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

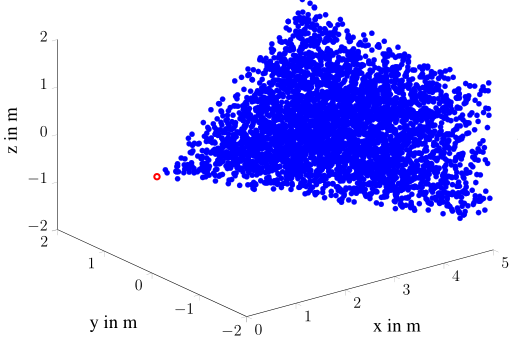
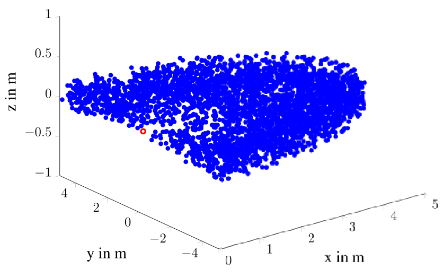
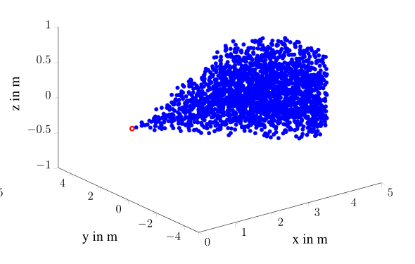
Our first application domain brings us into the field of rain clutter, fog and ice detection using radar and sensor systems and its effects on the road. In their abstract, S. Hasirlioglu and A. Riener[1] offer a solution to test the reliability of rain detection sensors using camera, lidar and radar 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.

3. Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Subsection

3.1.1. Subsubsection

Bulleted lists look like this:

* First bullet;
* Second bullet;
* Third bullet.

Numbered lists can be added as follows:

1. First item;
2. Second item;
3. Third item.

The text continues here.

3.2. Figures, Tables and Schemes

All figures and tables should be cited in the main text as Figure 1, Table 1, etc.



**Figure 1.** This is a figure. Schemes follow the same formatting.

**Table 1.** This is a table. Tables should be placed in the main text near to the first time they are cited.

|  |  |  |
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| **Title 1** | **Title 2** | **Title 3** |
| entry 1 | data | data |
| entry 2 | data | data 1 |

1 Tables may have a footer.

The text continues here (Figure 2 and Table 2).

|  |  |
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| C:\Users\martin\Downloads\testFigure.tif | C:\Users\martin\Downloads\testFigure.tif |
| (**a**) | (**b**) |

**Figure 2.** This is a figure. Schemes follow another format. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel; (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

**Table 2.** This is a table. Tables should be placed in the main text near to the first time they are cited.

|  |  |  |  |
| --- | --- | --- | --- |
| **Title 1** | **Title 2** | **Title 3** | **Title 4** |
| entry 1 \* | data | data | data |
| data | data | data |
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| entry 2 | data | data | data |
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| entry 3 | data | data | data |
| data | data | data |
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| data | data | data |
| entry 4 | data | data | data |
| data | data | data |

\* Tables may have a footer.

3.3. Formatting of Mathematical Components

This is example 1 of an equation:

|  |  |
| --- | --- |
| a = 1, | (1) |

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

This is example 2 of an equation:

|  |  |
| --- | --- |
| a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z | (2) |

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

**Theorem 1.** Example text of a theorem. Theorems, propositions, lemmas, etc. should be numbered sequentially (i.e., Proposition 2 follows Theorem 1). Examples or Remarks use the same formatting, but should be numbered separately, so a document may contain Theorem 1, Remark 1 and Example 1.

The text continues here. Proofs must be formatted as follows:

**Proof of Theorem 1.** Text of the proof. Note that the phrase “of Theorem 1” is optional if it is clear which theorem is being referred to. Always finish a proof with the following symbol. □

The text continues here.

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusions

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

6. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

**Supplementary Materials:** The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

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**Appendix A**

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

**Appendix B**

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled starting with “A”—e.g., Figure A1, Figure A2, etc.

References

References must be numbered in order of appearance in the text (including citations in tables and legends) and listed individually at the end of the manuscript. We recommend preparing the references with a bibliography software package, such as EndNote, ReferenceManager or Zotero to avoid typing mistakes and duplicated references. Include the digital object identifier (DOI) for all references where available.

Citations and references in the Supplementary Materials are permitted provided that they also appear in the reference list here.

In the text, reference numbers should be placed in square brackets [ ] and placed before the punctuation; for example [1], [1–3] or [1,3]. For embedded citations in the text with pagination, use both parentheses and brackets to indicate the reference number and page numbers; for example [5] (p. 10), or [6] (pp. 101–105).

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3. Alebel Arage, Wolf M. Steffens, Goetz Kuehnle, Rolf Jakoby; Effects of Water and Ice Layer on Automotive Radar; Robert Bosch GmbH, Automotive Electronics, Technische Universität of Darmstadt, Institute of Microwave Engineering
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