July 2020

Performance Testing for Sensors in Connected and Autonomous Vehicles: Feasibility Study

Contents

Executive summary

Connected and Autonomous Vehicles (CAVs) and vehicles with advanced driver assistance systems (ADAS) rely upon perception sensors to determine their physical environment and the behaviours of other road users around them.

These sensors take the place of the human driver's eyes, ears and other senses when the driving task is automated. Different sensor types possess attributes which tend to make them better suited to certain types of driving tasks, an example of which is given below:

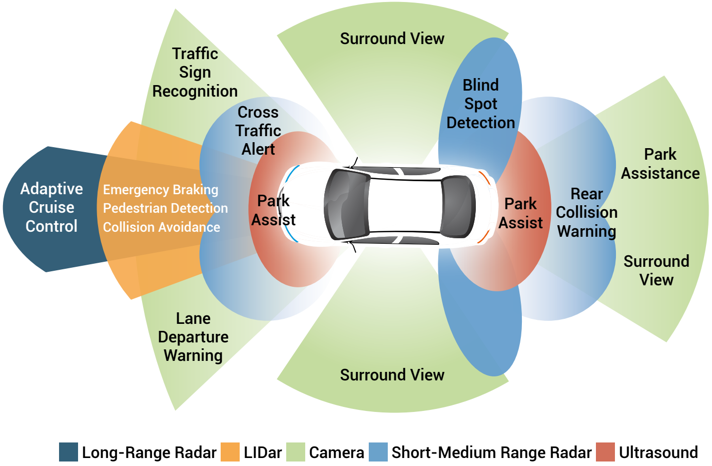

Figure 1: CAV sensors: generic description of usage.

The ability of these sensors to correctly perceive their surroundings is affected by weather conditions and other environmental factors. As deployment of such sensors accelerates, the automotive industry has a growing need to understand and characterise these affects so that suitable requirements can be established, and mitigations can be put in place when designing such systems. Specialised facilities are necessary to carry out the design, evaluation and validation processes required to achieve this.

The Centre for Connected and Autonomous Vehicles (CCAV) has commissioned Connected Places Catapult (CPC) and National Physical Laboratory (NPL) to investigate the requirements, infrastructure and facilities needed to enable reliable CAV sensor testing and validation, which can also support a safety evaluation and assurance programme. Such requirements will include new methodologies, standards, performance criteria and physical facilities - in particular, the key steps needed to be undertaken to characterise the performance of a typical sensor system (under a wide range of environmental conditions); and develop and validate robust sensor models for virtual simulation testing. The ultimate objective is to help UK businesses, including development and testing infrastructure, have access to solutions which enhance their global competitiveness.

Rationale for Intervention (summary)

Market Size and Demand

The UK automotive industry is a key contributor to the UK, employing over 800,000 people and generating £71.6bn in turnover[1].

It is estimated that the CAV market will be worth £28bn to the UK economy of 2035[2]. The global automotive LiDAR market size is expected to reach $2.9bn by 2026[3].

The CAV opportunity is not only relevant to businesses developing autonomous driving technologies but also those involved in the testing of CAV technologies.

Alignment with the Industrial Strategy and the Automotive Sector Deal

In order to realise the Government's ambitious target of having fully autonomous vehicles on the roads, without a safety driver, there is a requirement to have a strong testing regime that provides confidence that autonomous vehicles can safely operate.

This requirement is underlined by commitment in the Automotive Sector Deal of £100m for CAV testing infrastructure, to be matched by industry, which will develop the UK capabilities further.

The CAV testbed competition in 2017 aimed to develop the UK's CAV testing ecosystem.
The feedback from the stakeholder engagement has revealed that there are further testing requirements that can further enhance this ecosystem.

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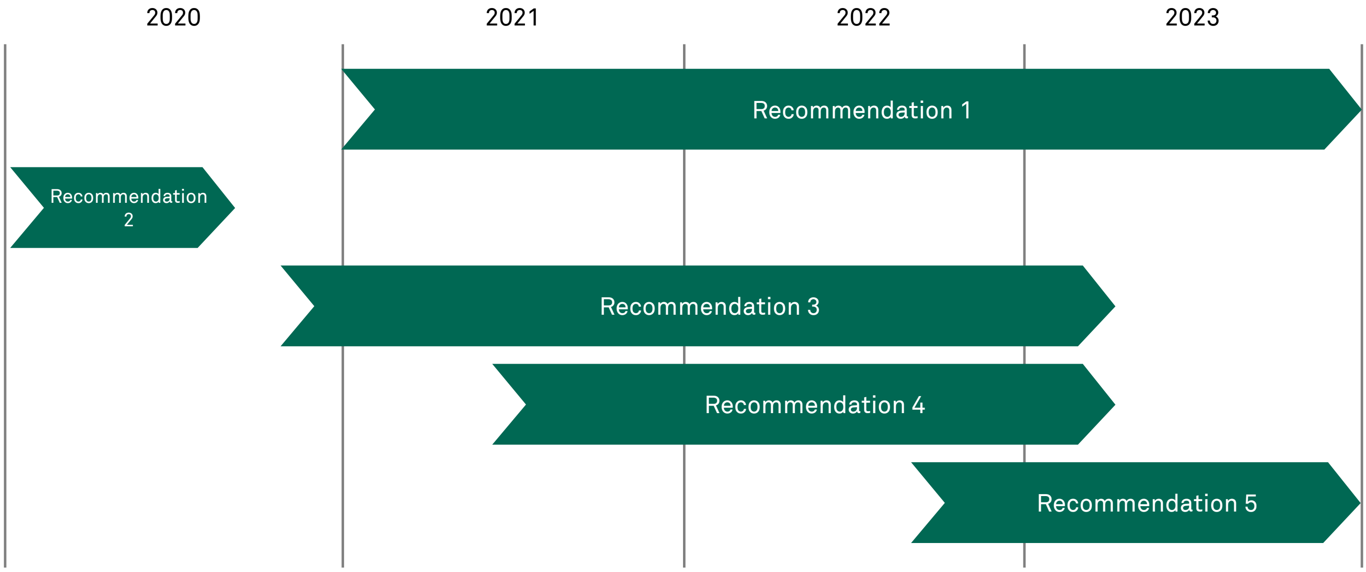
1. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642813/15780_TSC_Market_Forecast_for_CAV_Report_FINAL.pdf
2. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642813/15780_TSC_Market_Forecast_for_CAV_Report_FINAL.pdf
3. https://www.acumenresearchandconsulting.com/automotive-lidar-market
4. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/673045/automotive-sector-deal-single-pages.pdf

Recommendations

This study has been compiled from a combination of stakeholder interviews, desk research and business and scientific analysis from which a number of recommendations are made which are summarised below and explained in more detail throughout this report:

Recommendation 1: A programme is established to develop and validate a standardised, reliable and usable CAV sensor testing technical framework.
Recommendation 2: A short time frame project is undertaken as a proof of concept for a usable and reliable framework for characterising sensor performance in different weather-related conditions.
Recommendation 3: Establish a programme to deliver a usable and reliable framework for characterising sensor performance in different weather-related conditions, including the ability to assess performance outside the design envelope. (Dependent on recommendation 2)
Recommendation 4: Development of technologies which can repeatably recreate the weather conditions encountered by CAV sensors.
Recommendation 5: Creation of a Government/industry co-funded environmental testing infrastructure, to support both development and performance characterisation of single sensors and the testing and validation of sensor suites and whole vehicle systems.

A suggested timeframe for completion of each of the recommendations is given in the diagram below.



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[5] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/673045/automotive-sector-deal-single-pages.pdf

Strategic Impact (summary)

The UK already has a highly reputable automotive testing expertise, made significant investment in Testbed UK and has the advantage of being able to test CAV anywhere in the UK[5].

The recommended approach aims to develop next generation facilities for testing the influence of weather and environmental factors on sensors for autonomous vehicles. Existing test facilities and services have not necessarily been designed for the explicit needs of autonomous vehicles sensing capabilities.

The testing of sensors is an important part of the wider CAV Validation and Verification programme but must not be considered in isolation from the other parts.

The recommended approach will therefore build upon the 2017 CAV testbed programme.

Impact of doing nothing (summary)

The UK has already invested heavily in the CAV Testbed programme and has a strong automotive testing sector. If the development of this ecosystem does not continue there is a risk that UK testing capabilities fall behind International competitors, leading to OEMs and tier 1s taking their business elsewhere.

The Automotive Sector Deal outlines the aim to "…position the UK as a global leader in the development and deployment…", and continual investment in the ecosystem is recognised as important for this to be achieved and the UK to become synonymous with the CAV technology. Without further investment there is an increased risk that the UK does not meet the 2021 target for autonomous vehicles.

Main Report

This report is a feasibility study aimed at identifying current and future challenges, in terms of performance assessment, reliability and testing, for the effective deployment of perception sensors in CAV. The report identifies the types of tests that would need to be undertaken to characterise sensors used on Autonomous vehicles as well as the types of facilities required to conduct the tests within the operating boundaries and indicative measurements beyond that, considering the reasonable performance of standard test equipment.

This feasibility study involves a combination of industry interviews, desk research and business and scientific analysis. The report is structured around the five recommendations.

This report is not intended to be prescriptive in terms of the sensor technologies or combinations.

The report does not set out to comment on the definition of safety or liability as it relates to the performance of Connected Autonomous Vehicles.

Context

Autonomous vehicles and vehicles with advanced driver assistance systems rely upon perception sensors to determine their physical environment and other road users around them. Performance of most of the sensor technologies gets affected by different types of weather conditions and other environmental factors. Reliance on these sensors for safety critical applications means that the performance envelopes of the sensors in poor weather and harsh environment must be clearly established and suitable mitigation strategies employed when designing such systems.

An increasing number, type and quality of sensors can make the window of satisfactory operation wider, but at a cost. The automotive industry is extremely cost sensitive and needs a clear understanding of the incidence of adverse weather and the quantification of the particular type, together with a clear understanding of how their sensors will behave under those conditions. To date, the testing of sensors and fused systems is not standardised, and anecdotal evidence suggests that sensor suppliers do not understand the limitations of their products sufficiently well to allow accurate representation to the vehicle manufacturers.

Industry has acknowledged the importance of developing a set of common methodologies and definitions for characterising sensor performance under different conditions. This would provide a standardised framework to facilitate the validation and deployment of CAV on roads in the UK and elsewhere. There is a risk that in the absence of a coordinated approach, industry may adopt diverse and sub-standard approaches, leading to incidents which could undermine the market potential.

It is broadly acknowledged[6] that the simulation (virtual and physical) of automated driving functions is the only practical way to assess the many possible scenarios that shall comprise a sensor system design verification plan (DVP). Consequently, it is important that a) a computer model of a sensor should accurately represent its behaviour under all relevant circumstances, including poor weather; and b) physical simulation of driving scenarios should recreate equivalent environmental conditions and be able to do so on a repeatable basis. The same applies to sensor systems which fuse together data from individual sensors: the model of that fused system shall also need to be correlated by testing the fused system.

The importance of developing a common approach to testing sensor degradation to help ensure public confidence is emphasised in one recent report. The American Automobile Association (AAA) conducted a series of tests[7] using vehicles with automatic emergency braking and pedestrian detection alerts on a closed course with dummy pedestrians. The vehicles struck the dummy pedestrians that were crossing the road 60 percent of the time - in daylight hours at speeds of 20 mph. The researchers then swapped the adult dummies with a child-sized version, and the results deteriorated: a collision occurred 89 percent of the time. Testing at night or at higher speeds also yielded a high number of collisions. When encountering an adult pedestrian at night, the detection systems were found to be “ineffective,” AAA says. None of the cars tested were able to detect an adult pedestrian at night. Honda, for its part, acknowledged some of the limitations of its safety tech.

