander Kamann et. Al. [2] have used sensor data from radars to detect objects in conditions of uncertainty. By their intelligent use of radar sensors, they have improved performance of vehicle detection systems against false objects.

Continuing through the chapter of effects of water and ice on automotive radar systems, A. Arage et. al. [3] analised the signal degradation of milimeter wave radar sensors, and concluded that the presence of water or ice layer on the surface of antennae, lenses or sensors is the main cause of performance limitations on automotive radars.

In response to these effects, Hasirlioglu and Riener continued on their work on studying automotive sensor attenuation caused by fog and rain[4]. Here, they have focused on camera, lidar and radar sensors and described the attenuation in three different spectrums: visible, near infrared and milimeter. For simulating these sensors, they have developed disturbance models(noise) for each sensor type. Radar sensor radiation penetrate more effective through suspended water in the air, especially under foggy conditions. Camera and lidar sensors are strongly influenced by fog. However, due to the advantages of lidar and camera sensors regarding object classification and tracking, the sensors are essential for automated safety systems. Therefore, it is advisable to detect degraded sensor performance depending on the outdoor condition. Vehicles should use the most reliable sensor data by reducing the weighting of sensors with degraded performance.

The effects of water and ice on automotive sensors can be tested in either outdoor conditions or indoors, and that’s what S. Hasirlioglu et. al. [5] have done in their work on modeling and simulation of rain for the test of automotive sensor systems. The approach is based on an indoor test method, which helps to save test kilometers and test effort. For this purpose a theoretical model is developed in order to determine the sensor behavior. Subsequently, a rain simulator is constructed to validate the theoretical model. Furthermore the developed rain simulator is validated by comparison with real rain, and results indicated to a good correlation between the simulated environment, and the real-life scenario.

2.2. Advanced Automotive Sensors

The second application domain refers to advanced automotive sensors and its growing integration into electronic control units. Robert Bogue [6] has provided reviews for several emerging sensors on the automotive market:

* Silicone gyroscopes
* Accelerometers
* Sold-electrolyte oxygen (“lambda”) sensors
* Lane detection systems

In his review, Robert addressed the importance of correct packaging of these sensor parts, especially vacuum packaging of some silicone gyroscopes, and argued that their performance will be hindered by air and gas leakages. Moreover, he has addressed issues regarding silicon availability in the future of sensor development, and has concluded that the cost will increase as the materials are being more and more needed. He has given an example of the lambda sensor, which handles the flow control of the air which gets combined with the fuel injected in the vehicle. Lambda sensors are designed to keep the air/fuel ratio at a point of balance (stoichiometric point), where it is proven that combustion is at its most efficient point, and exhaust emissions are at their most emission rate. Another interesting advanced automotive sensor is represented by the adaptive cruise control and lane detection/departuring systems. These are built with either 77 or 24 GHz radar sensors, lidar sensors and video cameras, and offer functionality such as:

* Lane departure warning
* Lane guidance
* Curve entry speed adaptation
* Adaptive headlights
* Driver drowsiness monitoring

These systems require complex signal processing algorithms and hardware, which would increase its cost.

Diagram

Description automatically generated

**Figure 3.** The schematic of “Carsense”, a EU collaborative, forward-facing video sensor developed for lane detection and lane departure warning.

It is necessary to monitor not only the vehicle and outside parameters, but inside the vehicle as well, driver and passenger safety is essential. In this matter, George S. Maximous and Hany A. Bastawrous[7] have developed a simple and inexpensive touch sensor based on the humantenna effect to detect driver drowsiness. They have placed several sensors on the driver’s seat and seatbelt, which can measure cardiac and respiratory rhythms, and by using Guttersberg sensors placed on the steering wheel that can measure the hand grip on the steering wheel. For their experimentation part, 4 volunteers (2 male and 2 female) have agreed to participate. The basic functionality of this system is that it measures respiration rate and heartbeat from the driver, and its grip on the steering wheel. When the driver’s heartbeat and respiration rate begins to lower, and the grip on the steering wheel begins to loosen, then an alarm is triggered to wake the driver up.

