

Modern Middlewares for Automated Vehicles: A Tutorial

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Abstract—This paper offers a tutorial on current middlewares in automated vehicles. Our aim is to provide the reader with an overview of current middlewares and to identify open challenges in this field. We start by explaining the fundamentals of software architecture in distributed systems and the distinguishing requirements of Automated Vehicles. We then distinguish between *communication middlewares* and *architecture platforms* and highlight their key principles and differences. Next, we present five state-of-the-art middlewares as well as their capabilities and functions. We explore how these middlewares could be applied in the design of future vehicle software and their role in the automotive domain. Finally, we compare the five middlewares presented and discuss open research challenges.

Index Terms—Middleware, Architecture Platform, Automated Vehicles, ROS 2, Service-Oriented Architectures, Middleware Frameworks, Communication Middlewares

I. INTRODUCTION

A. Motivation

New challenges to computing in vehicles arise as Automated Vehicles (AVs) provide new automated driving functions, requiring advanced perception and complex decision making [13], [50]. These functions require resource-intensive processing of sensor data and the implementation of advanced decision-making algorithms. Changed perspectives lead customers of AVs to increasingly expect their vehicles to behave like other modern computing products with ongoing updates and enhancements to their capabilities [1]. These new computing challenges have consequences on the Electrical/Electronic (E/E) domain and the software domain in AVs [19].

In the E/E domain, these challenges are affecting a transition from domain-based architectures to centralized zone controller architectures [77], [81]. In current E/E distributed architectures, which are still prevalent today, embedded microcontrollers are used to perform some selected vehicle functions [81]. The hardware offers very limited excess compute capacity, as the hardware is cost-optimized to the software requirements. Updating an Electronic Control Unit (ECU) in a current architecture requires reflashing the complete ECU, and due to resource constraints, offers limited space for new functionalities [15]. In contrast, zone controller E/E architectures use more powerful, multi-function Zone Control Units

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(ZCUs) for compute intensive tasks. These platforms provide significantly more compute resources by incorporating many-core processors, different Operating Systems (OSs), and accelerators such as Field Programmable Gate Arrays (FPGAs) and Graphics Processing Units (GPUs). In these architectures, traditional ECUs at the edge of the system interact with hardware sensors and actuators, while zone controllers or central vehicle computers perform high-level functions [15], [81].

In the software domain, the automotive industry is moving from current signal-oriented software architectures to new software architectures built on modern automotive middlewares [77]. In signal-oriented software architectures, the software on each ECU is designed to implement a limited number of functions and, due to the strong dependence on the microcontroller, is often not reusable [75]. To alleviate these challenges and support new E/E architectures, new middlewares such as AUTOSAR Adaptive Platform (AP) seek to address them [4]. Modern middlewares have not yet reached market dominance in the automotive domain and are still under active development [4]. However, in other domains, such as robotics, middlewares have achieved the status of ubiquity and default tooling. In the robotics domain, the Robot Operating System 2 (ROS 2) middleware has emerged as the de facto standard middleware that attempts to solve similar challenges [53].

Middlewares should serve as foundational software for the development of automotive software [19]. They define elements of the vehicle software architecture and provide crucial functions such as communication, update, and security for automotive applications. Consequently, choosing the correct middleware for automotive application development is important for manufacturers, developers and researchers. Current state-of-the-art middlewares vary in supported features, software architecture, and license requirements. This paper provides an introduction to middlewares in AVs and an overview of the current state-of-the-art.

B. Main Contributions

The main contributions of this article include:

- 1) Introduction to E/E architectures, middlewares and underlying concepts.
- 2) Overview of five state-of-the-art middlewares from the robotics and automotive domain and comparison of their features.
- 3) Examples showing how middlewares affect the software architecture of a system.

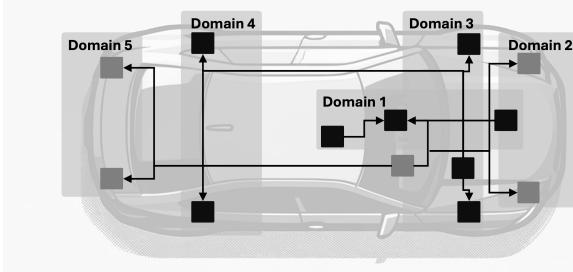


Fig. 1. Illustration of a domain-based E/E architecture. Actuator controllers are depicted in black with gray representing a sensor. The components are connected within their own domain. The domains are determined by the function that the ECUs contribute to, for example drive train control while cooperation between domains is limited [77].

- 4) Discussion of current challenges facing modern middlewares.

C. Outline

This article is structured as follows: Section II provides the background information necessary to understand middlewares in the automotive domain. Section III presents the fundamental concepts of middlewares and their function in a modern automotive software stack. It also provides an overview of the state-of-the-art middlewares FastDDS, Scalable service-Oriented MiddlewarE over IP (SOME/IP), Zenoh, ROS 2, and AUTOSAR AP. In Section IV, we compare these middlewares and discuss their features and Section V presents current research challenges for middlewares in the AV domain.

II. FUNDAMENTALS

Before addressing middlewares and system software architectures in AVs, this section outlines the fundamental aspects of the software and computing hardware utilized in modern vehicles. The computing hardware is defined by the vehicle's E/E architecture, which we explore through the following questions: What defines an E/E architecture and what is the current state of E/E architectures? Then we consider what challenges are associated with E/E architectures and what future direction attempts to address these challenges E/E architectures? Once the hardware and E/E architecture are understood, we focus on software architecture, addressed through the following questions: What defines a software architecture and why is a well-defined software architecture essential? To remain in the automotive domain, we consider how the software architecture influences an automotive software systems.

A. What defines an E/E architecture?

Definition II.1 (E/E Architecture). According to Zhu *et al.* [81], the E/E architecture can be defined as the organization of the electric and electronic components of the vehicle and their interactions. Key components of the architecture include ECUs, sensors, actuators, power systems, and In-Vehicular Network (IVN). The IVN allows for interactions between the components and enables the components to cooperate to perform their expected functions.

The core elements of the E/E architecture are various control units known as ECUs [75]. ECUs are traditionally responsible for executing control functions within the vehicle, including management of the engine, drive train, and body electronics [77]. These units vary in computational power, ranging from traditional embedded ECUs to high-performance zone controllers.

Definition II.2 (ECU). Electronic control units are the fundamental compute platforms in the vehicle. Classically based on microcontrollers and constrained in compute resources and interconnected via fieldbus systems, they operate fundamental components in the vehicle [3].

Furthermore, the E/E architecture specifies the interconnection of ECUs. Communication is achieved through a fieldbus system, such as Controller Area Network (CAN), FlexRay, or an Ethernet-based IVN, which provides higher bandwidth, or a combination of these systems [43]. The interconnection and placement of ECUs is also referred to as the ECU topology.

Definition II.3 (Automotive Software System). The automotive software system refers to all software components in a vehicle. These components range from the operating system, individual functions, to algorithms in the vehicle.

The choice between these communication systems and ECUs is driven by the requirements of the automotive software system [77]. Initially, Section II-B discusses the current domain-based E/E architectures and the challenges introduced by AVs and increased software demands at large in vehicles. Subsequently, Section II-C discusses these challenges extensively. Finally, Section II-D introduces the zone-based E/E architecture, which in cooperation with middlewares, addresses these challenges.

B. What is the current state of E/E architectures?

In current vehicles, the domain-based architecture is dominant [15], [81].

The core component of this current architecture is the dedicated single-application ECU, where processor and hardware have been narrowly selected, with limited additional computing resources, to support a single or few functions [22], [45], [81]. An example for such a single-application ECU, is the engine control unit, which is specifically tasked only with monitoring and controlling the internal combustion engine in a vehicle. These ECUs are commonly embedded microcontroller-based devices running real-time operating systems or software directly on the hardware. Changes in these embedded devices often require reflashing of the microcontrollers, making changes to the software difficult.

Communication in this architecture is characterized by static fieldbus systems with fixed mappings between senders and receivers [75]. This architecture pattern is also referred to as a signal-oriented architecture and is characterized by its statically defined IVN between ECUs. These signals follow predetermined routes from senders to receivers, organized in a communication matrix shared among all ECUs. The statically

defined communication matrix allows for real-time constraints and predictable behavior [75], [77].

The ECUs and their communication are structured by domains such as engine control or body control. Domain-based architectures require many component interconnections, as components in a single domain may not be physically close in location.

Different domains are interconnected by gateway ECUs, which bridge messages between the domains. Generally, domains are isolated from each other with gateways that provide limited interconnection between networks.

Definition II.4 (Domain-based E/E Architecture). A domain-based E/E architecture typically consists of multiple single-application ECUs interconnected to each other based on their domain. Communication is characterized by static fieldbus systems with fixed communication schedules saved in communication matrices.