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[6] Nidhi Kalra, Susan M. Paddock; “Driving to Safety , How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability?” RAND Corporation (2016)

[7] https://www.aaa.com/AAA/common/aar/files/Research-Report-Pedestrian-Detection.pdf

> “AAA testing of these systems at night speaks to the limitations present in all such driver-assistive systems, where technologies such as cameras, used primarily for object recognition, have diminished capacities in low-light and other conditions such as rain, snow and fog.[8]”

A Spokesperson

Summary of Findings:

This investigation of CAV sensor technology identified current and future challenges, in terms of performance assessment, reliability and testing, for the effective deployment in CAV of perception sensors. The report identified the types of tests that would need to be undertaken to characterise perception sensors used on Autonomous vehicles as well as the types of facilities that would be required to conduct the tests within the operating boundaries and indicative measurements beyond that, considering the reasonable performance of standard test equipment.

Lack of a standardisation in sensor interfaces and APIs makes full sensor’s characterisation difficult. In the future it is required that industry and international standardisation bodies identify common interfaces and testing standards for the sensors. A fundamental aspect of the standardisation procedure would be the provision of access to the low-level sensor data (e.g. I-Q data for radar, raw data for camera) produced in order to be able to separate the hardware tests from the algorithmic ones.

Interference that might arise in cases where multiple vehicles equipped with active sensor systems operate in close proximity is an open challenge. This will be more apparent in high traffic/congestion scenarios where even if appropriate interference mitigation methods, such as multiplexing and frequency hopping, are applied, the noise floor will rise significantly, degrading the dynamic range of the receiver. Extreme cases of malicious interferers aiming to blind or deceive the sensor systems must also be investigated.

CAV perception sensors testing facilities currently available are unable to provide complete testing scenarios required for the automotive industry. To adequately test the performance of sensor systems, through their development and integration cycle, there needs to be a diverse ecosystem of testing facilities; from bench top and compact chambers for development, calibration, and validation; to large centres for functional verification when integrated. There is a particular weakness in the ability to emulate weather conditions.

Moreover, appropriate physical definitions of weather-conditions so that they are adequately emulated and simulated must be developed. Though atmospheric conditions play a significant role in degrading the performance of all sensors examined for the majority of KPIs identified in this report, no adequate descriptions of weather over the distance; nor weather emulation and simulation, consistent over the bandwidths required have been identified. Ideally these definitions would relate the quantification of weather conditions, with high spatial-resolution and continuously over the electromagnetic spectrum, with the existing semantic descriptions.

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8. https://www.theverge.com/2019/10/4/20898773/aaa-study-automatic-emergency-braking-pedestrian-detection

1 Impact Analysis

Problem Statement

The analysis of the stakeholder feedback has highlighted three barriers to the accurate and comprehensive testing of CAV sensors:

- Testing sensor performance in different weather conditions is recognised as the largest gap in current testing facilities. In order to test performance in different weather scenarios and combinations there is a requirement for clear, standardised definitions for all weather types. Presently these definitions are missing with the exception of some Met Office definitions for rain.
    - As a result of this simulation environments do not have defined characteristics for different weather types, meaning that they are unable to accurately test the performance of sensors for autonomous driving systems.
- Understandably manufacturers are protective of their IP. However, a reluctance to share sensor data makes it impossible for the sensors to be accurately modelled in simulation environments and for sensor performance to be validated.
- There are no standardised metrics for measuring sensor performance within an autonomous/ADS context, this is impeding the creation of accurate modelling environments and therefore maintaining a significant risk for vehicle OEMs, autonomous driving systems developers, regulators and the public.
    - Without standardised metrics it is hard for ADS developers to self-validate their system's reliability; and it also stifles earlier stage investment in emerging companies to this sector.

Testing Landscape

A look at the current market environment for CAV and current CAV testing infrastructure capabilities, in the UK and globally, has revealed:

- The UK has a number of advanced automotive test facilities. For example,
  - In September 2019, Millbrook opened its Autonomous Village[9].
  - Horiba-MIRA has substantial ADAS and CAV testing facilities and are investing significantly in simulation and modelling capabilities.

- There has already been significant investment in CAV and CAV testing projects in the UK.
  - Any future competition and investment need to build on the existing capabilities of the UK automotive and sensor testing infrastructure, as well as identify a gap in what is an International market.
  - The testing of sensors is an important part of the wider CAV Validation and Verification programme but must not be considered in isolation from the other parts.

- Any new testing facility will need to compete Internationally. Facilities with most relevance to the testing of CAV sensors are:

- **North America**
  - In June 2019, the Ottawa L5 CAV test facility was launched, valued at $11m[10].
  - Fiat-Chrysler announced in September 2018 more than $30 million of investment in its proving ground facilities to further develop autonomous vehicle and advanced safety technologies.

- **Europe**
  - Sweden's AstaZero facility has been specifically developed for testing of active safety systems.
  - The Netherland's TASS International Mobility Centre provides automated driving testing facilities.
  - Fraunhofer in Germany is developing ATRIUM (Automobile Test Environment for RADAR In-the-loop Investigations and Measurements), a high-performance radar target simulator which aims to be capable of generating around 300 artificial radar reflections and targets, simulating a much closer "real-world view" than existing radar target emulators.

- **Asia**
  - Japan's Automobile Research Institute has a facility that is able to reproduce a broad range of environmental and weather conditions in controlled circumstances.
  - South Korea's $10 million K-City facility provides conditions for over 30 different real world driving situations.

- There remains an opportunity for testing facilities to validate the performance and limitations of CAV sensors specifically as existing capabilities tend to cater for the whole vehicle test requirements.

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[9] https://www.cittimagazine.co.uk/news/millbrook-to-launch-new-cav-test-facility.html
[10] https://www.newmobility.global/autonomous/invest-ottawa-opens-new-cav-test-facility-canada/

Strategic Impact

The recommended approach aims to develop next generation facilities for testing the influence of weather and environmental factors on sensors for autonomous vehicles. Existing test facilities and services have not necessarily been designed for the explicit needs of autonomous vehicles sensing capabilities.

The research carried out as part of this study has not identified a dynamic weather simulation environment that can control the distribution of rain or control the drop size, for example.

It is proposed that this is enhanced by replicating models that have been built in compact chambers, creating a diverse, yet complimentary, ecosystem for autonomous vehicle sensor testing in the UK. The recommended approach will build upon the 2017 CAV testbed programme.

The mix of facilities, plus definitions of weather characteristics, will give the UK a competitive advantage and help to attract development of autonomous driving systems to the UK.

The UK already has a highly reputable automotive testing expertise, made significant investment in Testbed UK and has the advantage of being able to test CAV anywhere in the UK[11].

This combination of factors will contribute to increasing the UK's national competitiveness in the field of autonomous vehicles, which should in turn lead to increased productivity and economic growth.

It is believed that the recommended scalable approach will provide testing facilities at a price point to meet the needs of the whole industry. For example, whilst a larger facility required for whole vehicle testing may provide costlier services which are more affordable for larger OEMs, the smaller prototype facilities (e.g. small boxes, compact chambers) could offer component testing at a cost that suits the requirements of SMEs and the automotive parts supply base.

Impact of CAV technology development on the UK economy

It is estimated that there could be an additional 6,000 direct and 3,900 indirect jobs in the production of CAV technologies in the UK by 2035[12].

The *'TSC Market Forecast for CAV report'* outlines that in a UK lead scenario, with a strong regulatory and testing landscape, this could increase to 10,200 additional direct jobs.
This scenario could generate £2.1bn in GVA to the UK economy, compared to £1.2bn in the baseline scenario.

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[11] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/673045/automotive-sector-deal-single-pages.pdf

[12] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642813/15780_TSC_Market_Forecast_for_CAV_Report_FINAL.pdf

Please note this data is for connected and autonomous vehicle technology.

Table 1: Key economic results for each scenario relating to the manufacture of CAV technologies (TSC Market Forecast for Connected and Autonomous Vehicles (July 2017).

Economic Impacts for CAV technologies		2020	2025	2030	2035
Low scenario	Direct GVA (£bn)	-	0.01	0.08	0.27
	Direct Jobs	-	100	600	1,500
Central scenario	**Direct GVA (£bn)**	**0.2**	**0.5**	**0.9**	**1.2**
	Direct Jobs	**1,500**	**3,400**	**5,400**	**6,000**
Central UK lead scenario	**Direct GVA (£bn)**	**0.2**	**1.0**	**1.6**	**2.1**
	Direct Jobs	**2,100**	**7,30**	**9,700**	**10,200**
High scenario	Direct GVA (£bn)	0.3	1.2	3.0	3.3
	Direct Jobs	2,100	8,200	17,900	17,000
High scenario with high UK capabilities	Direct GVA (£bn)	0,4	1.6	4.0	4.3
	Direct Jobs	3,500	12,500	26,400	25,000

According to the Reuter articles *'A chaotic market for one sensor stalls self-driving cars',* over £761m has been invested in over 50 Lidar start-ups in the last 3 years[13], whilst the rest of the article suggests that a lack of LiDAR standards and a clear "winning technology" are holding back the mass production that would be required to reduce costs.

The creation of a testing facility would encourage International start-ups to bring their sensors to the UK in order to establish their technology and gain the standards and traction required for mass production.

This will aid the UK in achieving the "Central UK lead scenario", which brings uptake of CAV ahead of Europe

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[13] https://uk.reuters.com/article/uk-autos-autonomous-lidar-focus/a-chaotic-market-for-one-sensor-stalls-self-driving-cars-idUKKCN1QN0HO

Logic Model

Context	Inputs	Outputs	Immediate Outcomes	Intermediate Outcomes	Impacts
It is unknown how the performance of perception sensors used in autonomous driving systems are impacted by different weather conditions	BEIS/CCAV public funding	World leading testing and development environment	Reduced barriers to CAV adoption	Industry, political and public confidence in CAVs	Increased in high value job creation in CAV related industries
It is unknown how weather will degrade the performance of perception sensors	Industry match funding	Definition of weather conditions and scenarios	Roadmap to develop world leader weather models for CAV testing	UK established as a CAV market leader	Industry & SME growth in the CAV related sectors
It is accepted that simulation environments are the practical method to test the numerous scenarios	Technical input from academia/NPL/other relevant partners	Data to inform and ensure accurate, representative simulations environments	Increased attractiveness of UK CAV testing facilities to International organisations	Safe, CAV environment	Increased national/ international CAV adoption
There are limited standards to define weather conditions – which are required to create a representative environment		Enhanced ecosystem of CAV testing facilities, establishing the UK as a 'one-stop-shop'	Increased UK expertise		A safer, more efficient transport network, resulting in economic, environment and societal gains
There are no standards to measure the performance of sensors against		Highly accurate and efficient method of modelling and testing sensor performance			UK technological advantage
		Identification and roadmap of future testing requirements			
		A testing framework for CAV sensors			

Impact of doing nothing

The UK has already invested heavily in the CAV Testbed programme and has a strong automotive testing sector. If the development of this ecosystem does not continue there is a risk that UK testing capabilities fall behind International competitors, leading to OEMs and tier 1s taking their business elsewhere.

As described in the Landscaping chapter, there are new CAV testing facilities being built internationally, such as the Ottawa L5 facility and the investment at Japan's Automobile Research Institute to reproduce a range of weather conditions, which the UK will wish to compete with.

The Automotive Sector Deal outlines the aim to "…position the UK as a global leader in the development and deployment…", and continual investment in the ecosystem is recognised as important for this to be achieved and the UK to become synonymous with the CAV technology.

Establishing a gold standard for how weather and other conditions are defined and modelled, alongside large-scale environmental test facilities, could help give the UK a lasting advantage in CAV by stimulating significant FDI. If the UK wants to be a leader in CAV, then it needs to set up this level of technical infrastructure soon.

