Proceedings

ATZ live

André Casal Kulzer
Hans-Christian Reuss
Andreas Wagner *Hrsg.*

2024 Stuttgart International Symposium on Automotive and Engine Technology

Teil 2

Springer Vieweg

Proceedings

Ein stetig steigender Fundus an Informationen ist heute notwendig, um die immer komplexer werdende Technik heutiger Kraftfahrzeuge zu verstehen. Funktionen, Arbeitsweise, Komponenten und Systeme entwickeln sich rasant. In immer schnelleren Zyklen verbreitet sich aktuelles Wissen gerade aus Konferenzen, Tagungen und Symposien in die Fachwelt. Den raschen Zugriff auf diese Informationen bietet diese Reihe Proceedings, die sich zur Aufgabe gestellt hat, das zum Verständnis topaktueller Technik rund um das Automobil erforderliche spezielle Wissen in der Systematik aus Konferenzen und Tagungen zusammen zu stellen und als Buch in Springer.com wie auch elektronisch in Springer Link und Springer Professional bereit zu stellen. Die Reihe wendet sich an Fahrzeug- und Motoreningenieure sowie Studierende, die aktuelles Fachwissen im Zusammenhang mit Fragestellungen ihres Arbeitsfeldes suchen. Professoren und Dozenten an Universitäten und Hochschulen mit Schwerpunkt Kraftfahrzeug- und Motorentechnik finden hier die Zusammenstellung von Veranstaltungen, die sie selber nicht besuchen konnten. Gutachtern, Forschern und Entwicklungsingenieuren in der Automobil- und Zulieferindustrie sowie Dienstleistern können die Proceedings wertvolle Antworten auf topaktuelle Fragen geben.

Today, a steadily growing store of information is called for in order to understand the increasingly complex technologies used in modern automobiles. Functions, modes of operation, components and systems are rapidly evolving, while at the same time the latest expertise is disseminated directly from conferences, congresses and symposia to the professional world in ever-faster cycles. This series of proceedings offers rapid access to this information, gathering the specific knowledge needed to keep up with cutting-edge advances in automotive technologies, employing the same systematic approach used at conferences and congresses and presenting it in print (available at Springer.com) and electronic (at Springer Link and Springer Professional) formats. The series addresses the needs of automotive engineers, motor design engineers and students looking for the latest expertise in connection with key questions in their field, while professors and instructors working in the areas of automotive and motor design engineering will also find summaries of industry events they weren't able to attend. The proceedings also offer valuable answers to the topical questions that concern assessors, researchers and developmental engineers in the automotive and supplier industry, as well as service providers.

André Casal Kulzer · Hans-Christian Reuss ·
Andreas Wagner
(Hrsg.)

2024 Stuttgart International Symposium on Automotive and Engine Technology

Teil 2

Springer Vieweg

Hrsg.
André Casal Kulzer
FKFS & IFS of University of Stuttgart
Stuttgart, Deutschland

Hans-Christian Reuss
FKFS & IFS of University of Stuttgart
Stuttgart, Deutschland

Andreas Wagner
FKFS & IFS of University of Stuttgart
Stuttgart, Baden-Württemberg, Deutschland

ISSN 2198-7432 ISSN 2198-7440 (electronic)
Proceedings
ISBN 978-3-658-45009-0 ISBN 978-3-658-45010-6 (eBook)
https://doi.org/10.1007/978-3-658-45010-6

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über https://portal.dnb.de abrufbar.

Springer Vieweg ist ein Imprint der eingetragenen Gesellschaft Springer Fachmedien Wiesbaden GmbH und ist ein Teil von Springer Nature.
Die Anschrift der Gesellschaft ist: Abraham-Lincoln-Str. 46, 65189 Wiesbaden, Germany

Vorwort zum Tagungsband des 2024 Stuttgart International Symposium

Der Bedarf an Mobilität wird mit wachsender Weltbevölkerung auch weiterhin steigen. Dies stellt uns aktuell vor große Herausforderungen angefangen bei der Nachfrage nach individuellen und regional sehr unterschiedlichen Mobilitätslösungen, über Ressourcenknappheit bis hin zu den von den Regierungen, weltweit festgelegten, zu erfüllenden Klimazielen.

Unter dem diesjährigen Leitthema „Global Mobility for Tomorrow“ präsentierten Experten aus Wissenschaft und Wirtschaft auf dem 2024 Stuttgart International Symposium neue, innovative Ansätze in der Fahrzeugentwicklung. Dabei wurde deutlich, dass der Fokus weg vom Produkt allein, hin zu Infrastruktur, Digitalisierung und Energieerzeugung erweitert werden und dass Mobilität zukünftig als Gesamtkette betrachtet werden muss. Globale Mobilität kann nur mit Hilfe von Technologieoffenheit, Vernetzung, Digitalisierung an individuelle Kundenwünsche angepasst und nachhaltig gestaltet werden.

Autonomes Fahren, Elektro- und Hybridantriebe, Nachhaltige Kraftstoffe, Kreislauf- und Lebenszyklusanalyse, Aerodynamik, Thermomanagement, sowie Cyber Security sind nur einige der Fachgebiete, zu denen auf dem Stuttgart International Symposium vom 2. bis 3. Juli 2024 im Haus der Wirtschaft, Stuttgart diskutiert wurde. Die entsprechenden Manuskripte zu ca. 45 Vorträgen und 10 Postern finden Sie nun in dieser Ausgabe.

