Toward metrological trustworthiness for automated and connected mobility

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# Toward Metrological Trustworthiness for Automated and Connected Mobility

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## Abstract

*The mobility of people and goods is moving into a new era of more automated services based on sensors networks and Artificial Intelligence.*

*At present, Automated Mobility, in the broadest meaning of the terms includes Advanced Driver Assistance System (ADAS) and Autonomous Vehicle (AV), beyond being attractive for many practical advantages, ranging from safety to traffic flow management, still presents several concerns on the trustworthiness of sensor networks integrated into vehicles, especially regarding sensors calibration, data uncertainty and data fusion approaches.*

*Currently, the trustworthiness of ADAS and AV functions is assessed with virtual and physical simulation of functions relying on synthetic sensor models, simulated and measured sensor data and equivalent environmental conditions. During the lifespan of vehicles, environmental effects including possible accidents and common usage, can have significant impact on the performance of ADAS sensors and customer functions. Current approach is to consider ADAS sensors output nominal, disregarding the uncertainty of sensors data and including all the possible tolerances and variability at sensors/system testing stage.*

*At present day, market offers several facilities and commercial set-up promoted as being able to do ADAS calibration: usually are modular equipment allowing alignment and sensitivity check of different ADAS sensors, especially front sensors and camera. However, sensor calibration involves specific calibration facilities, procedures to establishing sensors sensitivity and most of all, associated uncertainty. Accuracy and traceability of ADAS sensors beyond being fundamental requirements in measurement science, allow the quantitative evaluation of the trustworthiness of sensors and customer functions.*

*This paper suggests an approach to lay the foundation of Metrology of Trustworthiness for ADAS and AV complex sensors systems and provide a case study of IMU sensor trustworthiness.*

## Introduction

Attributes of Accuracy, Precision and Sensitivity are usually used to describe the metrological performances of sensors: *accuracy* describes the closeness of agreement between a measured quantity value and the reference value (def. 2.13 in [1]); *precision* quantifies the width of data dispersion (scattering of data) of the measured quantity value (def. 2.15 in [1]) ;and *sensitivity* is defined as the ratio between the change in the sensor output (indication) and the corresponding change in the value of the measurand (def. 4.12 in [1]). Figure 1 is a schematic representation of the metrological concepts of Accuracy and Precision applied to a series of measurement results: the empty circles represent the reference value of a quantity with uncertainty at different levels of coverage factors, while the full circles are the different measurement values.

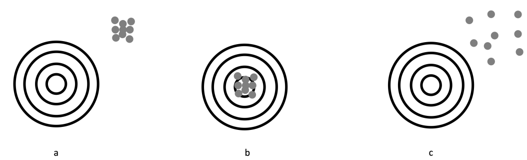


***Figure 1.*** *Representation of metrological attributes of Accuracy and Precision of measurement results. The empty circles represent the reference value and its different uncertainty coverage factors, the full circles are the measured values: a) good precision, poor accuracy; b) good precision, good accuracy; c) poor precision, poor accuracy*

As of now, Advanced Driver Assistance System (ADAS) and Autonomous Vehicle (AV) sensor performances are assessed at the manufacturing stage with the manufacturer's own testing procedures: sensors sensitivity is provided and then implemented into customer functions. Sensor's Manufacturers provide minimal data on actual sensor performances, also under different stressing environmental conditions: currently, component-level descriptions of performance criteria exist, but do not represent the actual needs for such complex in-field applications and typically do not include the sensor data fusion and metrological performances are mostly only expressed as sensor sensitivity, and accuracy and precision are disregarded.

Roadworthiness of ADAS, AV is then assessed with virtual and physical simulation of customer functions relying on synthetic sensor models, simulated and measured sensor data and equivalent environmental conditions [2] testing of all possible scenario and perturbations.