Without this there is a risk of damage to the UK's reputation and that the CAV technical expertise in other countries advances ahead of the UK, attracting new international businesses and investment to those areas, and potentially slowing CAV technology development in the UK. There is urgency because industry may adopt sub-standard approaches, leading to incidents which could undermine the market potential. A delay also means the UK would no longer be ahead of the pack and able to take advantage of the capabilities of science organisations such as Met Office and NPL.

Sensor costs are still high, and the lack of test results in sensor customers not having a full understanding of the tradeoff between cost, performance and reliability. This has the potential to slow the adaption and development of autonomous vehicles.

All of which increase the risk that the Zenzic CAV roadmap suffers significant slippage.

2 Stakeholder Engagement

Interviews have been conducted from a cross-section of the CAV Sector, including the categories:

- OEMs
- Sensor Developers and Manufacturers
- ADS Developers
- Testing - experts and facility providers
- Simulation Tool providers
- Government policy and standards bodies

Fifty organisations were approached for interview and 18 agreed to participate. Interviews were designed to elicit responses which provide us with a basic understanding of the state-of-the-art; current challenges with automotive sensor testing; where the gaps are; and what are the barriers to creating new methods, services and facilities to plug these gaps. Some organisations expressed caution about participating from a competitive standpoint as either:

a) they feel they are able to undertake their own sensor validation; or
b) they are concerned that this type of activity has the potential to interfere in their business models.

The information below constitutes a cross-section of highlights from the interviews undertaken.

Standards

- The UK CAV Standards Program has identified a series of standards to be created to assist in the development of Connected and Autonomous Vehicles.

- Standards which consider the underlying sensor performance currently do not exist. There is some evidence that standardisation of performance metrics would facilitate the understanding of sensor behavior, thereby enabling sensor models which are more accurate and representative of real-world limitations. Feedback from stakeholders has highlighted a need for standards which:
  - Consider the integration aspects of physical sensors in vehicles and sensor models in simulation and some standardisation of data outputs between components.
  - Are technology agnostic and do not mandate a particular design, but which focus on the KPI metrics which assess the perception performance of the sensor system as a whole rather than the fidelity of individual sensors.
  - Define a standardised way of characterising and measuring weather conditions and other environmental factors which affect sensor system performance.

Sensors: Challenges

> “With the whole AV industry still at a very young stage, it is time to support the development and testing efforts of car manufacturers and Tier 1 suppliers by deepening their understanding of lidar and applying stringent sensor validation. There is far too much – sometimes misleading – information on the precision, accuracy and range of lidar sensors. To be of value to the car manufacturers, all lidar sensors should be evaluated with the same measurements. Lidar manufacturers must be ambassadors for this approach, promoting transparency and comparability.”

Dr. Mircea Gradu, Senior VP of quality and validation, Velodyne.

A common issue noted by respondents is the constraints preventing commercial organisations to share information or standardise interfaces. This would seem to be motivated by concerns about giving away IP or confidential/proprietary data. This has translated into limited availability of performance specification at the level of detail required by ADS developers and Simulation environment operators.

Respondents expressed differing levels of confidence with regards under which conditions each sensor type would be operating outside its performance limitations. Lack of common approaches or reliable data for modelling conditions - in particular weather - or specifying performance is considered an issue across respondents.

There is evidence of divergence between the Tier 1/OEM sectors where the focus has so far been on ADAS integration; and the newer entrants into the market for ADS development and sensor design, who are focused on level 3 and above solutions. The latter placed a stronger emphasis on needing to understand the performance characteristics of their sensors and how they degrade under different conditions. Many agreed that what can be bought off the shelf is not good enough for L4/5: increased performance and functionality is required; and better-quality performance data. A regular response from Vehicle Manufacturers is that they want to be assessed on whether the outcome of the data fusion system is capable of delivering the desired performance; they are not interested in indicating the fidelity of each sensor type.

The key requirements in determining which sensors to use included:

- **Price** - Cost was a significant determinant. At the same time consideration is given by some respondents as to whether to spend more on a better sensor with more information.
- **Reliability.**
- P**erformance** - what does it do?

With regards the sensor supplier ecosystem, there are implications on quality/conformity/reliability as costs are driven down. Data from manufacturer varies, but it is not considered sufficient, for example with LIDAR there are no suitable standards (e.g. for range).

The primary use designated for different sensors was varied and this seemed to be guided by both modality of the vehicle and also the known performance of the sensor.

Sensor testing: identifying solutions

Better collaboration would be useful to help understand sensor performance criteria and a common, standardised language/interface for defining this. The industry will always be interested in common metrics/semantics and reference points which help with how they validate their own systems. There was consensus on the value of a common approach on the characterisation of different conditions affecting sensors: in particular, it would be useful to have definitions of weather types, and how that affects sensor performance. A sensor characterisation call would be welcome by the industry - a funded CR&D project along this theme which helps commercial organisations to de-risk this, could be beneficial.

Respondents have highlighted that the UK has different combinations of weather to other countries (and vice versa). Therefore, any sensors in the UK market need to be able to handle UK conditions, while for any UK test facility to attract international clients it needs to be able to replicate combinations of conditions available in different locations. This highlights the importance of developing standardised approaches to weather condition models, which can be re-used for local weather conditions around the world.

Sensor positioning on different platforms is considered key for different users and for overall reliability and is affected by known performance: recommended this as an item for validation.

There was interest in both smaller test chambers for reliable, repeatable testing of individual sensors; as well as a large-scale facility, for testing sensor systems, navigation systems and whole vehicles, where objects can be controlled, and weather conditions simulated.

With regards the gaps in the current testing facilities for CAV sensors, the general response was that the industry is reliant on the UK weather to provide 'variation', which they need to test with (not currently underpinned by common definitions). To become commercially viable, the facility would need to be able to emulate environmental conditions on a repeatable basis. For some this is not necessary at a whole vehicle level and could be done on a sensor level - it would still require a fairly large facility to provide the long range that modern sensors are required to detect at.

All respondents felt there is definitely a case for a facility where a manufacturer brings a sensor/sensor set to run a standardised set of tests which produce results/a set of data in a standardised way. There also needs to be test capabilities at all levels of integration from wafer through to chip, components and system and effective and agreed standardisation of the testing protocols.

Sensor models for simulation: challenges

Feedback from organisations developing/operating simulation environments was that Tier 1 suppliers and OEM's are providing minimal data on their sensors and not enough to create models to test with. Respondents indicated that the traditional Tier 1 suppliers have so far engaged less than some of the smaller sensor manufacturers. One respondent perceived that Tier 1's were only just getting involved with Simulation.

Fundamental challenge is how to replicate sensors in a simulation environment. It is necessary to have sufficient information from sensor suppliers to understand how the sensor works, however the data supplied is usually insufficient. In particular, correctly defining noise and performance levels for sensor models and quantifying fidelities. The lack of standardised interfaces between automotive sensors and other components is seen as a significant issue.

Agreement from respondents that simulation must play a role in both dev/testing and accreditation. But this raises questions such as what those requirements for accreditation of tools are?

Sensor models: for most of the industry, focus is on ADAS. A major concern for Tier 1 (and all sensor manufacturers) is that the internal information of sensors represents a big IP concern.

Industry as a whole are overly dependent on "idealised photorealistic" camera-based simulations - not electromagnetically valid for all (in some cases any) interrogating wavelengths. These do not account for weather conditions in any complete or meaningful way i.e. physically/electromagnetically valid. Sensor characterisation/models for conditions: these are considered essential for test scenarios (by the respondents) to move on from idealised tests.

Respondents who manage or develop simulation test environments agree with the need to understand better when/how sensors fail; this includes issues such as vibration and sensor misalignment; Installation and packaging also have an influence on sensor performance.

There have been numerous claims in company sales pitches that sensor models are validated, but this does not bear up under examination.

Simulation/sensor models: identifying solutions

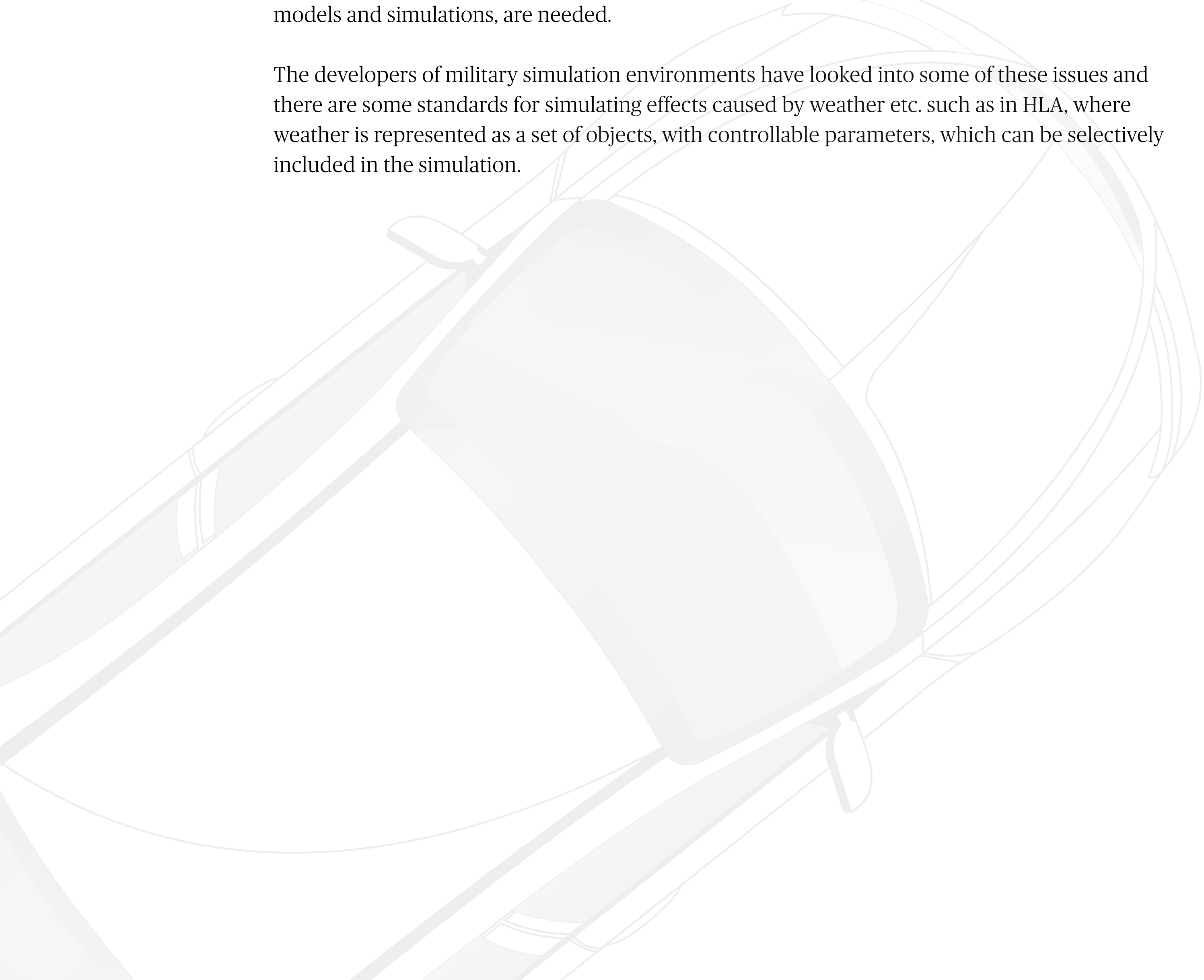
It has also been noted that respondents see benefits to linking a physical testing facility with simulation environments, and a desire to loop sensor hardware into the simulator in order to feed it synthetic data.

It has been discussed in several interviews that a large testing facility should be able to test the impacts of a combination of influencing factors, e.g. rainfall, leaves, loss of GPS coverage etc., and in particular replicating weather conditions as they impact CAV sensors. This could be a source of differentiation in the international market.