Preface to the Proceedings of the 2024 Stuttgart International Symposium

The need for mobility will continue to increase as the world's population grows. This currently presents us with major challenges, from the demand for individual and regionally very different mobility solutions, to resource scarcity and the climate targets set by governments worldwide that are to be met.

Under this year's guiding theme of "Global Mobility for Tomorrow", experts from science and industry presented new, innovative approaches to vehicle development at the 2024 Stuttgart International Symposium. It became clear that the focus must be expanded away from the product alone and towards infrastructure, digitalization and energy generation, and that mobility must be viewed as an overall chain in the future. Global mobility can only be adapted to individual customer requirements and designed sustainably with the help of technological openness, networking and digitalization.

Autonomous driving, electric and hybrid powertrains, sustainable fuels, circularity and life cycle analysis, aerodynamics, thermal management and cyber security are just some of the specialist areas that were discussed at the Stuttgart International Symposium at the Haus der Wirtschaft in Stuttgart from July 2 to 3, 2024. The corresponding manuscripts of approx. 45 presentations and 10 posters can now be found in this issue.

Inhaltsverzeichnis – Teil II

Inhaltsverzeichnis – Teil I

Battery

Charging & Infrastructure

Chassis Systems

Circularity & LCA

Connected Vehicle

Cyber Security

Data Science & AI

Development Methods

E/E Architecture

Intelligent Sensors in Dynamically Reconfigurable Automotive Architectures: A Proof of Concept

Lennard Hettich(✉) and Michael Weyrich

Institute of Industrial Automation and Software Engineering (IAS), University of Stuttgart, Stuttgart, Germany
lennard.hettich@ias.uni-stuttgart.de, michael.weyrich@ias.uni-stuttgart.de

Abstract. The necessity of a reconfigurable software-defined vehicle platform that is no longer sold as a one-off, but can be continuously adapted to dynamic customer requirements during its lifetime, is becoming increasingly clear. Political and economic institutions have become aware of these needs and initiated actions in the context of contested markets with declining sales figures. However, according to our research, existing vehicle architecture concepts and frameworks do not cover the upgradeability, dynamic reconfigurability at runtime and continuous adaptability aspects of vehicle sensors to the necessary extent. Vehicle sensor technology constitutes the fundamental basis for safe decisions of autonomous driving functions, we therefore consider the importance of this topic to be significant. Building upon the existing service-oriented E/E architecture framework ROSMARIN, we want to contribute a concept extension, allowing the seamless integration of intelligent sensors in vehicles. In addition to requirements for intelligent sensor technology in flexible architectures such as Plug-and-Play of sensor hardware, upgradeability through virtualization of sensor software and runtime resilience, our concept furthermore integrates a novel generalized approach for dynamic sensor calibration and fusion. We prove our concept on a physical demonstrator setup with ultrasonic, LiDAR and camera sensors and demonstrate the upgradeability and reconfigurability of sensor hardware and software. In addition, we show the dynamic online fusion of camera and LiDAR data with minimal effort, while also proving the resilience and automatic adaptability of our approach in case of unforeseeable events like sensor failures.

Keywords: Intelligent sensors · Sensor upgradeability · Sensor interoperability · Reconfiguarable automotive systems · Service-oriented E/E architectures

A. C. Kulzer et al. (Hrsg.): ISSYM 2024 Proceedings, S. 3–19, 2024.
https://doi.org/10.1007/978-3-658-45010-6_1

1 Introduction and Motivation

Autonomous Driving (AD) is one of four disruptive technology-driven developments in the automobile industry, according to a 2016 study from Gao et al. in [4]. In an optimistic scenario, assuming the primary obstacles of cost, safety concerns, legality, and consumer acceptance can be addressed shortly, 5 million vehicles will be fully autonomous by 2030. Referring to the SAE Levels of Driving Automation™ taxonomy[1], which defines six levels of driving automation, fully AD premises a SAE Level $\geq$ 4, enabling local autonomous driving without the need of a human backup driver. The findings from the same study state that 10% of vehicles may be supplied with highly autonomous Advanced Driving Assistance Systems (ADAS) of SAE Level 3 by 2030. Such would allow for local autonomy with a human backup driver constantly available. As this technology is maturing, predictions from Burkacky et al. of the post-pandemic situation estimate a hundredfold increase in the number of vehicles with SAE Level 3 compared to the year 2020 [1].

Sensor technology provides the fundamental tools for perceiving the vehicle's environment alongside with roadside infrastructure and other road traffic actors, and thus allow for safe decisions made by ADAS and AD functionality [10, 19]. The predominant sensor types for ADAS and AD functionality encompass camera, radar, and LiDAR sensors [1]. As the complexity of ADAS and AD functionality increases, the number of sensors required for safe operation also grows. Figure 1 shows the estimated number of sensors necessary for different automation levels. While an average of 12–14 sensors are typically required for SAE Level 3 ADAS, this number is assumed to reach 34–38 for SAE Level 4–5 AD functionality [1,7]. Since individual sensors have significant limitations, it is crucial to utilize such a substantial amount of sensors for safe ADAS and AD functionality. To further increase the reliability and accuracy of the perception and to achieve a more holistic understanding of the vehicle's environment, the fusion of signals from multiple sensors is a widespread process in automotive. As a foundation and vital preprocessing step for fusion, sensor calibration describes the process for determining the sensors' position and orientation in the vehicle's coordinate system. Both sensor calibration and fusion are complex processes and therefore commonly conducted once during vehicle production with specific calibration setups [2,19].