All these inputs are considered nominal (i.e. without uncertainty): neither in the sensor models, nor in sensor data, nor in environmental conditions simulation, the uncertainties are taken into account for the virtual driving scenario; all inputs are perturbed in order to enlarge the casuistry and scenario. The uncertainties are neglected because there is no availability of a recognized approach to their evaluation for this specific topic, additionally a measurement infrastructure for calibration and characterization is currently not available.

The measurement uncertainty is (def. 2.26 in [1]): "*non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used*". The current approach to the evaluation of measurement uncertainty is " *that the information from measurement permits assignment of an interval of reasonable values to the measurand, based on the assumption that no mistakes have been made in performing the measurements* " [1] by defining a measurement model [3]. This is very different from the previous Measurement Errors

Approach, where the target was to estimate the true value of the measurand and its deviation due to random and systematic errors.

The uncertainty is a quantifiable attribute of the quality of the results of a measurement: it enables the comparability of the results and to maintain quality control and quality assurance in production. But for the special case of ADAS and AV applications it will enable also the assessment of sensors data and customer functions trustworthiness.

A National Metrological Institutes (NMI) is an "*institute which is by national decision responsible for developing and maintaining national measurement standards, providing internationally recognised traceability to the SI, ensuring the suitability of these standard for national needs and providing metrological expertise and knowledge to national users through high level calibration services, advice, training and other assistance*" [4].

A calibration is an"*operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication*" of a sensors or measuring device (def. 2.39 in [1]).

NMIs and Accreditation Organization ensure calibration services, with a traceability chain starting at SI (International System of Units) for all base and derived quantities, for given ranges and conditions. Currently no dedicated calibration facilities, procedures and uncertainty evaluation, or traceable data-sets are available at NMIs level for the specific case of ADAS sensors. Currently calibration services (and uncertainty evaluation methods) based on a well distributed network of accredited laboratories in the different countries, are available only for instruments used in traffic monitoring ("speed trap") but cannot be directly applied to RADAR used in ADAS.

Sensor manufacturers, transport system industry, and vehicle makers have acknowledged the importance of developing a set of common methodologies for characterizing sensor performance, also under different conditions, to integrate physical sensors and sensor models in simulations. Standard Developing Organizations recognized the need for a new approach in standardization and have set up new technical committees and Working Group. IEEE P2020 group is committed to define fundamental sensor attributes and new metrics based on Key Performance Indicators (KPI) to compare digital camera performances for ADAS applications.

Obviously, a standardized performance metrics, in term of KPIs and reference conditions, would facilitate the understanding of sensors behavior and product comparison, however additional contributions from the metrology community are necessary. Metrologist should collaborate with industrial stakeholders to develop calibration procedures and facilities, to provide uncertainty assessments, to ensure the traceability to SI quantities of ADAS sensor measurements, and to define requirements for sensors and systems trustworthiness. By defining a reference conditions it would be possible, also for the sensor manufacturers, to provide statements on sensor's accuracy and precision for the given condition of application.

## Trustworthiness

The Trustworthiness is a quantitative indication of the reliability of measured data, for ADAS applications it provides indications on the reliability of the data provided by sensors, but should be extended also to the assessment of reliability of Machine Learning (ML) processes. The uncertainty expresses the quality of measured data, but does not provide indication on the reproducibility and mutual agreement of the results. The metrological community (NMIs and accredited laboratories) frequently conduct Proficieny Tests (PT) and Inter-Laboratory Comparisons (ILC) to ensure reproducibility and mutual agreement of the results achieved through different measurement methods [5]. A ILC "*evaluation of calibration/test results for the same or similar item by two or more laboratories in accordance with predetermined conditions*" [1] [6]. The approach of data Trustworthiness allows to combine the concept of data uncertainty with the concept of data comparability, providing awareness on the actual reliability of data.