With regards weather models, respondents indicated the need for: Development of a UK (and world) climatology of edge case weather, fully expressed in terms of CAV impacts; Development of meteorologically-based CAV sensor (and AI) performance standards; Development of test protocols that provide a traceable link between CAV standards and real-world system performance, including the creation of a “CAV meteorological testbed” and reference virtual environments

Facilities which are able to create repeatable conditions in which to test the effects of weather and environmental variation on RADAR sensor properties, and correlate against the results from models and simulations, are needed.

The developers of military simulation environments have looked into some of these issues and there are some standards for simulating effects caused by weather etc. such as in HLA, where weather is represented as a set of objects, with controllable parameters, which can be selectively included in the simulation.



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Recommendations and Supporting Analysis

Scope and Approach

In order to specify appropriate and relevant sensor test infrastructure to support the UK CAV industry, a common approach on methodologies to assess the performance of the sensor systems within a vehicle is required. This involves:

- Step by step analysis in documenting the process and resources required for a generic test and evaluation of a typical array of sensor systems, based on four individual sensor types; Radar, LiDAR, Camera, Ultrasonic. Includes:
  - A technical understanding of how to enable reliable comparison between different tests and sensors
  - A definition of test output requirements; acceptable levels of performance; data capture
  - A definition of requirements to provide validated, reliable sensor models

- An approach to generate replicable, usable, standardised weather models applicable to sensor testing

- The types of facilities that would be required to conduct the tests within the operating boundaries and indicative measurements beyond that, considering the reasonable performance of standard test equipment. This includes a technical understanding of the nature of tests required to inform the optimal infrastructure/facilities specification.

Recommendation 1:

A programme led through national government organisations in collaboration with the industry to develop and validate a standardised, reliable and usable CAV sensor testing technical framework.

This section analyses and identifies the types of standardised tests that would need to be undertaken to reliably characterise perception sensors used on Autonomous vehicles. It is expected that the findings provided in this study will evolve through the life of the programme as a result of research and engagement activities. Industry need for standardisation has been established as has the requirement to undertake more than functional testing; the latter is an important part of the assurance process, but does not help identify where the problem lies. For example, in the tests conducted by the AAA[14] these tests showed the system wasn't working but did not explain why.

The ground up approach for standardising sensor performance characterisation outlined here would help in the following ways:

- More reliable procurement of the optimal sensor mix for an ADS.
- Determining whether a problem with a system relates to a sensor failure under a specific condition.
- Reliable characterisation of sensor performance can also provide information about the performance of any AI/ML deployed in sensor post processing
- Enabling the creation of robust sensor models for virtual simulation testing.
- Promoting a development and testing audit trail

It should be noted that lack of a standardisation in sensor interfaces and APIs makes full sensor's characterisation difficult. In the future it is required that industry and international standardisation bodies identify common interfaces and testing standards for the sensors. Recommendations on the use or validation of Machine learning/deep learning deployed in sensors or perception systems is limited. This represents a gap in validation capability and should be a priority to address in the programme recommended above.

A fundamental aspect of the standardisation procedure would be the provision of access to the low-level sensor data (e.g. I-Q data for radar, raw data for camera) produced in order to be able to separate the hardware tests from the algorithmic ones.

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[14] https://www.aaa.com/AAA/common/aar/files/Research-Report-Pedestrian-Detection.pdf

Dissemination of outputs is a critical activity in this process; it is expected the development of any technical framework would involve other stakeholder groups working at a committee level to define and agree the methodologies and tools; which would then be propagated through standards organisations and industry bodies.

Overview:

The development of a common technical framework for sensor performance testing is underpinned by the multi step approach below.

Transducer	Calibrate	Test	Standardise	Disseminate
Generate method to determine and calibrate the following for each transducer: • Responsivity • Noise floor • Saturation level • Linearity • Linear range • Responsiveness	Generate standard method to determine and calibrate the important parameters of a sensor, under different conditions. Includes method to identify potential failure modes	Generate standard method of testing sensors outside of manufacturers recommended operating envelop &/or linear range	Generate standard method to translate information to valid robust simulation model	Dissemination of Good Practice Guidelines

This identifies methodologies for each stage of sensor characterisation, leading to a set of robust, reliable good practice guidelines for industry to use. These methodologies are built to address the characteristics of an archetypical sensor, rather than restricting to specific manufacturers or models.

In support of the Recommendation above, this section provides the following:

- An overview of the constituting components of typical CAV perception sensors, identifying those components which can be characterised reliably against those which cannot.

- Documentation of the process and resources required for a generic test and evaluation of a typical CAV perception sensors systems as evident in Autonomous or Advanced Driver Assist systems, to characterise sensor performance within the supplier's design envelope and to assess performance outside the design envelope (i.e. in edge cases, extreme conditions, failure modes). This will address the characteristics of archetypical perception sensors, rather than restricting to specific manufacturers or models.

- Suggestion for approaches on how to:
  - Determine how the response by the characterised devices to an agreed range of stimuli may be evaluated (parameter). This will include guidance and principles on how different environmental conditions need to be characterised for recreating in test environments; and how a common evaluation methodology might be established.
  - Determine the performance and uncertainty of individual perception sensors for the applications and conditions. Recommendations on the scope of what is included in the performance definition.

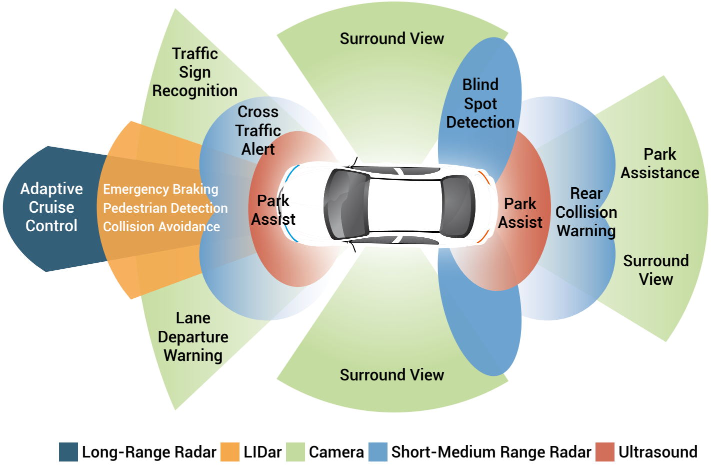
Methodology

After providing an overview of the constituting components of typical CAV perception sensors, this report identifies a set of KPIs for the CAV perception sensors covering the range of perception sensors capabilities, advanced sensing capabilities, operational capabilities, vertical capabilities and electromagnetic compatibility. For the identified KPIs the report suggests tests and calibration scenarios, indicates how to identify reasonable calibration ranges and suggests tests in order to identify sensors' failures and characterise performance in out of range scenarios.

1

Typical CAV Perception Sensors and Usage

Figure 2: CAV sensors: generic description of usage.



Radar (Radio detection and ranging)

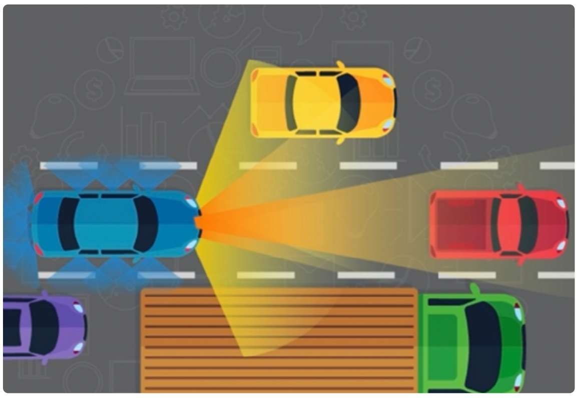


Image credit: Creative Commons from Flickr

Main Usages: These include Blind spot monitoring, changing lanes, rear-end collision warnings, parking cross traffic monitoring, braking, emergency braking, automatic distance control

- Electromagnetic radio waves
- Short range and long range, can monitor objects within a few cm or hundreds of m
- Long range for speed, distance, angular resolution
- Short range suffers less from interference problems
- Low cost

Camera

Main Usages: Lane departure warning; traffic light/sign identification; Visualising objects and obstacles; Environmental awareness

- Rear and forward facing
- Spot traffic lights and road/ speed signs
- CMOS compatible to reduce storage requirements
- Provides precise evaluation of speed/ distance
- Determines presence of objects via their outlines
- 2D and 3D
- Can categorise weather conditions

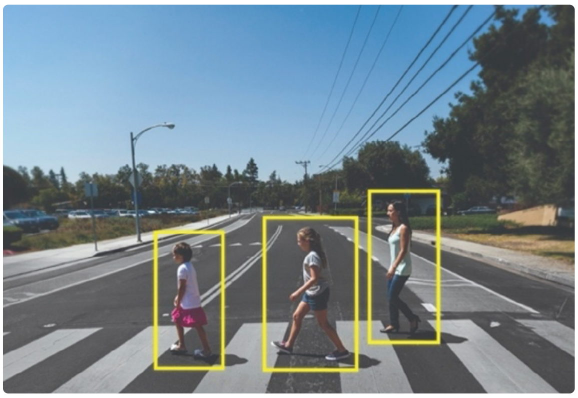


Image credit: Creative Commons from Flickr

LiDAR (Light and detection ranging)

Purpose: Visualising objects and obstacles

- Infrared laser, rotating or solid-state
- Spins to send out laser beams (up to a million per second) and interprets bounced back signals
- Forms 3D map of surroundings
- High cost
- Less reliable [than radar] in conditions of fog, snow, rain

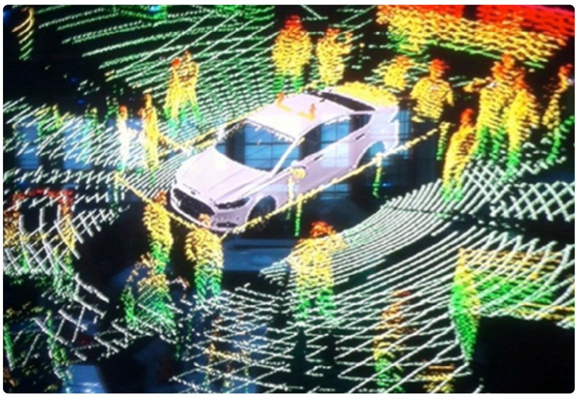


Image credit: Creative Commons from Flickr

Ultrasound

Main Usage: Proximity detection, e.g. parking assist and short distance collision avoidance.

- Acoustic pulses at frequencies above the range of human hearing
- Short range
- Can detect nearby vehicles/obstacles for changing lanes/ parking
- Can be 360 degree with sufficient distribution of sensors
- Could be redundant if short wave radar in use

Image credit: Creative Commons from Flickr

Figure 3 illustrates the general placement of sensors in a CAV. In particular, long and medium range sensors are generally placed in the front of the vehicle to be used for adaptive cruise control, lane keeping and emergency breaking; while medium to short range sensors are placed in the vehicle corners and on the side, to assist with reversing, collision avoidance, cross traffic alert and blind spot detection. Each class of sensor share a common architecture in order to provide target detection, identification and ranging.

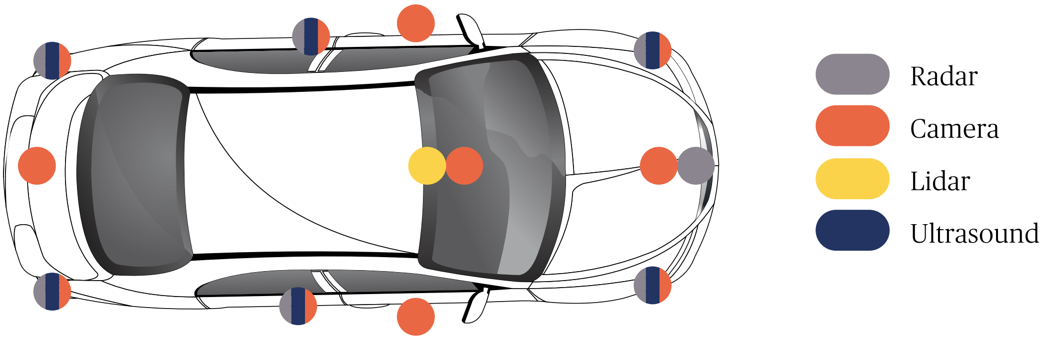


Figure 3: General sensor placement in a CAV.