Fig. 1 illustrates an exemplary domain-based E/E architecture, where multiple ECUs are interconnected using multiple CAN fieldbus systems according to the domain. The cooperation between applications in separate domains is generally limited due to bandwidth limitations. Data from connected sensors is primarily processed locally within each ECU and is not commonly shared across the IVN.

C. What challenges are associated with E/E architectures?

New challenges to vehicles in general also present challenges for E/E architectures. Providing increasingly automated functions requires additional compute resources, and software updates require other types of software architecture. Zhu *et al.* [81] define these challenges as follows:

- 1) The bandwidth bottleneck in modern vehicles is a significant challenge, as current IVNs have limited capacity to handle the data demands of advanced perception systems in AVs. This limitation requires more efficient data transmission methods to support increased bandwidth requirements.
- 2) With the addition of numerous ECUs to support new vehicle functions, the wiring complexity within vehicles has increased. This increase in complexity not only makes maintenance more challenging, but also contributes to more complicated vehicle architectures, negatively affecting performance and reliability.
- 3) Ensuring low deterministic latency in IVNs is critical, especially in the context of highly concurrent computations, and large traffic volumes, such as sensor data. The requirement for deterministic latencies poses a challenge, necessitating improved IVN management and data prioritization strategies.
- 4) The design of future automotive architectures must prioritize flexibility and scalability, facilitating online updates, maintenance, and dynamic reconfiguration.

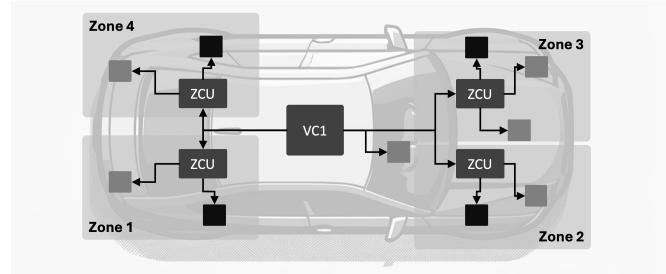


Fig. 2. Illustration of a zone-based E/E architecture. Actuator controllers are depicted in black with gray representing a sensor. Each component is connected to a zone control unit, which in turn is connected to a central vehicle computer VC1. This architecture divides the vehicle into four separate zones connected according to proximity with a high degree of cross-zone cooperation [77].

D. What is the near-future of E/E architectures?

The currently emerging E/E architecture, seeking to address current challenges, is the zone-based E/E architecture [81]. The components in this E/E architecture are structured in vehicle zones by proximity and ECUs interconnected within these zones. In contrast to the current domain-based architecture, components are no longer integrated based on function, but rather location.

In this architecture, traditional ECUs at the edge of the vehicle are supported within a zone by ZCUs and central vehicle computers. ZCUs represent higher performance ECUs supporting multiple vehicle functions rather than a single one. As required for co-hosting several functions at once, these architectures also support more modern software architectures. The ZCUs may employ a PC OS, such as Linux or QNX. [77], [81]

Communication in zone-based E/E architectures often uses automotive Ethernet as an IVN or a hybrid communication architecture. Hybrid topologies that integrate different fieldbus and ethernet networks, such as an ethernet IVN between ZCUs and fieldbus IVNs to the edge ECUs, are also employed [77]. Automotive ethernet is an extension to classical ethernet, allowing higher data rates and increases the possible amount of interconnected components in comparison the fieldbus IVNs [40], [41].

ECUs within a zone are connected to their zones ZCU, while the connection between zones is established by linking ZCUs either directly or using a central vehicle computer. Due to this simplified topology, the wiring complexity is greatly reduced and software updates and new communication paths can be more easily implemented using the ZCUs. However, more communication between ECUs and ZCUs is required, as cooperating ECUs are likely to be in separate zones [77], [81]. For example, in hybrid topologies, the in-zone communication between edge ECUs to the ZCU could be implemented using fieldbus-based networks, while the ZCUs use automotive ethernet to address greater bandwidth and latency requirements.

Fig. 2 illustrates an example zone-based E/E architecture. Based on the division of the vehicle into zones, the example

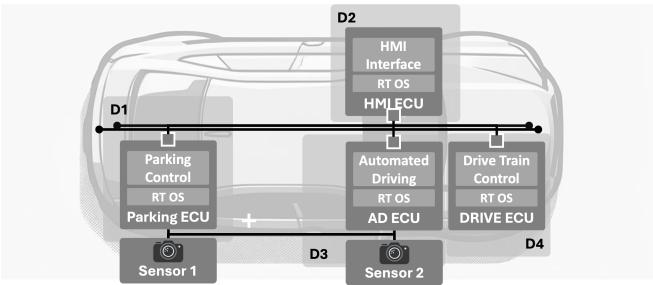


Fig. 3. Illustration of the interaction of software and hardware in a domain-based E/E architecture. The automotive software system depicted is based on the requirements outlined in Section II-G.

depicts multiple ZCUs performing multiple functions and interacting with ECUs at the edge of the vehicle.

Following the zone-based E/E architecture, the centralized architecture has emerged as the target architecture for multiple Original Equipment Manufacturers (OEMs) [81]. However, the exact implementation of this architecture remains an area of active research and development.

E. What defines a software architecture?

Definition II.5 (Software Architecture). A *software architecture* is defined by Bass *et al.* [11] as the structure or structures of the system. The structure is defined by the software elements, their properties, and relationships.

Similar to the E/E architecture in Section II-A, design decisions include the core components of the system and the key properties of each component. Components can take different forms, such as classes in an application, services for a web application, or individual applications composing a distributed system. A architecture also specifies the interactions between the components of the software system. For classes as components, interactions could be made via function calls or, in the case of web applications, HTTPS API calls. The software architecture ensures a clear division of the responsibilities and paths of interaction in the software system.

F. Why is a well-defined software architecture essential?

An automotive software architecture is based on design decisions which often have to be made quite early in the development process and have far-reaching effects on the quality of the resulting software. It is well known that architectural design decisions determine most non-functional attributes of a automotive software system, and therefore can either support or impair properties like maintainability, updateability, reusability [37].

- With the appropriate top-level design decision, the software architecture can ensure the *updateability* of the software system. The architecture can constrain the components and specify that the components must be designed with update mechanisms and modularity. Taking into account that continued development during the vehicle lifecycle is one of the drivers of automotive software

especially for Software Defined Vehicles (SDV), an architecture can contribute significantly to this goal.

- Architecting a software system with well-defined paths of interaction offers additional advantages for *reuse*. A software component with clear interfaces explicitly defines what the software system needs to provide and what the component offers the software system. For automotive software development, for example, multiple software components that share the same interfaces and interface definitions can easily be exchanged for one another.
- The division of responsibilities aids in the *construction* of software. Each component has well-defined tasks and responsibilities in the software system, allowing a developer to know what functions must be implemented and which are the responsibility of another developer.

G. How does the software architecture influence automotive software systems?

To show how a software architecture influences the capabilities and maintainability of a software system, we consider an example automotive software system. The example consists of an Automated Driving (AD) system, and we explore how the software affects an expansion of its functionality. As the expansion and improvement of software functions is a major consideration in automotive software architectures, this example highlights the advantages and disadvantages of the three presented software architectures.

In this example the automotive software system is responsible for the automated driving functions of the vehicle and can operate safely in the operational domain of a highway. This example has been derived from the UNICARagil project, where automated vehicles were developed [78]. For this purpose, the AV has long-range, narrow field-of-view cameras. Additionally, the AV can park using short-range, near-field cameras and sensors, to achieve automated parking functions. For safe operation, multiple requirements must be fulfilled and cooperation of multiple vehicle ECUs is required. We define the basic requirements for the original, unmodified automotive software system as follows.

- 1) *The automotive software system must detect lane boundaries, road users and traffic signs reliably on highways.*
- 2) *The automotive software system must plan a legal and safe trajectory through the detected highway environment.*
- 3) *The automotive software system must execute this trajectory safely.*

To analyze the expansion of an architecture, we introduce one new requirement: *The vehicle must drive automatically in city environments*. We assume that this new requirement must be satisfied by updating the automotive software system.

First, we consider an automotive software system built on a domain-based E/E and signal-oriented software architecture.