Despite advancements in automated driving and sensor technology, one-time vehicle sales are currently stagnating, due to longer vehicle operating times and changing customer behavior besides economic hardships [3,12,16] and growing competitiveness from Asian countries [4]. Customer expectations for automotive systems are rising, as they demand more fine-grained configurability to meet their specific requirements [16]. This tendency applies throughout the entire vehicle's lifecycle: owners are progressively more conscious of recent advances in technology and anticipate the benefit of novel mobility features in their existing

[1] https://www.sae.org/standards/content/j3016_202104

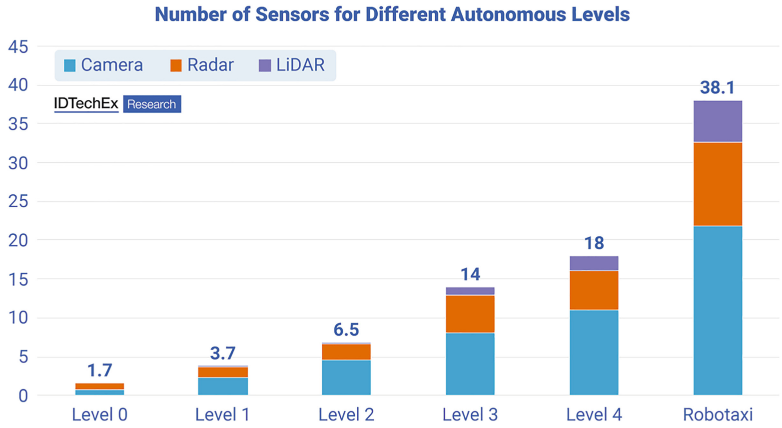

Fig. 1. Number of sensors for different automation levels, from [7]

vehicles, which are on average 12 years in operation[2]. Automotive players have to incorporate *mobility features as a service* and *after-sales* into their business models to stay economically viable in the future. While software will account for 90% of future innovations in the vehicle, the majority of those features will be software-based and can be offered through over-the-air (OTA) updates as a part of a subscription or one-time payment scheme [3,4]. Thereby, vehicle owners can ensure that their operating vehicles adhere to the most recent technological requirements despite the tremendous pace of innovation especially for software, even years after production [9,16]. Car manufacturers are already applying such business models: Tesla owners were offered an upgrade of the integrated parking assistant OTA to a vision-only version last year[3].

As a result of growing OTA upgradeability, individualization and diversification of vehicle systems, over hundreds of thousands of possible build configurations for a single vehicle will be generated, with mobility features as a service further increasing this number over time [3,16]. The resulting variability in the vehicle system is ultimately also reflected on vehicle sensors, as soon as configuration options are available for AD and ADAS functionalities. Car manufacturers will encounter numerous challenges as a result of the increasing variety of sensor configurations and number of sensors in vehicles [3].

We consider the most compelling questions to be, first, the *assurance of continuous reconfigurability and upgradeability of sensors (RQ1)*. Countless different sensor configurations may be realized in future vehicles, posing the question for concepts to achieve this as flexibly, seamlessly, and effortlessly as possible. Second, the *resilience and adaptability of those sensor configurations at runtime (RQ2)*, as preventive testing measures are progressively insufficient to uncover

[2] https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/

[3] https://www.autoevolution.com/news/tesla-s-high-fidelity-park-assist-in-the-2023-holiday-update-is-just-the-beginning-226211.html

all faults and deficits in vehicles [3,16]. Instead, sensor systems progressively need to respond to potential failures, alterations and sensor signal degradations with adaptive capabilities and resilience automatically at runtime [12,14]. Third, the *dynamic interoperability between sensors (RQ3)*. Determining which sensor signals should be optimally fused becomes more challenging as the number of sensors in the vehicle increases, alongside the variety of possible sensor configurations[4]. The upgradeability of sensor technology adds another level of complexity, which makes one-time sensor calibration during production no longer sufficient.

Our research findings indicate that efforts for developing suitable vehicle architectures for future vehicles have been made. However, current solutions are not sufficiently covering the aforementioned sensor challenges and research questions so far. Thus, we propose the following contribution for this paper:

Contribution: This paper presents a novel approach for the realization of dynamically upgradable, reconfigurable and resilient sensor technology in vehicles. By leveraging the concept of intelligent sensor technology, we propose a seamless extension to an existing architecture concept for future vehicles while also supporting dynamic online calibration and fusion of sensors. We prove our concept on a physical demonstrator setup with multiple sensors, showing the upgradeability and reconfigurability of sensors as well as a dynamic online calibration and fusion of camera and LiDAR sensor data.

Outline: The publication is organized as follows: Chapter 2 contains an explanation of the technical background, where we discuss relevant aspects of sensor technology. Chapter 3 provides an overview of existing architectural frameworks and an assessment of their suitability as a basis for our concept. In Chaps. 4 and 5, we concretize our requirements to our concept and subsequently present it. We conclude with the proof of our concept on a physical sensor setup in Chap. 6 and provide a conclusion as well as an insight into possible future research activities and directions in Chap. 7.