2

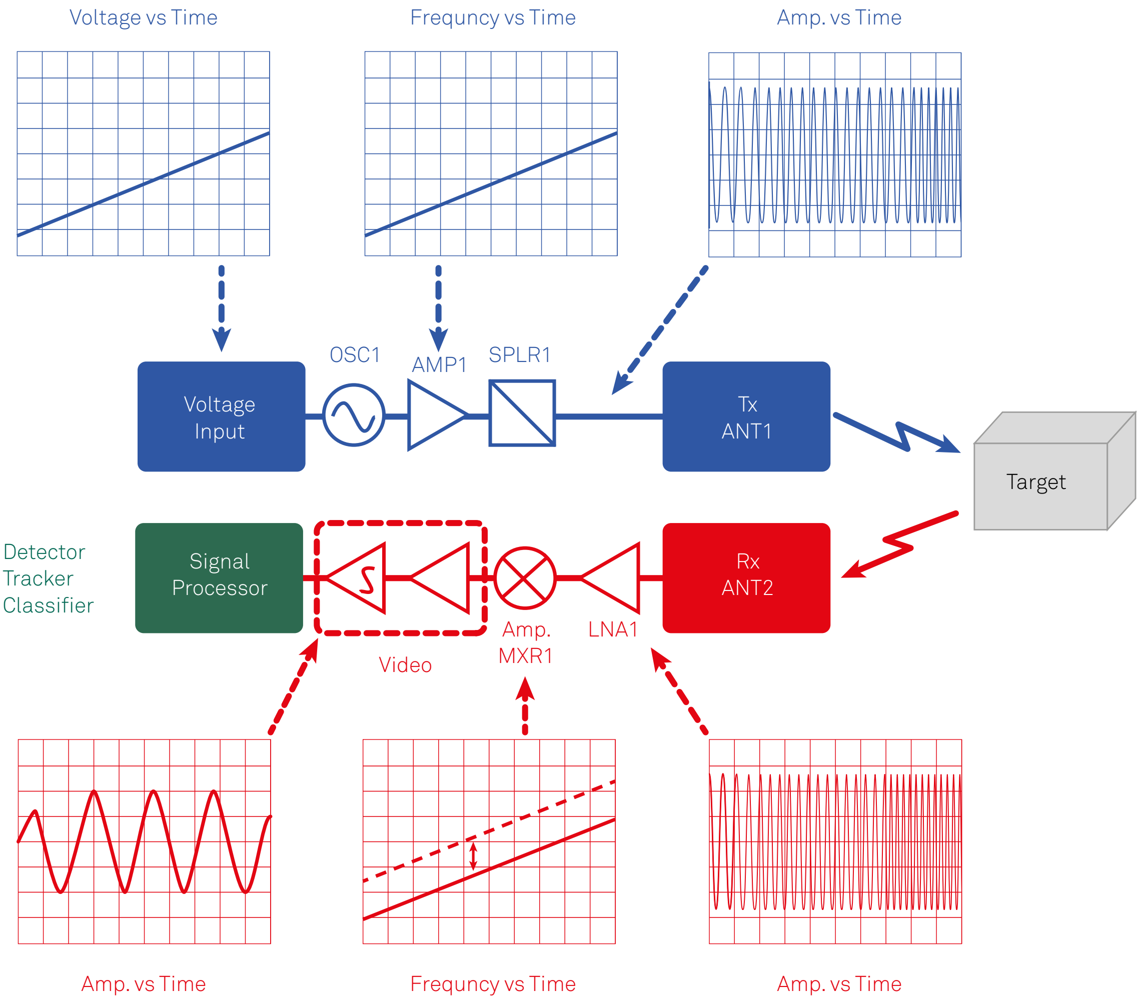
Overview of the constituting components of typical CAV perception sensors

In this section an overview of the constituting components of a typical perception sensor physically & functionally will be described. Furthermore, those components which can be characterised reliably will be identified. Four major classes of sensor have been identified as part of the typical CAV perception suite: Radar, Camera, Lidar and Ultrasound. Industry interviews indicate a bias towards Radar and Camera system due to the maturity, familiarity and cost of the technologies.

Radar

A simplified block diagram of a Frequency Modulated Continuous Wave (FMCW) radar is shown in Figure 4, where OSC1 is a voltage-controlled oscillator (VCO) that outputs a frequency in linear proportion to its input control voltage (Vtune). FM is achieved by changing OSC1's Vtune over time. In this case we modulate Vtune with a linear up-ramp. The output of OSC1 is a sinusoidal waveform that is changing frequency over time. This waveform is amplified by AMP1 and fed into power splitter SPLTR1, where half of it is radiated out of ANT1 and the rest is fed into the LO port of MXR1. What is radiated out of ANT1 looks like an 'accordion' waveform, where the early portion of the waveform is at a lower frequency than the later portion. This waveform propagates through space, scatters off the target, and propagates back toward the radar where a portion of it is collected by ANT2.

Figure 4: Simplified block diagram of linear FMCW Radar sensor - adapted from[15]



The waveform collected by ANT2 is a delayed version of the original accordionlike waveform. The signal from ANT2 is amplified by the low-noise amplifier LNA1 and fed into the RF port of MXR1. Within MXR1, the delayed version of the accordion-like scattered waveform is multiplied by the transmitted waveform. When the transmit waveform is multiplied by the delayed receive waveform within MXR1 the product difference (amplified and low-pass filtered by the video amplifier) is this constant frequency offset known as the beat frequency. The video out containing the beat frequency information is then passed to a signal processor that applies algorithms to perform detection, target velocity estimation, tracking and classification.

When multiple antennas are used multiple receiver branches would be present feeding the video outs to the signal processor that would be then able to estimate also the target's bearing (using angle of arrival techniques).

As described in the following sections the components that can be characterised of the radar sensors are the transmitting and receiving antennae, as well as the receiver amplification stages (jointly) and the signal processor. Furthermore, the emitted waveform can also be characterised through the use of a spectrum analyser.

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[15] Gregory L. Charvat. 2014. Small and Short-Range Radar Systems (1 ed.). CRC Press, Inc., Boca Raton, FL, USA.

Camera

A simplified block diagram of a camera is shown in Figure 5, consisting of 4 components: a lens package which focuses the light on to the photodetector; the photodetector array (CMOS) which converts photons to photoelectrons, this charge is accumulated during exposure, and then converted into a digital image signal; Image Signal Processor (ISP) applies various image enhancement and analysis functions such as dynamic range adjustment, scene analysis, segmentation and object tracking; and a Data In/Output (I/O), interfacing with standard communication protocols.

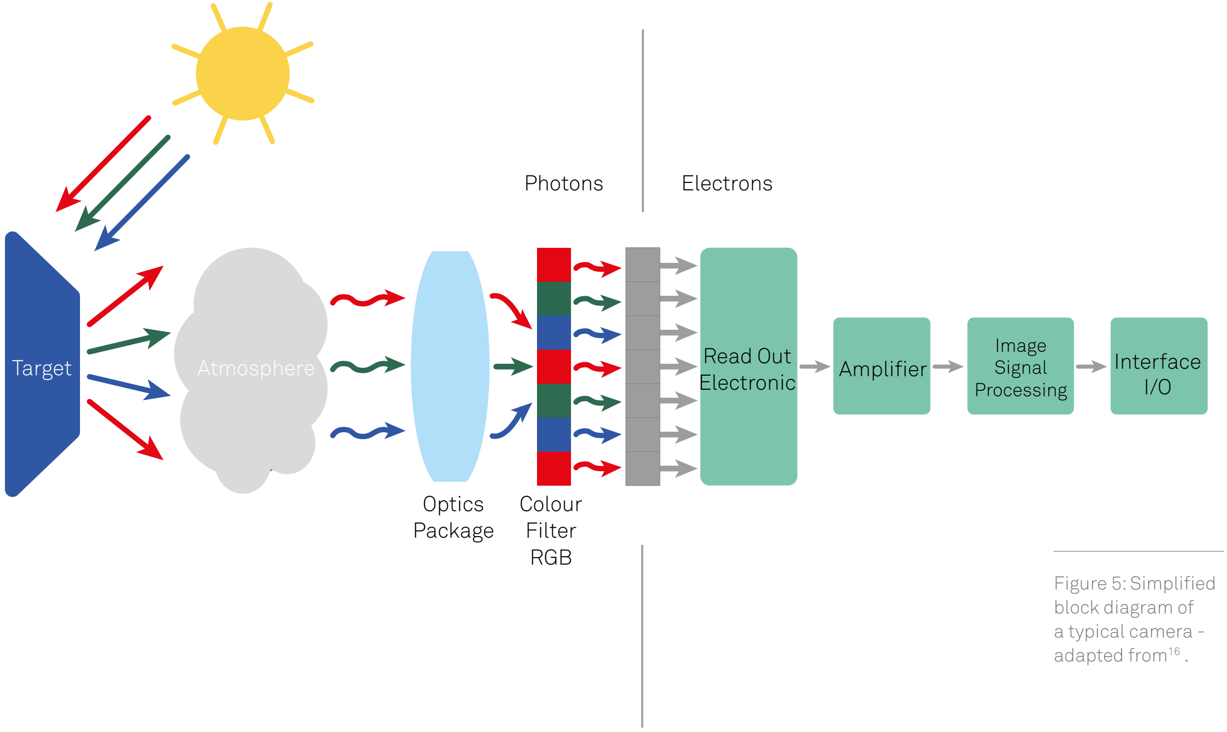

Figure 5: Simplified block diagram of a typical camera - adapted from[16].

As described in the following sections the components that can be characterised in camera sensors are the lens and detector, as well as the amplification stages (jointly). Camera systems should be analysed as whole systems as the module limiting performance varies with KPI. Significant challenges exist in assessing the performance of the ISP as the API is often proprietary and access to the raw data is often not available.

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[16] https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

Lidar

A simplified block diagram of a Lidar sensor is shown in Figure 6. Distance to an object is calculated from the “time of flight” for a laser signal transmitted to the object to be reflected back to the receiving system. The laser signal is typically either a pulsed waveform, or a frequency modulated continuous wave from (the latter being more robust to interference from sunlight or other lidar and providing a direct measurement of target velocity). The optical power output must be limited for eye safety reasons, and, for sufficient illumination at a distance, a low divergent laser with an optical system to scan the field of view is used. The system may integrate the transmission Tx and receiving Rx optical paths such the field of view of the detecting system matches the field of illumination. The detector comprises photodiodes, and as the received signal can be weak, photomultiplier technology may be used to provide a gain factor. The detector output is amplified and converted to a digital signal from which time of flight and distance to target are calculated.