In this architecture, each function is executed on a single ECU as depicted in Fig. 3. The ECUs for each function are connected via a CAN fieldbus with a fixed communication

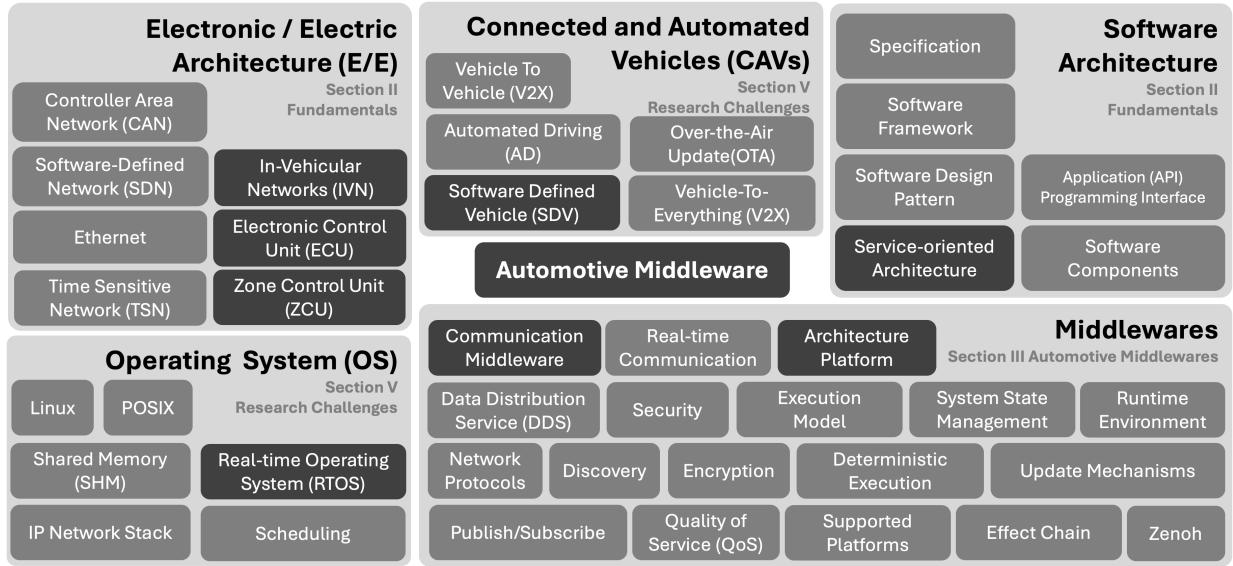


Fig. 4. Illustration of the different domains interacting with middlewares. Domains are positioned according to their topical closeness. Black signifies increased importance from the perspective of the authors.

schedule. The automotive software system architecture is illustrated in Fig. 3 involving the following ECUs:

- The automation ECU performs the automated driving functions in the vehicle on the highway. In this example, these include the perception and planning functions. It transmits trajectory commands using the fieldbus to the drivetrain module. Directly connected to this system are long range cameras for the highway domain.
- The Human Machine Interface (HMI) ECU provides the drive interface functions, such as information on the vehicles' states, and other interfaces, such as the infotainment system.
- The drive train ECU is responsible for controlling the drive train, including the vehicle engine, and communicating the state of the drive train back to other components of the automotive software system. In this example, it is also responsible for executing the vehicles planned trajectory.
- The parking ECU implements automated parking functions. For this purpose it has access to short range, near field cameras and ultra sound distance sensors which enable the vehicle to park itself automatically.

To satisfy the new requirement of city operations, the functions of the automated driving module must be expanded. To accomplish this, the core functionality of the automated driving module could be updated. The functionality of the perception component must be expanded for additional requirements of the city and the AD ECU requires access to the near-field sensors and cameras of the parking module. Motion planning capabilities must be expanded to deal with the additional complexity of city roads and crosswalks.

As ECUs are commonly sized for their specific task, this addition of requirements could require switching to another

ECU or even adding more ECUs. Both cases would then have to be integrated into the existing vehicle CAN fieldbus network, require additional gateways, or consume more bandwidth than is available. The benefits of this architecture are the avoidance of resource contention between applications, since each functionality is assigned to a dedicated ECU that is appropriately sized. Additionally, each ECUs can be cost-optimized to its specific function. Changes to the communication matrix and the vehicle gateways also avoid possible IVN contention. However, the costs of switching hardware platform or addition of a new ECU, additional wiring or gateways required to connect sensors or cameras, and the integration with other ECUs are high. Consequently, implementing such changes post-manufacture is highly impractical and cost prohibitive in such an architecture.

To solve the issues highlighted by this example, new approaches to software are equally required as well as new E/E architectures. The following Section III will present such a new approach in the form of modern automotive middlewares in conjunction with modern E/E architectures. First, we introduce automotive middlewares at large, then discuss how we classify middlewares and compare five state-of-the-art middlewares in detail.

III. AUTOMOTIVE MIDDLEWARES

Middlewares are used in various computing domains, including Internet of Things (IoT), web services and Cyber Physical Systems (CPS) with similar objectives [47], [67], [80].

Definition III.1 (Middlewares). Neely *et al.* broadly define middlewares as the layer between the application and system software, abstracting the underlying system to enable developers to focus on application-specific tasks [57].

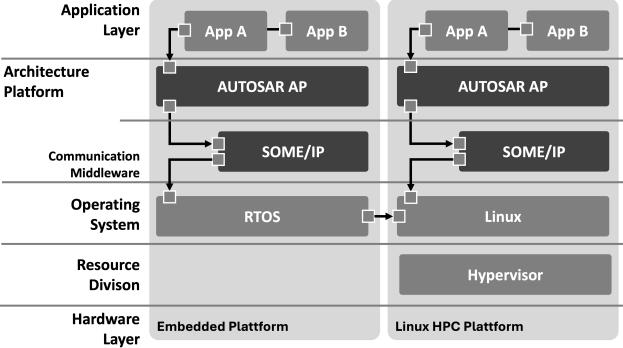


Fig. 5. Illustration depicting the role of a middleware in the development of distributed software. The middleware functions as an intermediary between the application and the operating system. In this case AUTOSAR AP makes use of DDS and the operating systems network stack to communicate across the two devices.

Built on modern E/E architectures, a new generation of automotive middlewares has emerged as the foundation of new software architectures in the automotive domain [39]. In contrast to other domains, the automotive domain is differentiated by distributed E/E architectures, heterogeneous computing platforms, and high safety requirements. Fig. 5 presents the software stack underlying such software architectures using the example of two communicating applications in a distributed system.

Definition III.2 (Automotive Software Stack). We define the automotive software stack as the layers of software used to support applications. Starting with either the OS or hypervisor, additional software frameworks and middlewares are added to provide functions to the application.

The application uses an Application Programming Interface (API) offered by the middleware layer to send messages from one ECU to another application on a second ECU. AUTOSAR AP in this case forwards the message to SOME/IP, which uses the operating systems network stack to relay the message from the microcontroller to the High-Performance Computer (HPC).

This example depicts a typical automotive software stack. In practice, as in Fig. 5, the automotive middleware is separated into two layers. The lower layer is a software framework concerned with communication in distributed systems, in this example SOME/IP. The upper layer, in this case AUTOSAR AP is built on the communication framework, to offer features beyond communication, such as Over-The-Air (OTA) updates, resource control and security.

In literature and in the automotive domain at large, the nomenclature for these two complementary layers is not well established, and terms are used loosely. While some authors refer to the combination of both layers as middlewares, others describe only the lower layer as a middleware, while referring to the upper layer using new, different nomenclature. This inconsistency extends to developers, as the developers of ROS 2 mostly refer to it as a *set of libraries and tools*, while AUTOSAR AP uses *platform* [4], [65]. In academia,

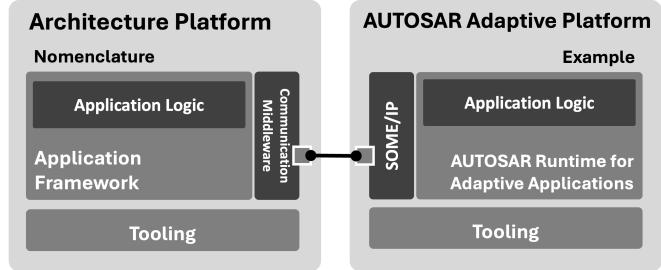


Fig. 6. Illustration depicting elements of the automotive software system with our proposed nomenclature. We distinguish between *communication middlewares*, *architecture platforms* and application frameworks, to refer to different elements of the automotive software stack. In the left half of the illustration, the nomenclature is shown. In the right half, AUTOSAR AP is used as an example.

researchers refer to ROS 2 as a middleware [79], while others use different nomenclature, such as architecture platform [39].

In an effort to establish uniform terminology, we propose the term *middleware* as a general descriptor of the class, in keeping with its original definition [57]. We also propose a new term for the lower communication layer, while making use of the *architecture platform* nomenclature defined by Henle *et al.* [39] to refer to the upper layer. Consequently, we define automotive middlewares by the following characteristics:

Definition III.3 (Automotive Middlewares). We define automotive middlewares as the software layer between the application and system software. These middlewares operate in distributed, heterogeneous automotive E/E architectures and due to the distributed system architecture, communication and structured software execution are their core functions.