2.3. Testing Methods of Automotive Systems

Modern vehicles use surround sensors to measure their local environment. The information are processed and forwarded to intelligent pre-crash or automation functions enhancing vehicle safety or enabling automated driving[8]. False or inaccurate measurements can lead to fatal consequences for humans and vehicles. High accuracy and robust environment perception in all driving situations, including high dynamic driving situations e.g. skidding, are compulsory requirements for these systems. Therefore, automotive surround sensors must be tested in various driving situations. This paper presents a new, non-destructive and reproducible test methodology for testing surround sensors in high dynamic driving situations. Therefore, the vehicle’s motion during a skid driving situation was mathematically described. The test methodology was validated through experiments carried out with a real test vehicle. Finally, the experimental setup and the results are presented and discussed.

Automotive safety systems aim to provide maximum protection to vehicle occupants and vulnerable road users. These safety features rely on data from surround sensors such as radar, lidar and camera, which provide detailed information about the environment of the vehicle. A minor error in the measurements of these sensors can lead to major injuries or death. Hence, the reliability and accuracy of these sensor systems is mandatory. The performance of surround sensors depends on their local environment, because of the attenuation of the ambient atmosphere. Environmental influences such as rain additionally affects the accuracy of sensor systems. Therefore, these sensors must be tested under various weather conditions. This paper presents a new test methodology for rain influence on automotive surround sensors. Therefore, a rain simulator was designed and validated. The proposed test methodology was applied to radar, lidar and camera sensors in an experimental setup.[9,10]

Safety systems in the automotive field were developed separately for a long time[11]. Nowadays active and passive safety systems are networked, exchange information and rely on each other. This leads to an increasing complexity of the communication channels and numerous control unit functions and variants. Therefore the development and test process is getting more and more complex and unmanageable. Also testing always means a compromise of duration, quality and costs. Despite those challenges a high error detection and therefore reliability shall be reached. Due to those changes especially the system test where different components interact for the first time and many functions that rely on collaboration of different elements can be tested for the first time in the development cycle is a big challenge. Here arises the potential to improve contemporary test methods and strategies and to examine new ones and to involve them in existing processes. This paper describes one possible approach for a combination of test methods leading to an efficient test strategy for the system test of the airbag control unit.

More and more applications and a steadily increasing market penetration are showing the success of radar based driver assistance systems. While in recent years most of those systems were focusing on the advance of the drivers’ comfort, today many safety applications are offered. As those systems can directly influence the vehicle dynamics, functional safety in terms of new normative requirements, such as the ISO 26262 is gaining more interest.[12,13] Therefore, in this paper a built-in self-test is presented which is able to monitor multiple receiver paths by measuring the amplitude and phase imbalance among all channels. Four different types of coupling elements to feed a test signal into receiver paths are investigated and evaluated in terms of their precision. Furthermore, a method for a baseband evaluation is proposed.

A new, flexible, and easily reconfigurable HIL simulation and test environment was created for function development and test automation of state-of-the-art automotive electronic control units. The implemented hardware and software environment was validated and successfully tested with the integration and verification of a mass-produced ABS ECU. A new pressure model was elaborated for the emulation of the hydraulic control unit (ABS HCU). In the HIL environment communication, ABS actuation and fail-safe tests were implemented and performed successfully; the results were in concordance with the expectations.[14]

Graphical user interface, diagram

Description automatically generated

**Figure 4.** The anatomy of the HIL simulation environment

Intelligent vehicles use surround sensors such as radar, lidar and camera to perceive their local environment. The generated information are processed by a control unit to identify critical traffic situations such as rear-end collisions and trigger reversible or irreversible safety systems. Incorrect measurements can result in accidents with fatal consequences. Therefore, high reliability and accuracy is a mandatory requirement.[15] The performance of surround sensors depend on the ambient atmosphere and weather conditions. It is known that fog has a negative influence on wave propagation especially in the visible range. Hence, surround sensors must be tested under realistic conditions.