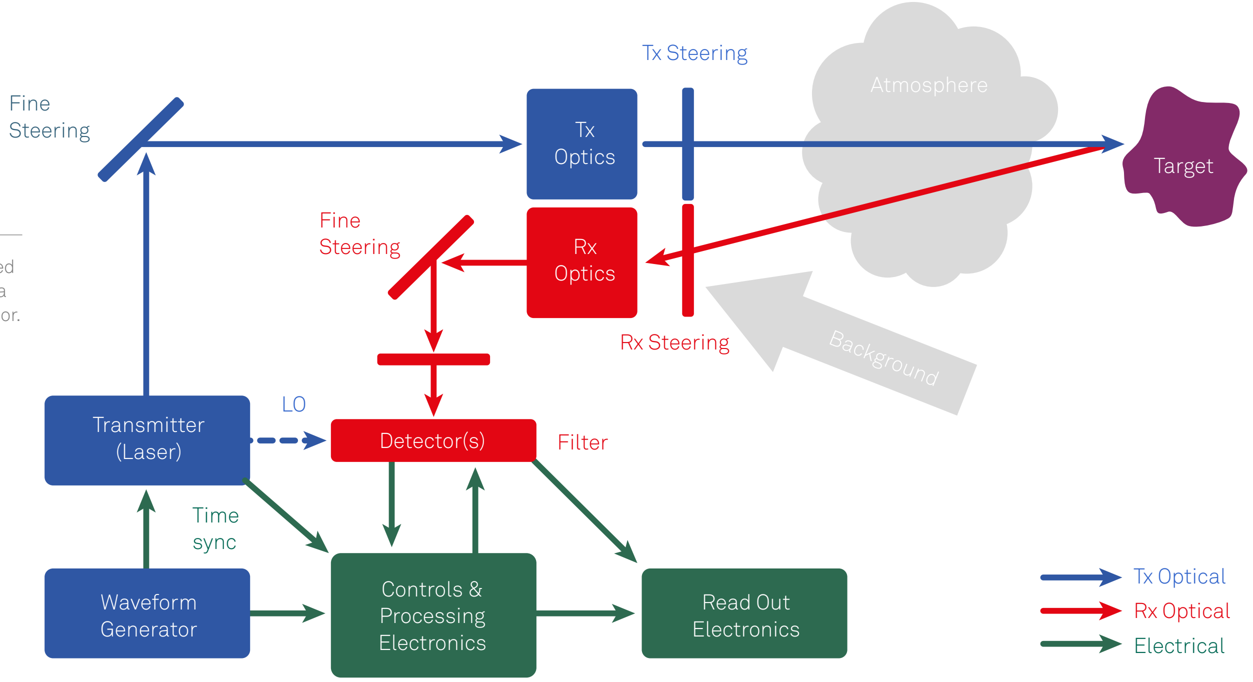


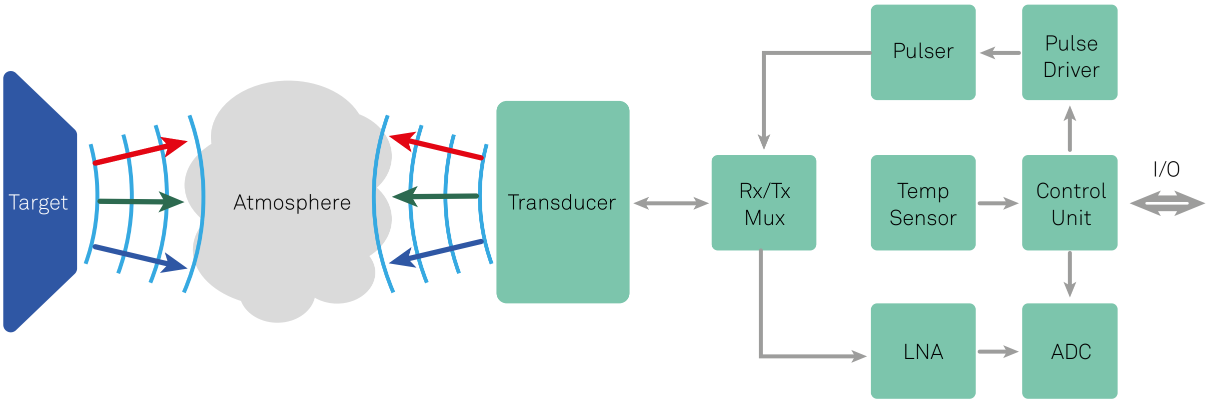
Figure 6: Simplified block diagram of a typical Lidar sensor.

Generally, lidar systems must be analysed as a single component; the digital signal processing is generally proprietary, and raw data at intermediate stages is not kept and is unavailable.

Ultrasound

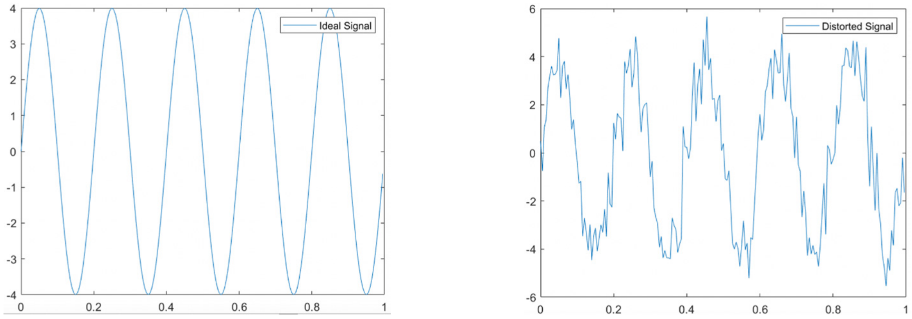
Ultrasound proximity sensor packages requires both a transmitter and receiver sensor (c.f. loudspeaker and microphone), but typically both functions are performed by a single reversible sensor that is switched between these modes.

Figure 7: Simplified block diagram of a typical Ultrasound sensor.



The principle of operation uses time of flight to determine the distance to the target. The sensor is a resonant device that is operated at its resonance frequency for maximum efficiency, which by design is set above 40 kHz (sufficiently higher than the upper frequency limit of human hearing of 16 kHz to 20 kHz). As transmitter, the sensor emits pulses of acoustic wave packets at its resonance frequencies. These pulse are emitted around 20 per second enabling time of flight detections in the null periods.

Figure 8: (a) Idealised and (b) practical form of signal used for proximity detection.



(a) (b)

Ideally the transmitter will stop emitting signal at the end of the pulse (Figure 8(a)), but in practice it continues for short time with a decaying envelop as it returns to rest (Figure 8(b)). This is called ringing and must be allowed to diminish before the receiver function can begin.

The receiver responds to the signal reflected from any nearby object to be detected. The time of flight and speed of sound determine the distance to the object. Since the speed of sound (between 330 m/s and 350 m/s for ambient temperatures between 0 ˚C and 30 ˚C) is significantly lower than the speed of electromagnetic waves, the time of flight over in the centimeter-range of distances is of the order of milliseconds for acoustic stimuli compared to nanoseconds for electromagnetic waves. Therefore, acoustic stimuli are more suited to detecting shorter distances for a given resolution in the time of flight detector.

Figure 9:
Illustrations of
mode of operation

The sound field emitted by the transmitted is very directional and forms a beam, rather than spreading in all directions. For a given size of sensor, this tendency increases at the operating frequency is raised. The ultrasound sensor is then essentially uni-directional. So, to cover a wide range of angles requires a number of sensors (typically 2-4 per side) to be deployed in a horizontal line array. Deploying multiple sensors on all 4 sides and corners of the vehicle provide for 360˚ azimuthal coverage.

Ultrasound sensors have traditionally been used as assisted parking aids, but application is evolving to use in automatic parking systems. The development of longer-range devices can provide close range obstacle detection capability for integration, alongside other sensors, into autonomous driving schemes.

3

Relevant KPIs

Key Performance Indicators of the perception system on board of a vehicle have been identified. These would need to be carefully tested and quantified in order to provide a reliable characterisation of the system. The identified KPIs can be grouped in the following areas:

- Sensor Capabilities;
- Advanced Sensing Capabilities;
- Operational Capabilities;
- Vertical Capabilities;
- Electromagnetic Compatibility;

For each area and sensor number of KPIs has been identified and are detailed in Appendix A.

4 Process and requirement for Testing and Calibration

In this section, after introducing facilities required for test CAV perception sensor, the process and requirements for testing and calibrating the KPIs identified in Section 5 and Appendix A are described.

4.1 Facilities required for Testing

The tests described in this report are examples and represent best practice to test key capabilities of perception sensors. The tests suggested have been designed assuming use of traditional testing tools, such as corner reflectors, waveform generators and anechoic chambers for radar, and ray-tracing, photometry and test targets for camera. For some KPIs near field testing can be used in order to extrapolate the far field behaviour of the sensor, however far field checkpoints would be required meaning that facilities allowing for this type of tests would be needed.

For some KPIs, a limited number of sector specific (automotive) perception sensors testing solutions are becoming available. These are taking the form of simulation and compact chambers suitable for over-the air echo generators or radar testbenches[17] which would represent cost-effective and fast solutions to test most of the capabilities of the radar in a hardware in the loop testing scenario. Another example of such a solution is the new inline testing tool for geometric distortion and 3d image reconstruction[18]. These innovations are market driven as sensor suppliers look to produce improved situational awareness for autonomous vehicles using advanced sensor based perceptions systems. The capital costs and requirement for skilled staff make them inaccessible for many SMEs.

However, current solutions cannot provide comprehensive testing of all the sensors' KPIs (i.e.: emulating real environmental conditions and robust testing of target recognition capabilities) and for this reason additional tests are need. Testing in other industrial sectors such as military, aerospace, astronomy, can serve as an inspiration or guide for the development of these advanced tests. Furthermore, improvements of test design for automation and inline testing has the potential to provide faster, cheaper and more effective characterisation of hardware performance in sensor systems.

However, significant unaddressed challenges will remain for testing and emulation of behaviour in complex atmospheric conditions, including rain, spray, fog, snow and heat etc. whether in compact or extended ranges.

4.2 Testing Procedures for KPI's

Test and calibration procedures for the KPIs identified in Section 5 and Appendix A are described in detail in Appendix B. In this section tests examples are reported, including suggestions for identification of failure modes and tests outside the recommended operational scenarios.

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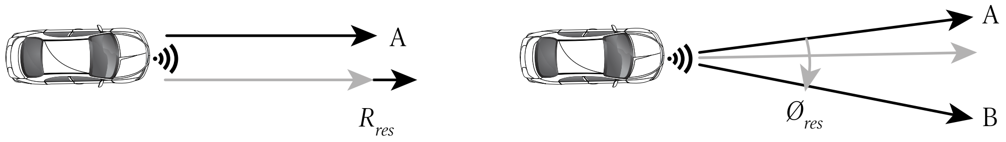
[17] https://www.dspace.com/en/ltd/home/products/hw/test_benches/radar_test_bench.cfm#144_41060
[18] http://www.imatest.com/solutions/geometric-camera-calibration/

Appendix B describes testing and calibration procedures for the KPIs of the four areas identified in Section 5, among these Range Resolution and Angular Resolution Testing have been selected as examples:

1. **Range Resolution:**

a. Radar:
In order to test and calibrate the range resolution, two corner reflectors closely spaced in range from the sensor should be positioned in front of the sensor. The range spacing of the two reflectors should be smaller than the nominal range resolution, in this case the test should demonstrate (by inspection of the range profile) that the radar is not able to discriminate the two reflectors in range. The test should be then performed with the corner reflectors spaced in range of the nominal range resolution. In this case the test should demonstrate the capability to discriminate the two targets in range (by inspection of the range profile). In the case that it would not be possible to discriminate the targets in range, then additional tests should be made increasing the spacing in range between the targets every time by 0.5 times the nominal range resolution until it becomes possible to discriminate the two targets, the minimum distance between the two targets when these can be discriminate will define the actual range resolution of the sensor. A representation of the test is shown in Figure 10-(a).

Figure 10:
Resolution
validation
examples.



(a) (b)

Figure 10. Resolution validation examples: (a) The range resolution is measured by increasing the distance between reflector B away from A and finding the minimum that the sensor can separate the two targets; (b) The angular resolution is measured by increasing the angular difference between targets A and B with the radar and finding the minimum that the sensor can separate the two targets.

b. Camera:
In order to test and calibrate the range resolution of stereo or multi-stereo cameras the procedure described in the radar chapter can be used, substituting using two closely spaced 18% Grey spherical targets for corner reflectors.