As a consequence of this position, middlewares interact with a wide variety of domains. Fig. 4 illustrates these domains and highlights the section in which they are discussed. Middlewares accomplish communication in distributed system by using new communication pattern on IVNs to interconnect applications on different ECUs. Some middlewares are comprehensive platforms that address many software domains in automated vehicles, such as communication, security, updates, and resource control.

To highlight the communication function of the lower layer framework, we define them as *communication middlewares* and will discuss them in detail in Section III-A. We use the definition by Henle *et al.* to refer to the higher layer, built on *communication middlewares*, as *architecture platforms* [39]. Beyond communication, *platforms* provide additional features such as resource control, deterministic execution, and security functions. These *platforms* also commonly rely on other software design patterns.

Definition III.4 (Software Design Pattern). Software design patterns are generalized solutions for common design problems. They are defined by Bass *et al.* as descriptions of elements, for example, clients and services, and relations, such as requests between these elements, with constraints on how

they can be used. They commonly describe only a subset or repeating pattern in a software architecture and classic patterns examples include the client-server pattern, the n-tier pattern, or service-orientation [10].

Employing such software design patterns, *architecture platforms* determine high-level architecture decisions, such as the components and communication methods of the software system. As such, the *architecture platform* is an integral part of the automotive software system. This class of middleware is discussed in Section III-B.

In Fig. 7, we present an illustration of common middlewares. The figure distinguishes between closed-source and open-source middlewares as well as our classification into *architecture platforms* and *communication middlewares*.

A. What are Communication Middlewares?

Communication middlewares are core to automotive software architectures, facilitating data exchange between various ECUs [7]. They accomplish this by separating the application from the underlying IVN topology. This is commonly implemented by discovery, where communication paths are not predetermined but are dynamically discovered at runtime. Alternatively, centralized definitions of network topology can be used to separate the IVN from the application. This conceptually simple software design pattern allows the application built on the middleware to be independent of the specific ECU and IVN topology, since all other applications in the network are dynamically discovered.

Definition III.5 (Communication Middlewares). *Communication middlewares* are middlewares designed to implement communication within distributed systems. They provide communication patterns such as publish-subscribe or request-response communication and configurable Quality of Service (QoS) [34].

Definition III.6 (Discovery). Discovery in a modern middleware allows an application to automatically discover and connect to all peer applications, commonly in the same network, without manual configuration of connections [31].

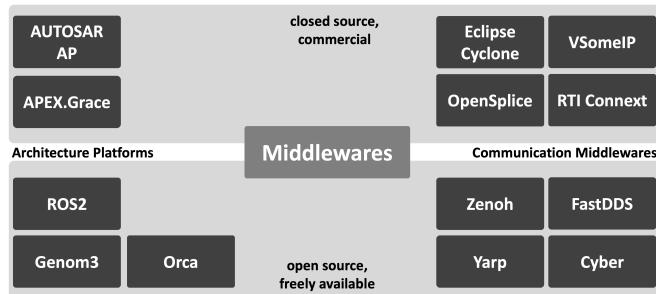


Fig. 7. Overview over common *communication middlewares* and *architecture platforms* in the automotive and CPS domain. The illustration divides middlewares according to the *communication middleware* and *architecture platform* distinction as well as according to their access limitations.

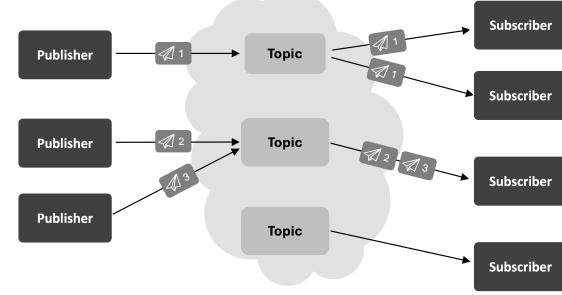


Fig. 8. Illustration depicting topic-based communication between publishers and subscribers components in a DDS domain.

As a result, no changes to communication parameters are necessary if an application is updated or moved to another ECU. For simplified communication, these middlewares implement communication patterns that define how communication is structured.

Definition III.7 (Communication Pattern). We define communication patterns, derived from the software pattern definition, as the structure and sequence of messages, whether it is one-sided communication or an exchange of messages, and how recipients of these messages are determined.

Simple communication patterns allow developers to focus on the core functions of their applications instead of IVN configuration. The two most common communication patterns in modern middlewares are publish-subscribe and request-response communication. These communication patterns are present in most middlewares presented in this tutorial.

In *Publish-Subscribe* communication, data is separated into messages, which are structured using topics [34]. Topics serve as separate channels of communication that allow access to all messages on them. Fig. 8 depicts an example of a topic-based communication. A participant can publish messages on a topic, and a participant which wants to receive the message can subscribe to it to be notified. As a result, messages are not directly associated with a recipient, but only with their topic. Thus, allowing new participants to easily join existing networks, as it can just interact with already existing topics. In *Request-Response* communication, a participant can send a request to another remote participant, which will return a response to the request [7]. This communication pattern is commonly used to call remote methods on other machines, similar to regular function calls.

Communication middlewares may also address reliability and security considerations in IVNs. To facilitate functional safety in communication, some middlewares offer configurable QoS which can ensure the reliability of message transmission. For security considerations, the middlewares may directly support encryption of exchanged messages while others may offer optional extensions to supplement security features.

The implementation of *communication middlewares* is commonly built on the IP network stack in the host operating

system to access ethernet-based IVN. Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and shared memory are commonly used as communication protocols. Commonly, middlewares automatically determine which transport to use depending on the IVN and E/E architecture.

The following sections present three *communication middlewares*. FastDDS, an open source implementation of the Data Distribution Service (DDS) standard, SOME/IP the automotive industries approach and Zenoh an emerging middleware.

1) *SOME/IP*: A standard that defines a *communication middleware* is the Scalable service-Oriented MiddlewarE over IPs (SOME/IPs). It was defined as an automotive *communication middleware* standard for the AUTOSAR project and maintained in connection with the project. It is under development by the AUTOSAR consortium consisting of major OEMs and automotive tier one suppliers. It represents an approach to middlewares by the automotive industry. It shares some concepts with other middlewares, such as DDS discussed in Section III-A2. These similarities include communication patterns and methods, such as the underlying protocols and the use of the OS network stack [7].

In its core design principles, SOME/IP was specifically developed to work with stringent resource budgets of embedded devices and aims to ensure compatibility across a wide range of use cases and communication partners. Due to its origin in the AUTOSAR project, it is specifically and narrowly designed for the automotive domain. Additional design objectives due to the origin of the middleware were compatibility with its predecessor AUTOSAR classic and the ability to scale to full automotive software system with hundreds of applications.

To transport SOME/IP messages, different transport protocols can be used, currently supporting UDP and TCP. SOME/IP can be configured to use both; however, developers recommend configurations depending on the network characteristics.

SOME/IP supports both publish-subscribe and request-response communication but uses proprietary names for these communication patterns, detailed in Section III-A. In addition to these common communication patterns, it also supports software design patterns to distribute values globally throughout a automotive software system. These values, called fields, are accessible by every application in a SOME/IP software system. These communication patterns are implemented in three features:

Methods are a *request-response* communication paradigm and allow remote methods to be called. A request sent to a local or remote application is processed and an optional response is returned to the calling service. This *request-response* communication also supports *fire-and-forget*, where only the request is transmitted without a response. The standard specifies this with an initial request message and a corresponding response message.

Events are transmitted by notification to inform other applications of an event in the automotive software system. Notifications follow the *publish-subscribe* concept, where applications can decide to subscribe to the notification. For

example, these events could be used to notify other components of a brake event when an automated system detects a possible collision. Notifications can be sent according to different strategies, such as cyclical, on-change, and epsilon-change when the considered value changes beyond an epsilon threshold.

Fields are shared values in a automotive system based on SOME/IP. They are accessible via the *getter and setter functions* and use event notification to distribute values throughout the software system. They allow applications to share values and receive updates on changes to this value. The *getter and setter* functionality builds on the methods functions, and updates are sent via events.

An exhaustive overview of the capabilities of SOME/IP can be found in [7]. SOME/IP also supports with an extension the automatic discovery of applications in a network [7]. The SOME/IP-SD (SOME/IP-Service Discovery) extension allows the application to locate service instances inside the IVN on other ECUs. It also enables SOME/IP to determine whether a service instance is running and subsequently implement the publish subscribe handling.

For its implementation, SOME/IP uses the network stack of the underlying POSIX operating system. It supports UDP and TCP communication and standard documentation recommends the use of both under specific conditions. The service discovery functionality is implemented using UDP multi-cast messages.

SOME/IP does not directly provide communication security features. In the AUTOSAR AP stack, security is provided by the Communication Management (CM) with the addition of another layer of security protocols layered on SOME/IP [8].