2 Technical Background

2.1 Sensor Technology in Autonomous Vehicles

Sensor technology can detect events or alterations in their application environment and transform those into a quantified measurement value. In autonomous vehicles, sensors are critical for acquiring information about the vehicle's environment, such as the presence of road infrastructure, other vehicles or pedestrians, alongside their position relative to the vehicle [2,19]. On the basis of this information, an autonomous vehicle can localize itself in a local or global reference frame, calculate the optimal behavior, and subsequently control its own movement. Autonomous vehicles primarily deploy camera, radar, and LiDAR sensors

[4] https://semiengineering.com/how-many-sensors-for-autonomous-driving/

to perceive the environment [10,19], while ultrasonic sensors still have significance, but are progressively replaced by more advanced solutions[5]. Other sources also mention the use of thermal and infrared cameras[4]. It is evident that a significant number of sensors is required to achieve a comprehensive perception of the vehicle environment. The Mercedes vehicle models with SAE Level 3 ADAS as options, for example, incorporate 8 cameras, 5 radar, and one LiDAR sensor [7]. The detailed discussion of the individual sensor technologies, as well as their strengths and weaknesses, is beyond the scope of this paper (see [19] for more details). Sensor application has seen major advances in recent years, fueled by the increasing performance of sensor technology, while simultaneously prices are eroding, particularly for LiDAR sensors. By leveraging solid-state technology, LiDAR producers such as the Israeli company Innoviz[6] as supplier for BMW are already capable of reducing the price of high-resolution 3D LiDARs to less than 1,000 USD [1].

2.2 Sensor Calibration and Fusion

Individual sensors show mayor uncertainties when perceiving the vehicle's environment, depending on their specific strengths and weaknesses [2,19]: cameras, for instance, prove excellent object recognition and classification capabilities but fail in challenging light conditions and lack distance perception while LiDARs can provide accurate distance measurements but are ineffective in rain or fog[4]. A large and diverse set of sensors is therefore essential for the application of ADAS and AD functionality, while sensor performance and cooperation has direct influence on their decisions and subsequently their safety [19]. Sensor cooperation can be achieved by fusing signals from different sensors with overlapping coverage areas to generate a signal of higher quality. The notion of quality is context-dependent and can target a higher accuracy, degree of coverage, robustness against environmental influences, or the acquisition of additional information. Mendez et al. proposed in [11] a camera-LiDAR fusion achieving accuracy improvement of an object detection algorithm compared to isolated sensor use as an example. Similar fusion approaches were proposed for various other sensor type combinations [10,19].

Sensor calibration is a critical process to be conducted before sensor fusion can be applied. As part of the calibration process, sensor parameters are estimated which are required to locate features as detected by sensors in the vehicle's coordinate system. A distinction has to be made in the two phases of calibration: *Intrinsic calibration* refers to the estimation of internal sensor parameters, such as the focal length of camera sensors. Those parameters are anticipated to be static over the sensor's life cycle and can be thus estimated by the manufacturer. *Extrinsic calibration* describes the calculation of a transformation for converting features as detected by sensors from the sensor to the vehicle coordinate system. In other words, the extrinsic calibration estimates the position and orientation

[5] https://www.tesla.com/support/transitioning-tesla-vision
[6] https://innoviz.tech/innovizone

of sensors in the vehicle's coordinate system. In the context of upgradeable and reconfigurable sensor configurations, this transformation is not static and has to be recalculated with each change in the configuration. Furthermore, the distinction has to be made between *target-based* calibration, requiring specialized calibration target or patterns, and *targetless* calibration, utilizing the perceived features in the vehicle's environment instead [19].

2.3 Smart and Intelligent Sensors

The terms "smart" and "intelligent" sensor continue to be the subject of discussion, no standardized definition exists so far. There is consensus that smart sensors are equipped with embedded computing units for preprocessing of the sensor signal within the sensing element, before transfer to remote computing units for further processing [8,19]. In the case of a camera sensor, such pre-processing can involve object recognition or target tracking algorithms, for instance, whereby the resulting insights are provided together with the raw sensor signal. Ultimately, this implies that a smart sensor represents an entity of hardware and software, whereby both of these aspects might be adapted in the context of upgrade or reconfiguration processes. In contrast, "non-smart" or "raw" sensors provide the sensor signal without additional information and are dependent on external resources for the processing of the sensor signal [1]. Karatzas et al. introduce a distinction between smart and intelligent sensors: As part of an investigation of several standards, an understanding of intelligent sensor technology is established which, in addition to aforementioned requirements, includes the requirements of standardized interfaces, error detection and compensation as well as internal fusion, if applicable [8]. The resulting generic architecture concept is shown in a simplified form in Fig. 2. Following the acquisition of an arbitrary number of sensor signals via corresponding sensor interfaces, an error detection is conducted by comparing sensor signals with each other or with a sensor model. If applicable, the sensor signals are then fused in order to generate a single sensor signal, which subsequently is communicated in a standardized format. Thereby, the control module handles the coordination of those tasks. We draw inspiration from the generic architectural concept of [8] and refer to its requirements for intelligent sensors in our concept.