A combined measure of spatial and range resolution can be determined for stereo or multi-stereo camera system by measuring an extruded resolution chart at increasing distances around the maximum extent of 3D imaging.[18]

c. Lidar:
Testing and calibration of the range resolution of a Lidar sensor can follow the general method used for Radar, substituting retro-reflective targets in place of corner reflectors.

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[18] Chris Osterwood, "How to Choose a 3D Vision Technology," Carnegie Robotics (2017)

d. Ultrasound:

While ultrasound sensors are generally not able to discriminate different sources simultaneously, ISO 17386 describes test methods for the effectiveness of target detection across predefined zones to be monitored, at the rear, front and corners of the vehicle. It also defines test grids in both horizontal and vertical planes.

The test involves the use of cylindrical test objects (diameter 75 mm, length 100 cm or the width of the vehicle under test, as appropriate), which are mounted either perpendicular (100 cm lengths) or parallel (100 cm lengths for corners zones and vehicle width for front and back zones) to the level floor surface, at the each grid location in succession. The purpose of the multiple test positions is to map the areas where detection does and does not occur. Criteria are specified for the percentage coverage in each of the given zones.

2. Angular Spatial Resolution:

a. Radar:

In order to test and calibrate the angular resolution, two corner reflectors closely spaced in angle from the sensor should be positioned in front of the sensor. The angular spacing of the two reflectors should be smaller than the nominal angular resolution of the sensor. In this case the test should demonstrate (by inspection of the range/angle map) that the radar is not able to discriminate the two reflectors in angle. The test should be then performed with the corner reflectors spaced in angle of the nominal angular resolution of the sensor. In this case the test should demonstrate the capability to discriminate the two targets in angle. If the sensor is not able to discriminate the targets in angle in this case, then the test should be re-iterated increasing the spacing of 0.5 times the nominal angle resolution until it becomes possible to discriminate the two targets. The minimum angular separation between the two targets when these can be discriminated will define the actual angular resolution of the sensor. A representation of the test is shown in Figure 10-(b).

b. Camera:

The ability of a camera to spatial resolve an object is defined by the resolution limit of the optics, the detector and the electronics in combination. The diffraction limit or theoretical maximum resolution may be calculated directly from knowledge of the individual system components i.e. lens and detector. However real systems are non-ideal, and functional resolution should be determined by imaging appropriately illuminated ISO test charts: Geometric ISO 17850:2015, Resolution and Spatial Frequency ISO 12233:2017, and calculating the Modulation Transfer Function. Most resolution metrics are designed for grey-scale systems and colour has not been well integrated. Moreover, resolution does not account for other factors such as responsivity and atmospheric transmittance, which need to be considered in when trying to determine the accurate detection of targets. Stereo or multi-stereo cameras can struggle in low texture scenes reducing their functional resolution, in this case the use of Grid Spherical Targets may be useful[19] .

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[19] Zhen Liu, Qun Wu, Suining Wu, Xiao Pan, "Flexible and accurate camera calibration using grid spherical images," Opt. Express 25, (2017);

c. Lidar:

Testing and calibration of the angular spatial resolution of a Lidar sensor can follow the general method used for Camera, using an appropriate extruded resolution chart. Note that a lidar may have different angular resolution in the vertical and horizontal directions.

d. Ultrasound:

As indicated above, ultrasonic sensors are unidirectional and do not provide detection capability off-axis. Multiple angles are covered using an array of sensors pointing to different key directions (e.g. vehicle corners).

4.3 Failure Modes Identification

In this section, suggestions for methods to identify potential failure modes of perception sensors will be provided.

1. **Dynamic Range Saturation:**

a. Radar:

The dynamic range of a radar sensor could saturate in presence of a close large target (i.e. lorry) or in case of a strong interferer (another sensor or a jammer) within the receiver bandwidth, the effect of the saturation would be then the loss of the ability of the radar to detect any other target with a much weaker return (smaller or further away targets).
In order to identify the failure due to saturation of the dynamic range of the sensor the test should be performed using a strong source of interference (i.e. an autonomous waveform generator) emitting a signal at the same receiver carrier frequency. The emitted power should be controllable so that the expected power at the radar receiver should be known. A corner reflector target (RCS of 1 square meter) should be placed at the maximum detectable range as defined in Appendix B.1 point IV. The emitted power from the interferer should then be increased until the target is no longer detected by the radar, this will provide indication of the failure of the radar in case of strong interreference or large targets saturating the radar dynamic range.

b. Camera:

In the case of cameras, the dynamic range the system could saturate in presence of direct or reflected sunlight, or high-intensity vehicle lights. The effect of the saturation would be the loss of the ability of the camera to detect any targets either in a portion or the whole of the field of view. In order to identify the failure due to saturation of the dynamic range of the sensor a test should be performed using a suitably intense photometric source e.g. CIE Illuminant A, the emitted power and temperature should be well calibrated so that the power incident on detector is known. Suitable illuminated test charts should then be imaged, e.g. ISO 15739:2017 and ISO 18844, to determine performance.

c. Lidar:

The dynamic range of a lidar sensor may saturate in the presence of a close, highly reflective target, for example a reflective road sign, or in the case of a strong interfering source within the receiver bandwidth, including malicious attempts. The effect would be the loss of detection ability for a portion of the field of view. Fast saturation recovery of the lidar's receiver ensures that the system is not blinded longer than necessary. Two tests are suggested. The first to determine whether the sensor becomes saturated by a highly reflective target close to the sensor. The second test would use a strong controllable light source at the appropriate frequency to determine the level of power incident on the receiver at which saturation occurs (similar to the test proposed for Radar and Camera sensors)

d. Ultrasound:

Dynamic range saturation should not be an issue for ultrasound sensors since the same sensor is responsible for producing and receiving the ultrasound signal. Low transduction efficiency (a characteristic of all types of electroacoustic sensor) prevents any possibility of self-induced saturation.

2. Sensor Blockage by Foreign Matter:

a. Radar:

Foreign matter or objects may undesirably block one or more portions of the radar sensor transmit and/or receive antennas may block portions of the RF energy propagating to and from the transmit and receive antennas of the radar sensor. Such blockage may, for example, be the result of an accumulation, over a period of time, of foreign matter or objects in the region of an antenna aperture. Such foreign matter may be caused for example by environmental conditions such as temperature, humidity, ice, rain and the like. Such blockage can degrade, or in extreme cases even prevent, proper operation of the automotive radar sensor. If the foreign matter accumulates over time, there might be a corresponding gradual decrease in sensor system performance. Since the accumulation is gradual, it is sometimes relatively difficult to detect the existence of antenna blockage.

In order to assess the fault due to blockage of foreign matter, the setup suggested to test the maximum detectable range (Appendix B.1 point IV) should be used. In this case layers of dirt should be built in front of the radar embodiment with known thickness and moisture level. The thickness should be gradually increased up to the level that generates the loss of the detection of the target. Different moisture levels of the dirt could also be tested.

b. Camera:

In the case of cameras foreign matter or objects may block all or portions of the camera aperture. Randomly applied dirt, where diameter of the dirt is much less than that of the aperture, will gradually degrade the SNR and contrast response of the camera sensor; while not significantly effecting the resolution at low factional coverage. If the foreign matter is on the scale of the aperture significant points of the FOV will be obscured resulting in the partial or complete failure of the unit.

In order to assess the fault due to blockage of foreign matter, the setup suggested to test the maximum detectable range (Appendix B.1 point I & IV) should be used. The factional area covered should be gradually increased up to the level that generates the loss of the detection of the target.

c. Lidar:
In the case of lidar sensors, dirt accumulating over the lidar transmitter and receiver systems will gradually reduce the power of the received signal, degrading the SNR, eventually rendering the lidar inoperative. An equivalent test to that for radar and camera sensors may be used to determine the amount of accumulated dirt that leads to loss of detection of a test target at maximum recommended range.

d. Ultrasound:
Ultrasound is able to propagate through solid and liquid materials at least as efficiently as it does in air. Therefore, the light build-up of debris, moisture and ice should not interfere with the operation of the system. One potential cause of degradation could be that a heavy build-up of foreign material causes the ultrasound beam to scatter, reducing directivity and operational efficiency. The ISO 17386 test could be used to evaluate the impact of different types of debris on system performance, by comparing the percentage of area coverage scores for the contaminated sensor, with that of unoccluded sensors.

4.4 Test Outside Manufacturers Operating Scenarios

In this section examples of methods to test the perception sensors outside the manufacturer's recommended operating scenarios are given:

- **Example 1: Mechanical stress test**
  To perform this test, the setup used to assess the effect of mechanical instability of the sensor reported in Appendix B.3 point III should be used. In order to test the sensor KPIs outside the manufacturer's recommended mechanical operating conditions a set of stimuli outside the recommended range should be used and the tests depicted in Appendix B.1 for the capabilities IV, V, IX, X, XI, XII, XIII, XIV, XV and in Appendix B.2 for the capabilities I, II and III in presence of these out of range stimuli should be performed.

- **Example 2: Test on sensor embodiments different from recommended**
  This test would be aimed at testing the sensor's KPIs when the sensor is fitted in an embodiment different from the ones recommended by the manufacturer. The differences in the embodiment to be tested should be in terms of the material, its thickness and the distance between the embodiment and the radar RF frontend. The tests depicted in Appendix B.1 for the capabilities IV, V, IX, X, XI, XII, XIII, XIV, XV and in Appendix B.2 for the capabilities I, II and III should be replicated for the different embodiment conditions assessing the sensor's KPIs.

5 Performance levels

In this section the acceptable performance levels for the KPIs tested in Appendix B.1, B.2, B.3 and B.4 are described, while for the KPI in sections B.5 the ETSI standards should be followed for radar and lidar systems.

- **Performance levels for KPIs in Appendix B.1, B.2 and B.3.**
  - **Ideal:** Performance at 100% of the nominal performance indicated by the manufacturer or better (i.e. finer range resolution);
  - **Standard:** Performance between 100 and 80% of the nominal performance indicated by the manufacturer or calibrated performance in ideal conditions measured in adverse conditions (i.e. in tests depicted in Appendix B.3);
  - **Adverse:** Performance below 80% of the nominal performance indicated by the manufacturer or calibrated performance in ideal conditions measured in adverse conditions. (i.e. in tests depicted in Appendix B.3).

- **Performance levels for KPIs in Appendix B.4**
  - **Ideal:** The sensor respects standards for integration, passes all the on-board tests, is able to reliably self-calibrate and assess faults and it requires servicing less than once per year, ideally to be done during yearly vehicle testing (i.e. MOT test).
  - **Standard:** The sensor requires minimal amendments before being integrated, can be calibrated following the on-board tests, is able to reliably self-calibrate, identifies 80% of the fault conditions, and it requires servicing once per year, ideally to be done during yearly vehicle testing (i.e. MOT test).
  - **Adverse:** The sensor requires significant work to be integrated in the vehicle, fails on-board tests and cannot be calibrated in order to pass them, does not account for self-calibration or does it incorrectly, is not able to identify at least 80% of the fault conditions and requires servicing more than once per year.

6

Reliable, Validated Sensor Models for simulation testing

A major challenge for pure computer simulation is the modelling of the modern autonomous vehicle sensor suite. This confirms the importance of a standardised approach to sensor and weather characterisation.

Sensor models for virtual testing are different from many applications of modelling, because the user of the models generally cannot change the operation of sensor (other than by exchanging it for another sensor), and so does not care why or how it is doing what it is doing, whereas many models are used either to design an object or to control a process so that understanding the link between cause and effect is a lot more important. This difference affects the model types that are of most use for sensor modelling for virtual testing.

The aim of the model is solely to reproduce the behaviour of the true sensor, rather than to explain that behaviour or to provide guidance on how to achieve a particular performance level.