A trustworthy automation system will be so founded on the inherent reliability of its components, elements, and interconnected sensors, and on the quality of data acquired, transferred, processed, stored and distributed. The knowledge of metrological attributes, such as accuracy, precision and traceability of sensors interfacing with the physical world and environment, allows improving the quality of data provided, with information on uncertainties, confidence levels, traceability and sensitivity, supplied by calibration procedures and metrological characterizations, while PT and ILC ensure not only the soundness of the results but also their trustworthiness.

Trustworthiness of ADAS sensors data can be achieved by a well defined metrological structure able to ensure sensor calibration (including uncertainty statement), agreed calibration and characterization procedures, substantial KPI with uncertainty statements, and reference testing conditions. More in general calibration and measurement principles and practices widely adopted and agreed are the core structure to ensure trustworthiness of data [5] [7] [8]. Subsequently the sensor trustworthiness should be extended to AI - ML algorithms used in AV, and ADAS, by investigating the impact of sensors data uncertainty on data fusion and AI decisions. To have a trustworthy system is not only a matter of having a calibration statement, but having a trustworthy system ensure the mutual agreement on the results (i.e. the actual AV, ADAS driving performance) even if the sensing technology and algorithms are fundamentally different.

To facilitate the validation and development of trustworthiness approach it is also necessary to define a framework of standard documents for sensors (and sensors networks) calibration and performance verification and AI trustworthiness. Standardization relating to ADAS , AV and ML is generally at an early stage and it is mostly performance-driven, only recently Standard Developing Organisations (SDOs) acknowledged a new approach not only performance and operability driven, but also on performances inclusive of new needs of safety and comparison among different smart and connected applications, systems, and sensors. European Community, just released a strategy document for AI trustworthiness [9], while IEEE P2020 is going to present prerelease on Camera characterization KPIs that will enable comparison among different camera products.

## Trustworthiness for ADAS sensors

### *Current situation and future needs in ADAS sensors calibration*

ADAS performances may be affected by sensors misplacement, usage, car accident, bodywork or even windscreen replacement. Currently, several commercial services are available for ADAS *calibration*, mostly based on reference equipment with different tags and pictures to be placed at a given distance from the car. The commercial services available offer, trough vehicle manufacturer procedure (for authorized workshop) or by reference equipments, ADAS checking and realignment. These operations cannot be defined as *calibration* by the definition of Vocabulary of Metrology [1], but instead are *validation* " *provision of objective evidence that a given item fulfils specified requirements adequate for an intended use*" (Def. 2.45 in [1]) . Companies developing high level of automation, namely L4 and L5 perform daily validation of AV system and sensors, this further underlines the relevance of metrology in the development of AV and ADAS as also stated in [10].

Calibration services, with the traceability chain starting at NMIs level, are not available for ADAS sensors applications in automated driving framework [10]. NMIs have well established procedures, Calibration and Measurement Capability (CMC) and ensure calibration services dissemination also for the quantities measured by ADAS sensors: length, velocity, and vibration, but not suitable for the peculiarities of ADAS. A CMC is a declaration, made by a NMI or a laboratory, on the calibration and measurement capability available to customers under given conditions [11]. CMC at NMI level are published in the Bureau International Poids et Measure (*BIPM- the international organization established by the Metre Convention, through which Member States act together on matters related to measurement science and measurement standards* [13]) Key Comparison DataBase (KCDB) web site [12]. Each CMC is related to a given quantity and range with the associated measurement uncertainty, method or instrument used for realization and any other relevant information, every CMC is supported by several ILC. For accredited laboratories CMCs are described in the laboratory's scope of accreditation granted by a recognized accreditation organization, CMCs reflect the metrological services actually available to customers. CMC published in the KCDB ensures the direct involvement of NMI in the dissemination of the quantity and calibration service: currently no CMC is declared for the special case of ADAS sensors related quantities, ranges and peculiarities (i.e. methodologies, and facilities).