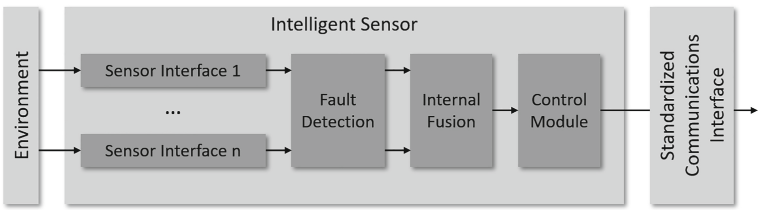

Fig. 2. Intelligent sensor architecture according to [8], simplified

3 Related Works

To understand the challenges facing the automotive industry today, it is necessary to look at the structures that have evolved over the past decades [15]. One of those structures are today's vehicle networks, where up to decentralized 150 electronic control units (ECUs) exchange information on up to 45,000 signals [17]. According to Zimmermann[7], such *signal-based electrical/electronic (E/E) architectures* depend on a fixed configuration management outlining static sender-receiver connections. Furthermore, software and executing hardware are rigidly linked together. As a result, upgradeability and reconfigurability of today's vehicle systems are restricted and major deficits regarding flexibility and resilience are noticeable [4,12,16]. In order to master those drawbacks, a paradigm shift towards *service-oriented architectures* (SOA) is currently taking place [9]. In an SOA, the individual functions are encapsulated in self-contained services with a clearly defined interface. These are flexibly executed on universal ECU platforms with standardized operating systems and a middleware layer that abstracts the hardware platform [14]. In an interconnected, constantly changing system, communication is dynamic, and connections must be established flexibly at runtime. To enable this flexibility, frameworks that specify services and standardize interfaces and communication are required. In this section, we will examine several of these frameworks for SOA and evaluate their suitability as extensible basis for the realization of our own concept:

Open European Software-Defined Vehicle Platform In the context of the European Chips Act, the European Commission is promoting an initiative to advance the development of an open software-defined vehicle ecosystem to reinforce EU sovereignty in automotive. A concept paper was published [5], detailing the first architecture concepts. To support the upgradeability of future vehicles, the development of standardized software building blocks, the introduction of abstraction layers, and the implementation of standardized interfaces are recommended. The concept thus aims to achieve a segregation of hardware and software. However, there is a lack of discussion on how the reconfigurability of e.g. sensor hardware can be achieved at runtime. The aspects of resilience and dynamic adaptation of the system to changing environmental conditions are also not addressed.

Adaptive AUTOSAR The AUTOSAR standard was created to streamline ECU development of ECUs between car manufacturers and electronics suppliers. Since the reference architecture AUTOSAR Classic does not focus on the segregation of hardware and software, but on classic signal-based architectures, Adaptive AUTOSAR was released in 2018. It enables the development of dynamic, service-oriented architectures by introducing the middleware protocol SOME/IP, while also supporting DDS starting with release 18–10. The middleware DDS is also

[7] W. Zimmermann and R. Schmidgall, Bussysteme in der Fahrzeugtechnik: Protokolle, Standards und Softwarearchitektur, 5th ed., ser. ATZ/MTZ-Fachbuch. Springer Fachmedien Wiesbaden, 2014.

deployed by Robot Operating System (ROS) 2, an open-source set of libraries and tools for the development of robot control software, which also enables service-oriented communication. Henle et al. compared ROS2 and the Adaptive AUTOSAR API in an automotive domain in [6], coming to the conclusion that ROS2 seems to be a promising alternative to Adaptive AUTOSAR and can provide nearly all the functionality. While AUTOSAR Adaptive does support reconfigurability, and resilience and dynamic adaption can be realized, it has major downsides like the enormous extent, poor documentation, and licenses are not available free of charge. Further, Adaptive AUTOSAR is closed-source.

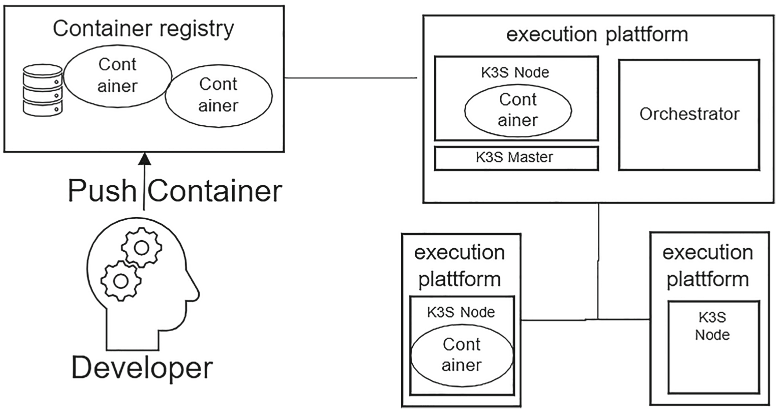

Fig. 3. The ROSMARIN concept according to [16]

ROSMARIN The ROS Middleware Adaptive Intelligent Network (ROSMARIN) framework was proposed by Schindewolf et al. in [14] and provides an approach for the development of SOA by realizing services through the containerization of software. ROSMARIN is implemented in ROS2, thus can reach functionality close to Adaptive AUTOSAR [6]. An overview of the ROSMARIN concept is given in Fig. 3. ROSMARIN applies a dynamic orchestrator for the deployment of services to a distributed network of ECUs and the situation-specific matching of service providers with service consumers based on their capability descriptions at runtime. As shown in [12] and [15], ROSMARIN is capable of realizing resilient and dynamically adaptable sensor configurations, which can manage sensor failures or sensor signal degradations at runtime, while also supporting the flexible integration of new sensor hardware. However, so far, no concept for dynamic sensor interoperability, i.e. dynamic sensor calibration and fusion was proposed for ROSMARIN.