2) *FastDDS*: An open-source *communication middleware* standard in competition with SOME/IP is the DDS standard defined by the Object Management Group (OMG). FastDDS is an open-source implementation of this standard. The DDS standard defines communication patterns in distributed systems and a wire protocol [34]. Due to the open-source nature, large community, and inclusion in the ROS 2 project, it represents a good choice for communication middleware.

Communication in DDS is data centric. Data in DDS is structured using the publish-subscribe communication pattern. It is associated with a topic and is accessible to all participants who are subscribed to the topic. This type of communication can also be classified as anonymous communication because the sender is not required to determine a specific receiver [28].

The core component for communication on the DDS layer is the domain participant which an application can create to begin FastDDS communication. To send data to a topic, a participant can create a publisher for this topic [30]. To receive this data, a participant that requires this data can create a subscriber to be informed when new data is available. This mechanism continues to work even for newly joined FastDDS applications, which can subscribe and/or publish to existing topics and seamlessly interact with the existing network at runtime.

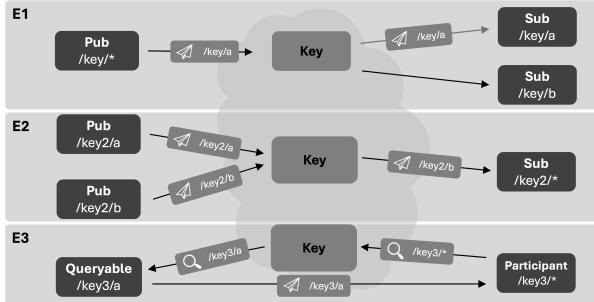


Fig. 9. Non-comprehensive illustration of Zenohs resource-structured communication patterns. Publishers and subscribers communicating using keys and selectors and Queryables operating as sources of Zenohs resources.

The integration of new participants is enabled by dynamic service discovery, where FastDDS applications advertise their presence using multicast UDP messages to other applications on the same network [31]. Discovery takes place in two phases; In the first phase, other applications in the same network using FastDDS are discovered. Once these are known, information about endpoints such as subscribers and publishers is exchanged and communication channels are established. FastDDS also offers other mechanisms, such as manual, static, or predefined discovery, to reduce discovery times and to have more control over the discovery process. This allows for the configuration of a fixed communication topology, eliminating the need for the discovery process, or a dynamic discovery process, where new participants are connected at runtime into the communication at the cost of overhead discovery traffic. DDS specifies the RTPS protocol on top of TCP or UDP for communication, but additionally FastDDS also supports shared memory [32]. It seamlessly switches between these depending on the network topology, similar to SOME/IP.

To address mixed-criticality traffic with different requirements, FastDDS offers control over QoS to configure transmission reliability, message history storage behavior, among other settings for each topic, endpoint, and participants in the network [29]. Using these QoS settings, the application can configure if a history of past sent messages should be kept, if the communication must be reliable, or if only the best transmission effort should be made. These configurations present a trade off, as reliability may incur overhead while best-effort may result in messages lost in case of contention. FastDDS offers extensive QoS parameters, defined in [29].

To address security challenges in IVNs, the DDS standard offers multiple extensions. From these extensions, FastDDS implements tools for the authentication of participants when joining a DDS network [33]. In addition, it implements access control methods to prevent participants from performing protected operations, cryptographic extensions that enable the encryption of traffic between endpoints, and additional security features.

3) *Zenoh*: Zenoh is a recent addition to the domain of *communication middlewares*. According to the developers Corsaro *et al.* [20], it was designed with the lessons learned from more

established middlewares, such as DDS and Message Queuing Telemetry Transport (MQTT). It aims to improve performance by decreasing protocol transmission overhead and reducing latency in contrast to existing protocols. In addition, Zenoh seeks to address a multitude of challenges, such as scale, network topology, resource constrained devices, and data in motion and at rest.

In Zenoh, data is structured in *resources* (*key, value*) and associated with keys [20]. Keys are used to identify data, such as */key/a* and accessed by using either the key or a selector [20]. A selector allows for the specification of matching operators that enable access to multiple keys at once.

For instance, to select multiple subresources at once, */key/** could be used. Fig. 9 illustrates the communication paradigms used by Zenoh, such as resource-structured publish-subscribe and queryables.

Supporting this data model, the core components of Zenoh are publishers, subscribers, and queryables. Publishers can be understood as origins of Zenoh resources, creating resources for a single key or for a key expression. Shown in Fig. 9 in example one. Similarly, subscribers can be understood as the sink of resources, again delivering all resources that match either a single key or an expression. This is shown in Fig. 9 in example two by a subscriber for */key2/**, as this subscriber receives both messages from */key2/a* and */key2/b* publishers. Queryables deviate from the known publish-subscribe communication pattern by delivering a resource if a key to which their expression matches is queried [20]. Fig. 9 again illustrates this in example three, where a participant queries for */key3/**, to which the queryable that generates */key3/a* resources responds with a */key3/a* resource.

The components in Zenoh are built from a limited set of primitives. These allow for the declaration of the previously discussed components, such as subscribers, publishers, resources, and queryables. However, they can also be used directly as atomic primitives. These primitive are *put*, *delete*, and *get*. The *put* primitive allows for the creation of new resources, while the *delete* allows for destruction. The query operation *get* issues queries to the Zenoh system. The parameters allow for the specification of the matching policy.

The Zenoh protocol can be used on the data link, network, or transport layer, which enables it to operate with embedded systems in resource constraint environments. To secure communication, Zenoh offers support for authentication and secure channel plugins and can operate on the TLS security layer.

4) *Communication Middleware example*: In a automotive software system built on a *communication middleware* and a modern E/E architecture, a single ECU can support multiple applications and is likely to have additional compute capacity. The middleware allows applications to communicate transparently between different ECUs and new applications can dynamically extend the automotive software system.

To implement the expansion of the operational domain to the city, presented in Section II-G, the applications in an architecture based on a *communication middleware* could be updated. If sufficient compute resources are available,

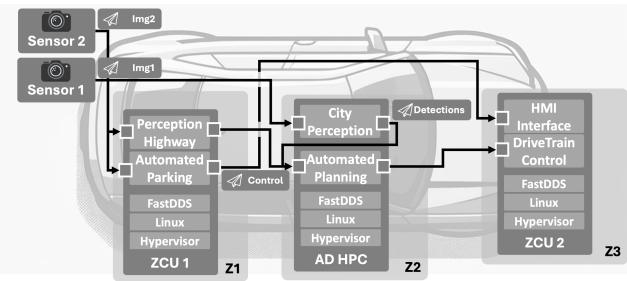


Fig. 10. Example software system architecture using a *communication middleware*. Multiple applications share ECUs and communicate using DDS. In DDS, topics serve as the communication keys. In signal-oriented architectures fieldbus systems structure communication, illustrated in Section II-G.

the updated applications could be deployed to the existing ECU. The deployment of such an application is illustrated in Fig. 10, in contrast Section II-G illustrates the system in a domain-based architecture. No changes to the communication infrastructure or other applications are required, as the new application can integrate into the DDS domain. To accomplish this, the application can subscribe to existing topics and access the data required for its function. The new application can then easily collect images and sensor data from all sensors in the vehicle, including the near-field sensors, originally included in the vehicle for automated parking. In addition, it can also send new trajectory commands using the existing *Control* topic to send commands to the drivetrain ECU. This can be accomplished by publishing new messages using DDS and can occur without changes to the drivetrain ECU.

The core advantage of this approach is that no new dedicated ECU is required to add new functions. However, *communication middlewares* do not provide automated tools for this process and offer few other assurances, as their focus is on communication. No changes are required to the remaining applications as a result of the extension. However, this approach presents the risk of computing resource contention on the automation module and possible network contention. Additionally, ECUs or vehicle computers running a full operating system and communicating over ethernet introduce new cyber security attack vectors over a signal-oriented architecture.

B. What are architecture platforms?

Definition III.8 (*Architecture platforms*). *Architecture platforms* are comprehensive frameworks for the development of automotive software systems. Beyond communication, they enforce software design patterns, offer comprehensive tooling for development and deployment, and often provide execution models, security features, and system state management concepts.

While communication is the core challenge of any middleware, automotive software systems present additional challenges. Among these challenges are wide-ranging questions such as real-time requirements and deterministic compute in distributed systems, requiring mechanisms to ensure communication and compute deadlines are met, and computations are

unaffected by varying propagation delays through the software system. In the same vein, in a distributed software system, allocation of resources becomes a non-trivial task, especially in a changing software system supporting OTA updates. *Communication middlewares* commonly offer no solutions to these questions, while *architecture platforms* seek to address them.