Additionally ADAS sensors have digital outputs: traceability of digital sensors is a metrological challenge [8] and a priority for BIPM. Traditional calibration procedures are not suitable for all digital sensors, which use digital interfaces for data and communications and whose output is given in digital units. BIPM and the European Association of Metrological Institutes, promote both the role of metrology in digitalisation and recognises that "the deployment of such systems needs to be underpinned by new metrology to support reliable and safe operation (including digital sensoring) and for underpinning traceability chains and quality management requirements" [14], [15], [16].

It is clear that in the current situation, to establish common definitions and glossary and to identify the measurable quantities and ranges, are the first targets: this will ensure more fruitful interaction among all actors in ADAS and AV development, but it needs the engagement of Standardization Organizations in the development of new and well agreed documents, testing procedures, requirements and KPIs for ADAS sensors.

Meanwhile NMIs should work to ensure an unbroken chain of calibration and characterisation facilities disseminated up to customer services with traceability to SI specific quantities. This structure needs afterwards to arrange at NMI level calibration and characterisation methodologies specific for ADAS sensors like RADAR, LIDAR, camera, Inertial Measurement Unit (IMU). The community of sensor manufacturers and end users will benefit from this metrological structure and of the new calibration services traceable to NMIs manufacturers' statements on sensitivity and batch performance will be improved by accuracy statement also related to batches. The metrological framework will also ensure not only comparability and reliability of results, two basic requirements for the foundation of the Common Mobility Data Space as requested by Connected Mobility and Smart Cities [17].

The last step will be to engage with the impact of uncertainty in ML and AI: measurements uncertainty can have not only impact on ML choices and functionality but it can be also useful in data flow to detect anomalies in digital sensors performances as well. This latter motivation should encourage manufacturers to engage even more

### *The case of IMU trustworthiness*

Inertial Measurement Units (IMU) are digital MEMS (Micro-Electro-Mechanical Systems) sensors used in Automotive applications are used to control simultaneously 3D accelerations, along with vertical and horizontal directions, and angular rate, around the same directions, of the vehicle. Currently very few European NMIs are able to provide proper calibration procedures with metrological traceability of digital IMU: INRIM (National Metrology Institute of Italy) and PTB (National Metrology Institute of Germany) are the two most engaged. At INRIM full calibration procedure and service is available for 3-Axis IMU accelerometers for both inertial and dynamic conditions, with the proper accuracy, precision and detailed uncertainty budgets [18]. The calibration set-up realised at INRiM, is based on a single-axis vibrating table on which an aluminum inclined plane is screwed, using an inclined plane a projection of the reference acceleration is possible to simultaneously calibrate the three sensitive axes of the sensor [18] by generating the projection of the single-axis excitation acceleration, along the three sensitive axes ($a_x$, $a_y$,$a_z$) simultaneously. A single vertical sinusoidal acceleration at nearly-constant amplitude on the vibrating table, acts as reference acceleration $a_{ref}$ along the vertical axis z' of the system (parallel to $g$). Figure2 shows the geometrical principle of the calibration method with the actual inclined plane on which the digital MEMS accelerometer is fixed during calibration.

Calibration is carried out at 5 Hz, 10 Hz, 20 Hz, 40 Hz, 80 Hz, 160 Hz, 315 Hz, 630 Hz and 1000 Hz, at nearly constant amplitude of 10 $\mathrm{m\,s^{-2}}$, along the vertical z'-axis of the system. Measurements are performed in 4 configurations, obtained by fixing the MEMS accelerometer to the center of the vibrating table at 4 different angles of rotation $\omega$ and at 4 different inclination angles (with inclination of 0°, 15° and 35°, with respect to horizontal axis), according to procedure described in [18] [19].