In this paper, we aim to extend the ROSMARIN framework to seamlessly integrate the relevant aspects of sensor calibration and sensor fusion. ROSMARIN has a high suitability potential, as it offers a lightweight, open-source solution in contrast to Adaptive AUTOSAR.

4 Contribution Towards Intelligent Sensors for Automated Driving Functionality

With the understanding of the aforementioned sensor aspects and SOA in future vehicles, a concretization of the research questions and contribution is required:

RQ1: How to ensure continuous reconfigurability and upgradeability of sensors? As intelligent sensors connect sensor hardware and software, reconfigurability and upgradability must be realized for both aspects: on the hardware side, our concept shall provide *standardized interfaces* for data transmission in compliance with the intelligent sensor definition (*RQ1.1*). Further, support of a *Plug-and-Play (PnP)* approach for sensor hardware into the vehicle's network shall enable the effortless, seamless and flexible integration, replacement, and relocation of sensor hardware (*RQ1.2*), even during runtime [9,12]. In practice, standardized interfaces with PnP support not only support the simple replacement of damaged sensor hardware but also the transition to an alternative or improved sensor without manufacturer dependency [12,15].

On the software side, SOA also necessitate the use of *standardized interfaces* (*RQ1.3*) to ensure the flexible reconfiguration of and dynamic communication between services [15]. A *segregation of hardware and software* shall remove existing dependencies and thus facilitate the process of updating sensor software (*RQ1.4*). In practice, development, testing and deployment of sensor software is less demanding through segregation [14]. In addition, the best possible utilization of existing hardware is supported[8].

RQ2: How can resilience and adaptability be incorporated into sensors? As the preventive testing of service-oriented architectures proves less suitable with increasing variability and upgradeability during operation, mechanisms for *safety by design* shall be incorporated into the sensor systems (*RQ2.1*). Therefore, an orchestrator component shall continuously *monitor and sustain the functionality of the sensors and calibration or fusion processes* at runtime (*RQ2.2*) in order to achieve resilience. Orchestrator measures thereby may include the automated restart of sensor software in case of failure or deployment of missing functionality. Since resilience can only be provided by redundancy of sensors, multiple options for providing the sensor functionality exist. For this reason, the orchestrator shall continuously pursue the *optimization of the sensor functionality* through adaptions (*RQ2.3*) [14].

RQ3: Which concepts support dynamic interoperability between sensors? Since updates and reconfigurations of the sensor configuration of vehicles increasingly occur at runtime, an *online calibration and fusion approach* is required (RQ3.1), which continuously reevaluates and, if necessary, repeats the calibration process at runtime [13]. Additionally, a *generic concept* for intelligent sensors as well

[8] https://teslamag.de/news/bessere-bilder-tesla-software-update-kamera-hardware-61710

as calibration and fusion shall be targeted (*RQ3.2*), to ensure realizability for various types of sensors and sensor combinations.

5 Concept Presentation

As announced in Chap. 3, we developed our intelligent sensor concept based on ROSMARIN, which we extended accordingly as part of this development process. Equivalent to Adaptive AUTOSAR, ROSMARIN uses an Ethernet backbone [15], and follows a distributed approach for the deployment of services and the realization of inter-service communication [16]. Figure 4 shows an exemplary distributed system leveraging ROSMARIN for the execution of flexibly interacting services.

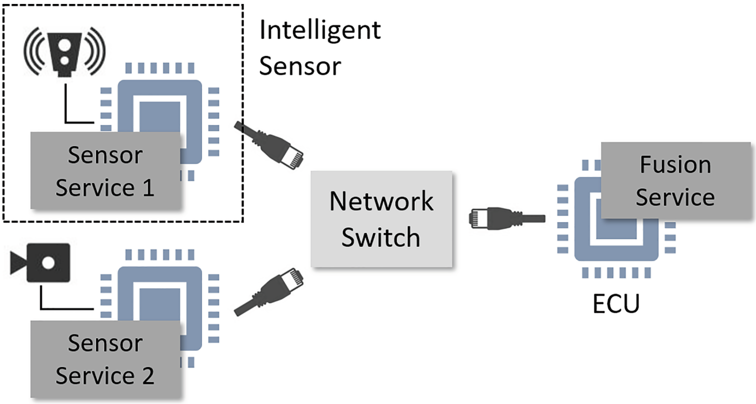

Fig. 4. Distributed system with hardware and software components, adapted from [9]

At the hardware level, the distributed system is realized by multiple general-purpose ECUs with standardized operating system, which are connected to each other via a central Ethernet switch. In addition to ensuring data exchange between ECUs, the Ethernet switch also provides the necessary power supply via Power over Ethernet (PoE). As depicted in Fig. 4, sensor hardware may be connected to ECUs via signal-based and sensor-specific interfaces [12]. At the software level, sensor software and fusion and calibration functionality is provided in the form of encapsulated, containerized services. Each ECU may host one or multiple services. Virtualization of the hardware introduces an additional abstraction layer to provide protected, enclosed runtime environments for services, reducing the risk of potential side effects between services and increasing reliability of the overall system. Virtualization also supports the segregation of hardware and software as prerequisite for the flexible deployment of services on suitable execution platforms [16].