Architecture platforms are broad software frameworks that address multiple challenges from different domains, such as software updates, maintenance, resource allocation, and determinism. To provide communication, they generally make use of a *communication middleware* discussed in Section III-A. This relationship was already illustrated in Fig. 5, where AUTOSAR AP uses SOME/IP for its communication. Thereby, inheriting the advantages these *communication middlewares* offered to applications and building on them. In addition *architecture platforms* commonly use software design patterns. An example of these software design patterns is service-orientation, which proposes a division of software into individual components according to their functionality [43]. This offers advantages for reuse, development, management of responsibilities, and updatability of the software system.

Examples of these *architecture platforms* include ROS 2 and AUTOSAR AP, which will be discussed in the following Sections III-B1 and III-B2.

1) *ROS 2*: The dominant *architecture platform* in the robotics domain is ROS 2 [53]. We classify it as a *architecture platform*, as it is a feature-rich framework for robotic software development [51]. ROS 2 is a publicly available open-source project. Researchers and organizations have suggested adopting ROS 2 in the automotive sector, given the success of ROS 2 in the robotic domain and similarities to the automotive domain [39]. A private company seeking to bring ROS 2 to the automotive domain is Apex.AI. The company provides a proprietary spin-off variant of ROS 2, known as Apex.OS, which is tailored for the automotive industry. Apex.OS is certified to ISO 26262, ASIL D. Consequently, this framework is suitable for use in safety-critical automotive software applications [12], [27].

The software architecture in a ROS 2-based software system follows Service-oriented Architecture (SOA) software design patterns, as the software is divided into distributed nodes in a compute graph [62]. These nodes perform functions similar to services and are in general independent of their underlying hardware.

ROS 2 employs a DDS-based *communication middleware* for its communication. This *communication middleware* provides features as discussed in Section III-A2, such as discovery and publish-subscribe communication pattern. However ROS 2 also builds on DDS to implement additional functions and offers the option to exchange DDS implementations [60]. For basic communication between nodes, two communication patterns are available in the framework.

- Publish-Subscribe communication is used by ROS 2 for connections between nodes. Consequently, the DDS topic software design pattern is retained, but ROS 2 provides its own serialization solution. With this solution, ROS 2

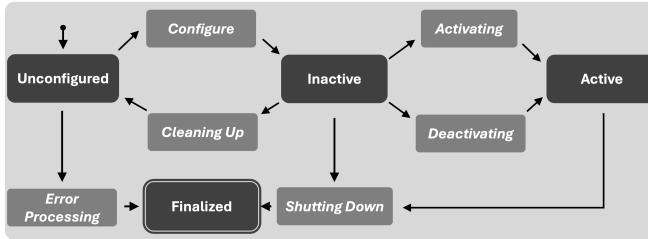


Fig. 11. Overview of the ROS 2 lifecycle state machine. Transitory states are shown in grey and primary states in black[52].

enables communication between multiple programming languages. Thereby allowing for cooperation between nodes using different languages. Additionally, ROS 2 provides an execution model that controls communication callbacks to user code. In this model, imposes an execution order on these callbacks and timer activation's using the executor execution model.

- Request-Response is build on DDS publish-subscribe communication. This software design pattern is implemented in services and actions. Services expose a remote interface possibly on another ECU, which can be called and returns a response upon completion. Actions behave similarly; however, in addition to responding, they provide periodic feedback to the calling node on the progress of the request.

In ROS 2, the execution model takes the form of the executor model with a callback-driven interface [51], [58]. User-specified timers, events, and message handlers can be enrolled in the executor instance. The executor itself then processes the callbacks of the enrolled function, such as the callbacks of the message handler, in a partially predictable manner [51]. Execution models, such as executors, enable assumptions about the behavior of a node and, by conclusion, the automotive software system at large.

However, the standard execution model of ROS 2 does not support a strict execution order or deterministic execution times [39]. When events or messages must be queued for processing, which could be the case when the frequency and processing time of callbacks exceed the capacity of a single thread, the executor handles them using a round-robin approach. This can have adverse consequences, such as priority inversion and task starvation. Consequently, critical task timings may be missed, making it difficult to reliably estimate worst-case execution times for task execution [14], [58].

An improved version of the ROS 2 execution model is implemented in the *micro-ROS* framework. Designed for embedded systems, it offers an improved executor compared to the default in ROS 2 [14], [52]. This executor, called *rclc*, enables a fixed execution order and deterministic scheduling [74]. In addition, it can directly manage the operating system scheduler, enabling custom task prioritization [14].

ROS 2 also supports configuration management. It provides

a parameter API that allows the user to set default parameters and change the parameterization of nodes at runtime [51], [63]. To start a ROS 2 software system of multiple nodes, it provides launch files to define the required nodes and start them automatically [61].

To start a ROS 2 software system and transition it to an active state, multiple steps, such as initialization of software components or hardware, might be required. To formalize this startup process and the larger lifecycle of nodes, ROS 2 supports a lifecycle model. This model is implemented as a state machine in every *lifecycle* node. Fig. 11 illustrates the transitions between *primary* states. These state transitions allow for the representation of tasks at the start and termination of nodes. These may include the start sequence for a sensor system or initialization of external software components. This mechanism can also be used to free system resources if a node is temporarily inactivated or shutdown. The transitions of the state machine within the node can be controlled both externally by a central controller or internally by the node itself [51], [52].

ROS 2 supports secure communications between nodes using the DDS security standard [65]. The standard supports extensions for access control to limit the operations that each entity can perform. Authentication ensures that only permitted entities can join the ROS 2 network. The cryptographic service in the standard allows message encryption to prevent unauthorized access. The security services in ROS 2 are, consequently, provided by the underlying *communication middleware*. To enable security in ROS 2, each participant in the ROS 2 software system needs configuration files, which require additional software for setup. However, to simplify the configuration process, ROS 2 offers the *sros2* package, which includes tools that facilitate the setup of the underlying DDS-Security layer [66], [76].

ROS 2 provides as an expansive open-source project additional tools such as logging with a common interface. To visualize data in an ROS 2 network, the RQT visualization supports many ROS 2 standard messages and can visualize them graphically. ROS 2 rosbag supports recording data in a ROS 2 network and replaying the data to easily replicate and test the nodes.

2) *AUTOSAR Adaptive Platform*: AUTOSAR AP is a standard proposed by the automotive industry for an automotive *architecture platform* [69]. This standard originated in industry to realize the shift from signal-oriented architectures, standardized in AUTOSAR Classic, to middleware-based architectures. It is developed by a large consortium of OEMs and automotive suppliers specifically for the automotive domain. Due to its commercial origin, implementations of the standard are commercially available by a number of companies. AUTOSAR AP form a comprehensive standard, providing solutions to many challenges in modern centralized or domain controller architectures [36].

The explanation of the standards outlines several core software design patterns [5], such as planned dynamics, service-oriented architecture, and parallel processing, among others.

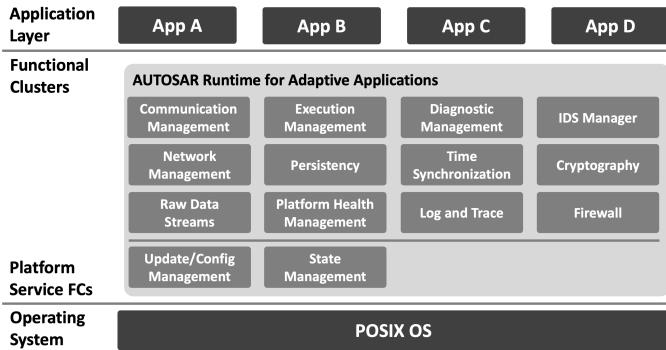


Fig. 12. Overview of the AUTOSAR Adaptive Platform Functional Clusters, derived from [5].

Under the idea of planned dynamics, dynamic operations should be pre-planned in the vehicle such as to ensure their safety and move the computation from the moment of change to before. In the software design pattern of service-oriented software architectures, software is divided into separate services to harness simplified updateability and understanding of the software system.

Adaptive Applications (AAs) are built on AUTOSAR AP and use functionalities provided by it. To access functionality provided by AP Function Clusters (FCs) applications use the AUTOSAR Runtime for Adaptive Applications (ARA) API [3]. In AUTOSAR AP several clusters exist that serve purposes such as communication, execution, and state management, with an exhaustive list enumerated in Fig. 12. Adaptive applications and functional clusters are implemented on a POSIX OS and provide their functions through requests or directly using a library interface. Both of these components run on the underlying machine as processes and generally communicate via Inter-Process Communication (IPC). This communication method uses operating system functions, such as pipes or shared memory, to efficiently communicate between processes.