Virtual testing of autonomous vehicles is clearly a safety-critical application, and so every aspect of the modelling and software associated with the application must be tested and documented to the highest standards. For physics-based models, this means a complete mathematical specification of the equations being solved, a list of the assumptions made in their derivation, any input parameters, and a description of the methods used to solve the equations. For data-driven models it means that mathematical form of the model and all parameters must be specified, and a specification of the measurement data on which the model is based and the method used for parameter estimation should also be supplied. In both cases a test specification and associated results should be supplied. In order for the reliability of decision-making to be quantified, the uncertainties associated with the sensor model outputs must be evaluated so that the decision-making process, whether human or AI, can use this information to inform its choice.

Modelling of sensors for simulation of autonomous vehicle testing is a good example of an application that is well served by a predominantly data-driven model. This is because a typical sensor would contain a range of elements (e.g. reactive elements, stimulus, probing systems, signal processing etc.) and in general the detailed nature of these elements and how they are connected together is not available to the end user of the sensor, usually because it is proprietary information. It would therefore be difficult to construct a reliable model of the system that was purely physics-based. Hence a data-driven approach is preferable.

Sensor models for virtual testing essentially act as an interface between the vehicle AI and the artificial testing environment. If testing is to be set in a regulatory environment, each of the information flows within this figure will need to be in a standardised form so that the system for test can easily be integrated into the test environment.

The full analysis on sensor models can be found in Appendix D.

Recommendation 2 and 3:

***Recommendation 2:* A short time frame project is undertaken as a proof of concept for a usable and reliable framework for characterising sensor performance in different weather-related conditions.**

***Recommendation 3:* Establish a programme to deliver a usable and reliable framework for characterising sensor performance in different weather-related conditions, including the ability to assess performance outside the design envelope (dependent on recommendation 2).**

All CAV sensors have their performance reduced by adverse weather to some extent or another and so weather information is a key consideration in the development and operation of CAV's, as well as other intelligent mobility solutions.

There is a need for a more structured and quantitative approach that provides a traceable link from observable weather to CAV impacts at the vehicle, fleet and network level; and in turn to understand and validate sensor performance and downstream AI-based perception systems under different conditions.

The Met Office have already been engaged on the challenge of understanding the impact of weather conditions on CAV sensors/perception systems and have been consulted on this study and have provided substantial feedback into this section of the report.

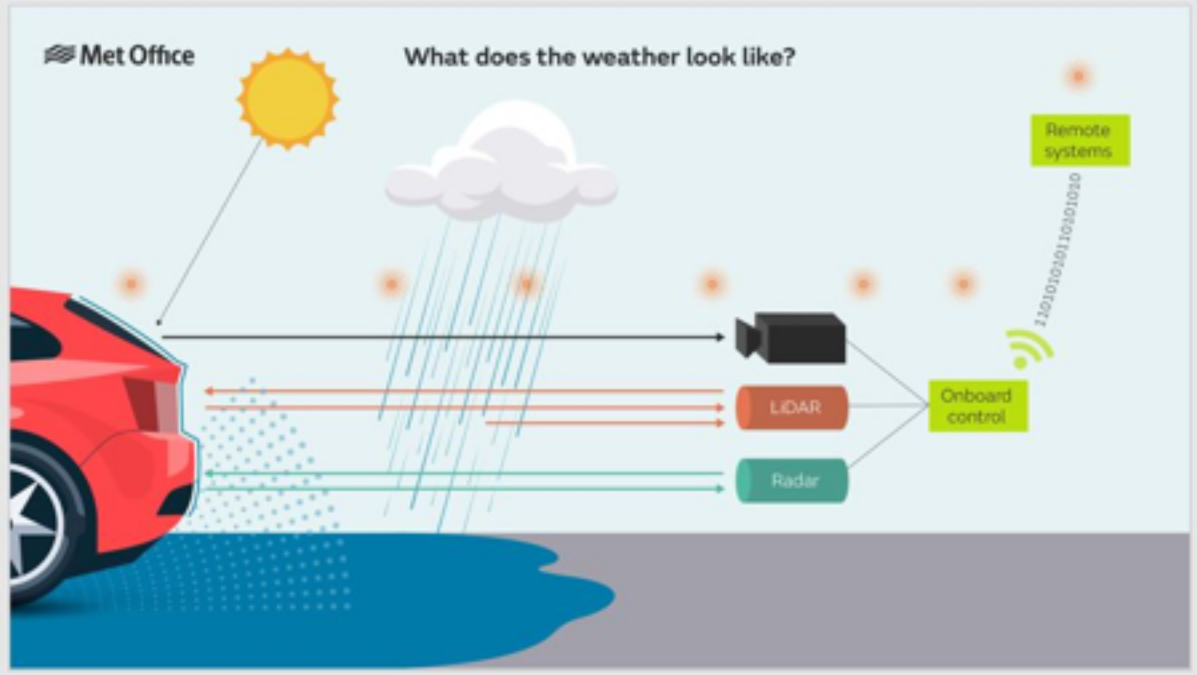

Figure 11: Indicative image of different impact of weather types on sensors.

(image Courtesy of The Met Office)

The view, also shared by the report authors, is that as the number of connected vehicles and their on-board sensors increases, there will be an unprecedented ability to form a detailed and timely picture of the CAV-relevant environment. Key areas to focus research and development on are:

- Characterisation of the relationship between observable weather phenomena and CAV system impacts at the "traffic scale", in order to adequately inform the Operational Design Domain (ODD)
- Development of a UK (and world) climatology of edge case weather, fully expressed in terms of CAV impacts
- Development of meteorologically-based CAV sensor (and AI) performance standards
- Development of test protocols that provide a traceable link between CAV standards and real-world system performance, including the creation of a "CAV meteorological testbed" and reference virtual environments
- Maximisation of the use of 'traditional' meteorological data and CAV sensor data to ensure the safe and efficient operation of individual CAV vehicles and contribute to the enhancement of the UK National Meteorological Service for the wider public good
- Development of demonstration meteorological data and consultancy services which might form the basis of a future market in CAV information services "

A usable and reliable framework for characterising sensor performance in different weather-related conditions is therefore recommended. *(Recommendation 3)* Uses of this framework include validation, safety assurance and simulation testing of AV. Underpinning this would be a standardised methodology for the characterisation of sensors, such as the one outlined below, which requires a common approach for testing, calibration, definitions, facilities and data quality.

The propagation of uncertainties in sensor performance through to the performance of perception algorithms and autonomous decision making must be understood and then reflected in the setting of pragmatic industry standards. Through direct engagement with current UK stakeholders and trials, this will ensure the framework's usability and acceptability, early in its development.

The programme stages would likely evolve as follows:

- **Definition:** e.g. taxonomies, technical descriptions. Looking at weather - putting sensor suites (use of representative instrumentation) with artefacts, data capture infrastructure, correlation with weather types/conditions
- **Model:** i.e. "if you are characterising your sensor for the market these are the models you must work to, because this is what will be tested." Development of technical definitions which organisations (such as sensor manufacturers/designers) can access, e.g. loss, high and low side of sensor capability.
- **Specify/build:** Representative or prototype facilities either made or specified. e.g. small boxes; compact chambers; artefacts; software/computing requirement.

Prior to a fully costed development programme, it is recommended *(recommendation 2*) that a short time frame project is undertaken as a proof of concept for this testing and data framework to demonstrate with market input, and at an early stage, the ability to process complex multi-dimensional data sets to enable sensor performance characterisation as well as modelling for simulation across different weather conditions:

- Common taxonomies for relevant weather types (i.e. how CAV sensors are affected) and technical descriptions underneath these.
- Technical definitions which can access, e.g. loss, high and low side of sensor capability.
- Specification of set of representative or prototype tools and facilities.

Recommendation 4:

Development of technologies which can repeatably recreate the weather conditions encountered by CAV sensors in physical test environments.

A brief review of how existing test sites (internationally) emulate weather conditions was undertaken. The conclusions are the UK is in a position to build on the experience they have gathered and combine this with the programmes for weather models outlined above. This would enable the UK to offer facilities dedicated to testing CAV under different weather conditions, which were a reliable representation of the impact of those conditions. It is also clear that such test facilities are part of the verification solution to complement the work of the testbeds.

See Appendix E for review details

Recommendation 5:

A programme to create a Government/industry co-funded environmental testing infrastructure, to support both development and performance characterisation of single sensors and the testing and validation of sensor suites and whole vehicle systems.

There exists an opportunity for testing facilities to validate the performance and limitations of CAV sensors specifically as existing capabilities tend to cater for the whole vehicle test requirements. It is evident that existing overseas facilities are limited in their ability to cater to demand for testing perception system performance.

CAV perception sensors testing facilities currently available are unable to provide complete testing scenarios required for the automotive industry. To adequately test the performance of sensor systems, through their development and integration cycle, there needs to be a diverse ecosystem of testing facilities; from bench top and compact chambers for development, calibration, and validation; to large centres for functional verification when integrated. There is a particular weakness in the ability to emulate weather conditions. Moreover, appropriate physical definitions of weather-conditions so that they are adequately emulated and simulated must be developed.

Large environmental “sheds” in which different weather conditions can be simulated would provide great value for testing and calibration given the capability to control the environment. Despite the cost of such a facility, in the long term the benefits for testing and calibration would allow the full characterisation of the autonomous car as well as provide support for validation and development of novel technologies. Furthermore, such a facility would avoid the need for industry to test vehicles in remote areas (where severe weather is more frequent), with impact on costs and logistic.

In conjunction with the large environmental “shed”, a number of compact test chambers should also be developed, these would have the capability to test the different KPIs. These could be not only used for the entire vehicle characterisation but industry can also use it for sensor characterisation and certification (i.e. when a novel algorithm that would be released as an updated to vehicles on the road).

The tests described in this report are examples and represent best practice to test key capabilities of perception sensors. The tests suggested have been designed assuming use of traditional testing tools, such as corner reflectors, waveform generators and anechoic chambers for radar, and ray-tracing, photometry and test targets for camera. For some KPIs near field testing can be used in order to extrapolate the far field behaviour of the sensor, however far field checkpoints would be required meaning that facilities allowing for this type of tests would be needed.

For some KPIs, a limited number of sector specific (automotive) perception sensors testing solutions are becoming available. These are taking the form of simulation and compact chambers suitable for over-the air echo generators or radar testbenches[21] which would represent cost-effective and fast solutions to test most of the capabilities of the radar in a hardware in the loop testing scenario. Another example of such a solution is the new inline testing tool for geometric distortion and 3d image reconstruction.[22]

These innovations are market driven as sensor suppliers look to produce improved situational awareness for autonomous vehicles using advanced sensor based perceptions systems. The capital costs and requirement for skilled staff make them inaccessible for many SMEs However, current solutions cannot provide comprehensive testing of all the sensors' KPIs (i.e.: emulating real environmental conditions and robust testing of target recognition capabilities) and for this reason additional tests are need. Testing in other industrial sectors such as military, aerospace, astronomy, can serve as an inspiration or guide for the development of these advanced tests. Furthermore, improvements of test design for automation and inline testing has the potential to provide faster, cheaper and more effective characterisation of hardware performance in sensor systems.

However, significant unaddressed challenges will remain for testing and emulation of behaviour in complex atmospheric conditions, including rain, spray, fog, snow and heat etc. whether in compact or extended ranges.

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[21] https://www.dspace.com/en/ltd/home/products/hw/test_benches/radar_test_bench.cfm#144_41060

[22] http://www.imatest.com/solutions/geometric-camera-calibration/

4 Appendices

The Appendices for the report can be downloaded as a document ***here,*** *containing the following:*

A. Sensor Capabilities Definitions

B. Sensor Capabilities Testing Methodologies

C. Market Analysis Detail

D. Sensor models for virtual testing

E. Informal commentary on facility capabilities

Notifications

The authors would like to thank the organisations who took part in workshops or interviews and provided valuable input for this work.

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