In our concept, an entity consisting of sensor hardware, ECU with connection to the sensor and sensor service with sensor-specific code forms an intelligent sensor (see Fig. 4). The entity can be flexibly and seamlessly connected to the vehicle network using the Ethernet interface. As this approach is applicable to all sensors and sensor types, it is generic. Ultimately, our research question and requirement regarding standardized hardware interfaces (*RQ1.1*) and hardware-software separation (*RQ1.4*) is thereby satisfied by the concept: reconfigurability and upgradeability of sensor-specific software can be achieved effortlessly through the deployment of new sensor services on ECUs with connection to the corresponding sensor hardware. The ROSMARIN framework performs discovery and management of hardware resources and services through the application of an orchestrator component. In our concept, a contract-based service and resource management is applied, which is based on a concept by Schindewolf et al. and Krauter et al. from [15] and [9]. This concept is illustrated in Fig. 5.

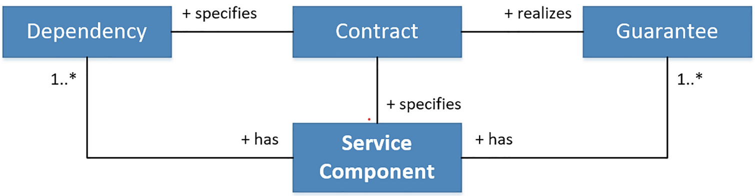

Fig. 5. Contract-based concept for the hardware and service management, from [15]

Each service component and hardware resource is specified via a contract, which in turn may specify several dependencies and guarantees. Guarantees list the capabilities that a service can provide as long as all its dependencies are fulfilled. ECUs specify system properties such as CPU performance, memory or GPU availability via their guarantees [14]. In our concept, the specification of potentially connected sensor hardware is also part of their guarantees. Sensor services, on the other hand, specify the necessity of specific sensor hardware being connected to the executing ECU in its dependencies, while they can guarantee the provision of a specific sensor signal. Since sensor calibration and fusion are typically more computationally intensive processes, fusion services specify hardware requirements on the dependency side in addition to the sensor signals to be fused. Guaranteed is the fused signal. Besides static system properties, dependencies and guarantees may also contain properties that change dynamically at runtime, such as a Quality of Service (QoS) indicator in sensor or fusion services [15]. The orchestrator of the ROSMARIN framework is responsible for the dynamic coordination of service deployment and service communication at runtime. For this purpose, dependencies and guarantees of services are continuously compared and loose couplings between services are established and adapted in order to sustain their fulfillment. Service contracts can therefore be understood as safety certificates, whereby each individual certificate must be fulfilled in order to guarantee the overall system functionality [9]. This satisfies our requirement for safety by design (*RQ2.1*). In addition, the orchestrator is based on k3s, a lightweight Kubernetes variant, and is therefore able to automatically deploy missing services from a container registry and restart services in the event of an error [16]. Our concept is therefore resilient and satisfies *RQ2.2*. As a specific degree of redundancy is necessary for resilience, the orchestrator can perform an optimization of dependencies beyond their fulfillment [15]. For instance, in a setup with two identical sensors, where one can provide a higher QoS, its signal is preferred by dependent services. This capability fulfills our adaptability requirement (*RQ2.3*). Furthermore, the ROSMARIN orchestrator provides discovery capabilities for executing platforms and services at runtime [14], enabling a PnP approach for intelligent sensor entities and their immediate availability after connection (*RQ1.2*).

While sensor calibration and fusion gains greater importance in the automotive domain, we aim for the conceptualization and development of a generic calibration and fusion service for intelligent sensors. Our sensor calibration and fusion concept with seamless integration capability into the ROSMARIN framework is visualized in Fig. 6.