As a core functionality, the communication management functional cluster exposes several methods for communication between services [8]. Based on the SOME/IP *communication middleware*, it enables inter- and intra-machine communication. It supports the same communication patterns in fields, methods, events, and static or dynamic application discovery as SOME/IP. In addition, it also ensures the type and allowable range of every field in a message. To support communication with the AUTOSAR Classic ECUs, Service-to-Signal (S2S) components can also be employed. These enable transparent mapping between SOME/IP ethernet-based communication and fieldbus systems.

To manage all adaptive applications and functional clusters in a vehicle and ensure their correct startup procedure, the state management and execution management functional clusters exist [9]. The Execution Management (EM) cluster controls execution in adaptive applications, starting and pausing applications as OS processes, while the State Management

(SM) decides which function group to start. In AUTOSAR AP the state management is modeled as a state machine, which controls the initial startup and the configuration of the function group at run-time. Like in ROS 2, the lifecycle can be modeled by transitioning the state machine between multiple discrete states, such as *Startup*, *Shutdown* or *Restart* [9], [39]. Additional responsibilities of the state management include the enforcement of resource constraints and ensuring that only trusted applications can be executed.

AUTOSAR AP also supports methods for deterministic execution in the form of data and time determinism [8]. In the case of execution determinism, the same internal state and input data deterministically produce a predictable result, whereas time determinism ensures that the computation completes before the deadline. To this end, the execution management supports event-based and cyclically triggered execution using the deterministic client interface. To allow for parallelism, the execution management also supports worker pools that a main thread can defer execution to. This approach enables deterministic execution, which is currently not achievable in ROS 2 [52]. However, Menard *et al.* claim that this approach is insufficient to yield a deterministic system and present an approach to address this shortcoming [54].

To ensure security, AUTOSAR AP contains functional clusters for cryptography, firewall, and intrusion detection. These clusters enable encryption of IVN traffic, ensure that all machines only expose necessary ports to the IVN and attempt to detect intrusion attempts [4].

The Update and Configuration Management (UCM) functional cluster in AUTOSAR AP performs package management functions. It supports operations such as updating, installing, removing, and keeping records, similar to traditional package managers. UCM maintains a local registry of packages, which serve as the units of installation within the AUTOSAR AP. Using this mechanism, OTA updates can be applied [5], [39].

AUTOSAR Adaptive also offers clusters for persistence in vehicles, automatic configuration of the IVN, time syncing, diagnostic services, logging and efficient data transmission using raw data streams. Fig. 12 depicts a comprehensive overview of all functional clusters specified in AUTOSAR AP.

3) *Architecture platform example:* In a software system built on a *architecture platform*, the *platform* commonly enforces a service-oriented architecture of the applications. Furthermore, *architecture platforms* often have a run-time environment in which the application runs. This environment supports additional functions to help in the deployment, maintenance, and development of the automotive software system and its applications.

In our example, using a *architecture platform* would make it possible to implement the expansion of the operational design domain by automatically deploying a new service to the automated driving ECU. This deployment can be accomplished using OTA updates using AUTOSAR APs UCM cluster, and the service is provisioned with the required resources by the execution management functional cluster. This approach inher-

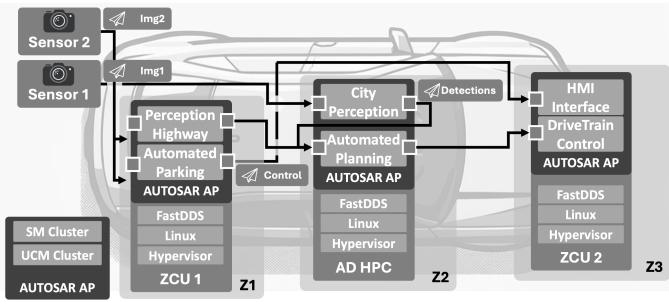


Fig. 13. Example software system architecture using a *architecture platform*. All components are finely divided into individual service-oriented components and have an individual runtime environment provided by the *platform*.

its the benefits of the underlying *communication middleware*, such as modular and flexible communication, as depicted in Fig. 13. Applications can still use the topic-based publish-subscribe paradigm for message exchange, and the service could access all sensors in the vehicle. It would also be able to issue commands seamlessly, similar to the *communication middleware* example.

The core advantage of this approach is that *architecture platforms* require the division of software components into services and offers support for these services. The service-oriented architecture ensures a clear division of responsibilities and therefore simplifies updates, maintenance, and even development. The *architecture platform* introduces additional capabilities for OTA updates, software system parameterization, and resource management. The runtime environment aids in the deployment of the new service, employing virtualization techniques to efficiently allocate and manage computational resources. However, the increased cyber-security risk is also retained, due to the increased complexity of components involved in supporting an application.

IV. COMPARISON OF MODERN MIDDLEWARES

We compare the five introduced middlewares, ROS 2, AUTOSAR AP, FastDDS, SOME/IP and Zenoh in Table I from an automotive perspective. Each column contains information about a single middleware and they are sorted according to our *communication middleware* and *architecture platform* classification. The middlewares were assessed based on non-technical and technical criteria, reflecting their design purposes, adoption in the community, communication patterns, real-time capabilities, and other significant features.

In conclusion of the presented *communication middlewares*, DDS and its implementations is the most fully featured and proven middleware. Its large set of discovery features, highly configurable quality of service settings, and large number of security features are among its advantages. In addition, its use in ROS 2 and now the inclusion of DDS in the AUTOSAR AP standard attest to the maturity and feature richness of DDS. In contrast, SOME/IP offers a reduced feature set, especially in the context of security, shared memory transport, and

limited quality of service configurability. Additionally, for a time, no open-source SOME/IP implementation was available, while multiple DDS implementations are freely accessible, well supported, and tested. However, due to the support of the AUTOSAR Consortium and its focus specifically on the automotive domain, it may remain relevant in the domain. The newest and least proven *communication middleware* in this comparison is Zenoh. In our opinion Zenoh does not present fundamentally different paradigms in comparison to existing *communication middlewares*, but may present a performance improvement over DDS implementations or SOME/IP. Zenoh promises to be more efficient and offer higher communication throughput than the other two *communication middlewares*. However, the amount of independent literature to verify these claims is limited. Furthermore, Zenoh supports both resource-constrained and embedded devices and various network topologies, making it more versatile than DDS. Consequently, Zenoh should be evaluated in future work for its performance in different automotive environments and could present a challenger to DDS.

When comparing the two presented *architecture platforms*, the main difference is the part of the development cycle at which these *platforms* are aimed. While AUTOSAR AP provides a large number of features for the deployment of applications to production vehicles, ROS 2 is focused on development. This is reflected in the license model of these *platforms*. ROS 2 targets research and development, is free and open-source, while AUTOSAR AP is only accessible through the purchase from commercial partners, as it targets OEMs and automotive suppliers. Consistent with this focus, AUTOSAR AP specifies many features for resource control, configuration management, and state management, to ensure that applications can be correctly deployed in real vehicles. ROS 2 on the other hand, offers many features such as visualizations, standard messages, already implemented packages, and a large ecosystem to support the easy and fast development of new applications. Although provisions for starting applications are implemented, for example, no system health monitoring or complete software system configuration tools, as can be found in AUTOSAR AP, is build into ROS 2. This reduces the suitability of ROS 2 for deploying applications in production vehicles. In this context, the developments of APEX.AI should be examined, as their proprietary ROS 2 fork combines some advantages of both software systems.

V. RESEARCH CHALLENGES

Middleware-based software architectures in cooperation with zone-based E/E architectures address many current challenges for AVs. However, despite being the solution to considerable challenges, middlewares also face open research challenges themselves. These challenges range from real-time communication in ethernet-based IVNs to resource allocation in a automotive software system where services can be arbitrarily assigned to ECUs. The following section presents some of these challenges, organized into five categories, and research seeking to address them.