This paper describes a road test using a printed circuit board (PCB) used for automotive applications. In order to characterize the vibration stresses, a series of road tests were conducted which included different automobiles and road conditions such as city and highway. During the road tests, a comprehensive data acquisition system was used which can record temperature, acceleration, driving speed, strain, etc. Strain sensors are mounted on the PCB module close to a major IC component. Experimental results show a clear correlation between acceleration, speed and road conditions. The stresses obtained from vibration during the road tests are generally much smaller compared to the lab tests on a vibration table. However, the maximum board strain may be significant and worthy of further studies. The objective is to assess the fatigue risk of solder joints during field use to warranty operation of 10k hours in 15 years.[16]

2.4. Target detection for Automotive Radars

The FMCW (frequency modulated continuous wave) automotive radar[17,20] has been widely used in the advanced driving assistant system of vehicles. The basic idea of FMCW automotive radar is to obtain the range and velocity information from the beat signal. However, the information extracted from one frequency ramp will suffer from the range-velocity ambiguity problem. In this paper, several subsequent ramps have been generated to eliminate this ambiguity and a two dimensional FFT algorithm for the FMCW radar is presented. The parameters of FMCW signal are derived mathematically. An experiment in actual traffic environment is conducted and the offline raw radar data are captured by using the AWR1642BOOST. The data processed by MATLAB shows that the 2D FFT algorithm can obtain the range and velocity information of moving targets without ambiguity.

The typical FMCW radar, however, has serious problems in multi-target situations. That is, range-velocity processing gives rise to so-called ghost targets due to Doppler shift in the received beat-frequency. In this paper, we propose a new transmit wave and detection algorithm. In the proposed method, the rough range is detected in the first period, and the fine range and velocity are obtained in the second period.[18]

A novel concept of employing BPSK codes to achieve a simultaneous transmission in a 79 GHz FMCW automotive radar is presented in this paper. With a MIMO topology, simultaneous azimuth and elevation measurements become possible by utilizing the angle-dependent phase difference between the antenna arrays. Hence, this approach can offer a 4D detection of range, azimuth, elevation and Doppler-velocity for each detected target. This concept has been verified through test drives in multiple scenarios and the measurements showed that the elevation accuracy is only limited by calibration.[19]

3. Results

Automated vehicles are equipped with surround sensors, which use electromagnetic waves, to perceive their local environment. It is well known that electromagnetic waves suffer much attenuation while propagating through the atmosphere. In adverse weather conditions, such as rain and fog, the attenuation is increased due to the additional large water particles in the air. Therefore, it is advisable to detect degraded sensor performance depending on the outdoor condition. Vehicles should use the most reliable sensor data by reducing the weighting of sensors with degraded performance.

This paper also shows an approach to a combination of test methods and wants to be the groundwork for the development of an efficient test strategy for the system test of networked safety systems. The objective is the research what potential different existing and innovative test methods imply and how the system test can be optimized.

In contrast to CCTV systems, IR imaging requires less computational power, is immune to light variations and adverse weather conditions and needs minimal processing to achieve powerful detection and tracking algorithms. As such, it is inexpensive and well suited to several automotive applications. Some of those being considered include: traffic tracking and counting, typically from motorway gantries; traffic control; people counting at pedestrian crossings; blind spot detection; and uses in safety systems where the position of the occupants must be accurately measured prior to the deployment of the airbag.

4. Conclusions

In closing words, we can observe just how complex automotive sensor systems are at the moment, and we are safe to say that these technologies would continue to evolve with a much greater rate than before. The work presented here was a compilation of information from scientific articles and journal entries which could lead to a better understanding of complex automotive embedded systems and could help developers and scientists broaden their field of knowledge.

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