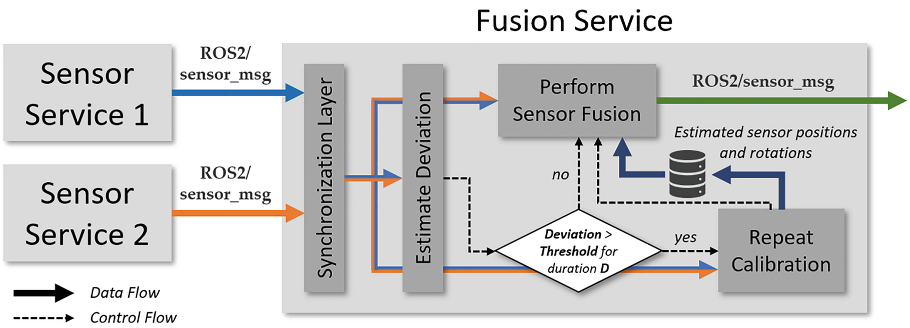

Fig. 6. Sensor calibration and fusion concept for ROSMARIN

With this concept, we focus exclusively on extrinsic sensor calibration, as intrinsic calibration parameters are static and therefore conventional methods can be applied [19]. Our concept is based on the generic architecture of [8], shown in Fig. 2. As a starting point, sensor services, in [8] so-called sensor interfaces, send the sensor signals to be consolidated to the fusion service, continuously and according to their reading frequency. For this purpose, we utilize standardized ROS2 message formats, which are available for a wide range of sensor types, to simultaneously satisfy our requirement for standardized software interfaces (*RQ1.3*). A time synchronization of the sensor signals using standardized procedures is required as a preparatory step to enable an application in dynamic environments. The synchronized sensor signals are then transformed into the vehicle's coordinate system and superimposed in order to evaluate the quality of the current calibration parameters [13], which corresponds to the fault detection step in Fig. 2. Current calibration parameters values are loaded from a service-internal database for this purpose; besides the static intrinsic parameters, the positions and orientations of the sensors in the vehicle coordinate system are particularly relevant here. As a result, a mean deviation value of the sensor signals is determined. A deviation value above a user-defined threshold T may signify reconfiguration or relocation of sensors, and the calibration process is repeated before a fusion of the sensor signals is performed. In the opposite case, the fusion of the sensor signals proceeds directly. To improve the stability of the fusion service, recalibration is only triggered when the calculated deviation exceeds T for a period $\geq D$. During the calibration process, an adaptation of the sensor positions and orientations is estimated, which minimizes the deviation of a signal superimposition. The calibration parameters in the database are updated accordingly. The fused signal is likewise communicated via a standardized ROS2 message. Furthermore, the communication of a QoS inversely proportional to the calculated signal deviation via the guarantees of the fusion service is an option.

It must be noted that the described process is continuously repeated with each received signal from the sensor services. The calibration and fusion process for the ROSMARIN framework is executed online, i.e. during vehicle operation, and thus fulfills *RQ3.1.* In addition, as it is not bound to specific sensor types, calibration and fusion approaches and can be used generically *(RQ3.2).* To the best of our knowledge, our superimposition approach can be applied to the most common sensor type combinations for sensor fusion. The involvement of a QoS estimation additionally permits a dynamic, automated response to, for example, a degradation of fusion quality by comparing and initiating measures such as switching to an alternative fusion service or refraining from fusion completely.

However, our approach is also subject to restrictions: To enable the initial calibration of a sensor, its approximate position and orientation must be specified in the service database manually for the convergence of the approach. In addition, the approach presupposes that at least one of the sensors can be considered as a static reference point whose correct position and orientation are known are advance. We therefore consider only the reconfiguration or relocation of one sensor at a time in our concept.

6 Implementation and Proof of Concept

We implemented our approach for an ultrasonic sensor, a ZED 2i[9] stereo camera, and a Blickfeld Cube 1[10] 3D LiDAR. For the ECUs, we resorted to conventional single board computers (SBC). The sensor and fusion services were implemented within the ROSMARIN framework using ROS2 and C++, with virtualization and containerization of the applications through Docker. Guarantees and dependencies as part of the service contracts were defined in the metadata .yaml files

[9] https://www.stereolabs.com/products/zed-2
[10] https://www.blickfeld.com/de/produkte/cube-1/

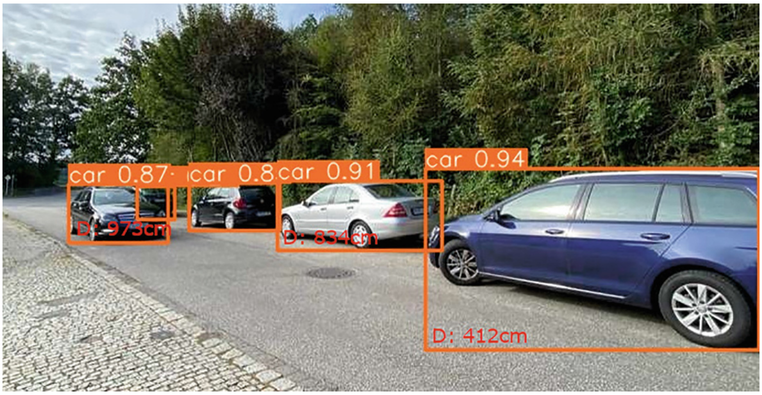

Fig. 7. Exemplary camera and LiDAR fusion result

of the services in a partially manual process. Subsequently, the resulting container images were built on the SBCs and automated service execution with the boot process was configured. To perform a proof of concept, we have defined the following upgrade and fusion scenario:

PoC scenario – initial setup Starting point is a setup with a stereo camera, an ultrasonic sensor and the corresponding SBCs, i.e. sensor entities, which are connected and powered via a PoE network switch. The corresponding sensor services on the SBCs are active. A third computing unit in the network executes a separate service for the visualization of the sensor signals. While the ultrasonic sensor continuously publishes a single distance value, the stereo camera communicates an image with depth information in addition to the RGB color information. The signals from both sensors are subscribed by and displayed in the visualization component.

Phase 1 – LiDAR integration The LiDAR sensor entity is integrated into the network as part of a hardware upgrade via effortless Ethernet-based PnP. After connecting the associated SBC, the corresponding service is discovered by the orchestrator. Since ultrasonic and LiDAR sensors offer equivalent guarantees, i.e. distance information, the latter is considered superior due to its larger field of view and resolution, the visualization component switches to displaying the LIDAR signal. Thus, we show that our concept supports upgradeability and reconfigurability of hardware as well as adaptability to ensure the best possible fulfillment of the system functionality.

Phase 2 – Fusion service deployment A service for fusing the camera and LiDAR signals is initiated as part of a software upgrade. The target of the fusion process is to assign precise distance information to detected objects in the camera image, since the stereo camera shows increasing inaccuracies for objects at distances $>$ 10 meters. The point clouds generated by the stereo camera and LiDAR are used