INRIM defined also a procedure for a full metrological char-

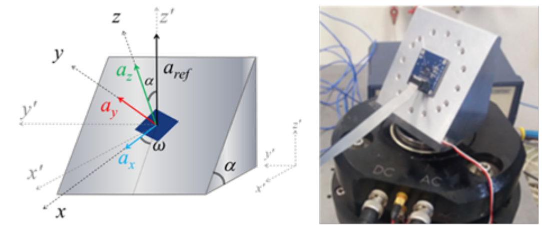

*Figure 2. The INRIM set-up for IMU calibration: 3-D scheme (left) and actual set-up (right): the MEMS is fixed to the inclined plane on the vibrating table*

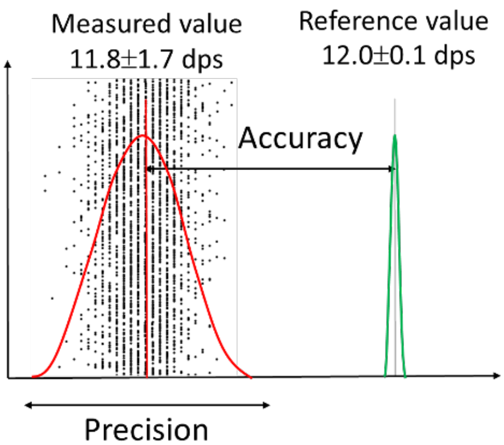


*Figure 3. Visualization of the Trustworthiness of an IMU at 12 dps rotation under dynamic condition of oscillation at 2 Hz*

acterization of IMU in static and dynamic conditions by combining gravitational and vibrational stimuli as described in [19], allowing the evaluation of sensitivity and data dispersion (stability of the sensor included) under different working conditions. Considering the aforesaid results of metrological characterization of IMU and its calibration and measurement uncertainty analysis, doing a comparison of the IMU output to a reference value it is possible to provide evidence of the trustworthiness of the IMU.

In general terms, once the IMU output is calibrated and its uncertainty stated, and the IMU behavior iunder different conditions is well known (namely the output data dispersion) it can be possible to evaluate the IMU trustworthiness by comparing the IMU outputs to the reference value (with its uncertainty), Figure 3 is an illustrative example of the trustworthiness of a calibrated and characterized IMU considering its output on the x-axis at 12 dps (degree per second) and assumed as reference value, when the IMU is subjected to a dynamic oscillation of 2 Hz.

As aforesaid Accuracy is a qualitative evaluation only, to achieve the goal of expressing the Trustworthiness is necessary to quantify also the comparability and reproducibility of data considering the "distance" of measured data from the reference condition, including the reciprocal uncertainties. Currently there is a large literature on how to evaluate the comparability and the Degree Of Equivalence (DOE) of results in ILC and Key Comparison, depending on the statistical distribution of measured results and of the reference value [20] [21].

## Conclusions

The trustworthiness of a sensor is the quantitative indication of the quality of data provided by the sensor itself, its evaluation requires not only the knowledge of the sensors data uncertainty, by also the sensor calibration. Today, information on accuracy, uncertainties, confidence levels, traceability, and sensitivity of ADAS sensors, are not fully available in general. So far, NMIs are not engaged in providing calibration chain and metrology structure up to testing laboratories. The current lack of suitable calibration standards, protocols, and procedures of characterization do not allow to fully implement an approach to ADAS sensor trustworthiness evaluation.

The evaluation of sensor trustworthiness needs the knowledge of all metrological attributes, such as accuracy, precision and traceability (calibration), and of their performances in complex working condition. Then with the application of the most appropriate statistical techniques for data analysis in ILC it is possible to acheive a quantitative evaluation of trustworthiness. The paper presents the results achieved by INRIM in IMU trustworthiness evaluation.

Being able to establish ADAS sensors trustworthiness, by also establishing calibration facilities and full metrological structure, it would increase reliability of data, open new market opportunities for accredited laboratories and help the development oh highly automated features. But also a huge and coordinate effort at normative level is needed to define the relevant conditions, KPI and reference conditions for sensors characterization and calibration. This task would be really suitable for a consortium of research institutes, industries involved in Autonomous Vehicle sensors development, standardization organizations and road authorities.

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