TABLE I
MIDDLEWARES IN THE AUTOMOTIVE DOMAIN

Criteria	Robot Operating System 2	AUTOSAR Adaptive Platform	DDS (FastDDS)	SOME/IP	Zenoh
Non-Technical Criteria					
Type of Middleware	<i>Platform</i> robotics [51]	<i>Platform</i> automotive [5]	<i>Communication</i> general [28]	<i>Communication</i> automotive [5]	<i>Communication</i> general [20]
Operation Domain	open-source, free [51]	closed-source, commercial [5]	open-source, free [28]	closed-source, commercial [5]	open-source, free [23]
License and Accessibility					
Documentation	open, comprehensive documentation [51]	standards, commercial partner ² [5]	open, comprehensive documentation [28]	standards, commercial partner ²	open documentation [23]
Software Tooling	extensive [65]	commercial partner ²	extensive	commercial partner ²	limited
Industry Adoption	widely, robotics [53]	emerging, automotive industry [81]	widely, various industries	emerging, automotive industry	emerging, various industry [25]
Technical Criteria					
Communication patterns	publish-subscribe, request-response [51]	methods, fields, events [8]	publish-subscribe [28]	methods, fields, events [6]	publish-subscribe, put-get, queryables [20], [23]
Real-Time Communication	soft real-time [51]	soft real-time [8]	soft real-time [28]	soft real-time [6]	unsupported
Quality of Service	derived from DDS [64]	derived from DDS [8]	extensive [29]	lim-ited/unsupported [6]	limited - Reliable/BestEffort [25]
Communication Protocols	DDS - RTPS [51]	DDS - RTPS, SOME/IP	RTPS - TCP/UDP, shared memory [32]	proprietary - TCP/UDP [6]	proprietary [20]
Execution Model	executors concept [58]	EM deterministic client [9]	unsupported	unsupported	Zenoh-Flow [26]
System State Management	lifecycle nodes [51]	State Management [4]	unsupported	unsupported	unsupported
Application Configuration Management	node parametrization [51]	UCM [4]	unsupported	unsupported	unsupported
Application Discovery	automatic [31], [51]	automatic [7]	manual / automatic [31]	manual / automatic - SOME/IP-SD [7]	automatic [24]
Application Update Mechanism	unsupported	UCM [4]	unsupported	unsupported	unsupported
Feature Extension	supported ³ [51]	unsupported [4] ¹	supported ³ [28]	unsupported [4] ¹	supported [25]
Application Resource Management	unsupported	supported, EM [9]	unsupported	unsupported	unsupported
Communication Encryption	supported, SROS 2 [51], [65]	supported, CM [8]	supported [33]	unsupported ⁴	supported, TLS [20]
Application Authentication	supported, SROS 2 [51], [65]	supported, CM [8]	supported, DDS Sec [33]	unsupported ⁴	supported, TLS [20]
Additional Security Features	DDS Sec, SROS 2 [51], [65]	IDS, Firewall, Network	access control [33]	unsupported ⁴	unsupported
Platform Support	Linux, MacOS, Windows [59]	POSIX OS [4]	Linux, MacOS, Windows, Android, QNX [35]	POSIX OS	Desktop OS, embedded devices [20]

¹ Outside of the AUTOSAR Consortium and the cooperation processes. ² As a standard, the implementation and support provided depends on the individual company that completed the implementation and the tools they provide. ³ As open source software, additions are possible without membership in a committee.

⁴ Handled in the AUTOSAR AP by the Communication Management functional cluster. ⁵ An open-source implementation of SOME/IP exists, in the form of VSOMEIP by BMW.

A. Challenges in Real-time Communication

Despite the disadvantages of legacy E/E architectures, an advantage is better predictability and control over message scheduling. However, in regular ethernet-based IVNs the same property is not guaranteed, as network congestion, packet loss, and mutual interference in communication between ECUs are possible [77]. To address this challenge, researchers propose the use of Time-sensitive Networking (TSN), an ethernet extension that introduces additional controls on communication and flow [48]. Brunner *et al.* [18] proposed an initial research on this topic, which highlights the advantages of TSN use in the automotive domain. Migge *et al.* [55], present details on the performance and configuration of TSN in the ethernet IVNs. However, currently no standard solution has been introduced in ROS 2 and AUTOSAR AP. Another approach to provide more guarantees for IVNs is the use of Software-Defined Network (SDN) features. Häckel *et al.* [38] investigate the combination of TSN and SDN combination to assess its suitability for the automotive domain. Rotermund *et al.* [70] research the performance of SDN controllers for vehicles. To achieve heterogeneous systems, where middlewares operate on all devices in a automotive software systems, support for embedded devices is necessary. Kampmann *et al.* [46] implement DDS for multiple automotive platforms.

B. Challenges in Real-time Execution

The introduction of ZCU and high performance ECUs in vehicles E/E architecture also requires the use of full-scale operating systems, such as Linux [36]. This change of platform directly affects the execution of software and associated hard real-time requirements. However, the use of Linux in safety-critical systems remains also an area of active research [72]. By default, Linux does not guarantee real-time execution, and with OTA updates and updates to vehicle software, tight control over thread execution, timing, and predictability are not guaranteed [17]. Furthermore, with possible resource congestion both on the IVN and between applications, new approaches are necessary to guarantee reliable and deterministic execution. To address this challenge and ensure intelligent resource provisioning, Blass *et al.* propose a latency management framework for ROS 2 [17]. A similar problem is addressed by Menard *et al.* [54] in the context of the AUTOSAR Adaptive framework. However, in the case of ROS 2 and AUTOSAR Adaptive, no holistic implementation has been integrated into the framework and the standard yet. It remains an active research question as to how best to achieve a deterministic distributed automotive software system.

C. Challenges in Security and Safety

Another consequence of the inclusion of Ethernet-based IVNs and high performance ECUs is the increased cybersecurity attack vectors [21], [71], [76]. While in traditional ECUs the code was deeply embedded in the hardware, now the middleware, the OS, and the network present new attack vectors. To survey these challenges, Rumez *et al.* [71] provides an overview of the security implications of the application of

service-orientation to automotive software architectures. Approaches, such as Intrusion Detection System (IDS), firewalls and encryption can already be found in some middleware, for instance AUTOSAR AP offers functional clusters for these challenges [4] [68]. Vilches *et al.* [76] propose a security approach for ROS 2, while ROS 2 also offers some features based on the DDS security extension. However, more research is required to identify whether these solutions are comprehensive and what additional approaches might be required.

D. Challenges in Orchestration and Resource Management

Applications build on middlewares are, unless they require interaction with specific sensors, actuators, or compute accelerators, such as GPUs, independent of the platform that executes them [19]. This independence also presents a resource allocation challenge for applications in the automotive software system and the specific ECU. An approach to manage resource use and separation of applications is containerization and virtualization [16]. Enabled by containerized applications, multiple research questions emerge such as where to deploy individual applications and how to orchestrate them. To address this question, Nayak *et al.* in [56] presents an overview of the requirements, challenges, and directions of containerization for automotive applications. Similarly to the ability to control containerized applications, ROS 2 lifecycle nodes and AUTOSAR AP applications offer lifecycle controls. These controls enable a controller, such as an Orchestrator, Kubernetes, or AUTOSAR AP SM to free parts of the resources used by a service by deactivating it [4], [44]. One approach by Kampmann *et al.* using an orchestrator to manage an automotive software system, is the Automotive Service Oriented Architecture (ASOA) [43]. More research is required to achieve an optimal assignment of resources and to conform the software system to the requirements of the specific situation [42].

E. Challenges in Machine Learning Applications

Modern software systems and software in automated vehicles are increasingly based on artificial intelligence and Machine Learning (ML) capabilities. Applications built on these technologies present unique challenges to software architecture in general [2], and specifically to the automotive domain, as recognized by Kugele *et al.* Serban *et al.* [73] and Amershi *et al.* [2] discuss in detail the unique challenges of artificial intelligence that applications pose. The challenges include the limited interpretability of Deep Learning (DL) models and their potential non-robustness on unseen data. In a software system with multiple DL components, the authors predict a potential cascade of failures as each component produces adverse results for the next. From these requirements, they derive increased monitoring requirements and the need to increase robustness using, for instance, n-versioning. These challenges are interwoven with the application design, but middlewares could offer solutions to these challenges.

VI. CONCLUSIONS

This article presented a tutorial on middlewares for automated vehicles. The tutorial introduced the fundamentals of automotive computing, gave an overview of five modern middleware, and compared them. We classified middlewares into *communication middlewares* and *architecture platforms*, to highlight the former's communication purpose and the multi-domain, framework nature of the latter. Among the *communication middlewares* we presented, DDS remains the most fully-featured solution, while the Zenoh *communication middleware* represents a new challenger to DDS promising improved performance and latency. Among *architecture platforms* we concluded that the place in the development cycle determines the *platform* to choose. ROS 2 focuses on features for development and testing, while AUTOSAR Adaptive offers comprehensive features for deployment. Although middleware addresses many challenges in vehicles, research questions remain. Finally, the article presented open research questions for middlewares. The most prominent questions were related to real-time or deterministic communication and execution in automotive software systems. Increasing complexity and capability of automotive software systems also require new approaches to safety and security. Middleware-based architecture also pose resource allocation and orchestration challenges.

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VIII. ACRONYMS

AA	Adaptive Application
AD	Automated Driving
AP	Adaptive Platform
API	Application Programming Interface
ARA	AUTOSAR Runtime for Adaptive Applications
ASOA	Automotive Service Oriented Architecture
AV	Automated Vehicle
CAN	Controller Area Network
CM	Communication Management
CPS	Cyber Physical Systems
DDS	Data Distribution Service
DL	Deep Learning
E/E	Electrical/Electronic
ECU	Electronic Control Unit
EM	Execution Management
FC	Function Cluster
FPGA	Field Programmable Gate Array
GPU	Graphics Processing Unit
HMI	Human Machine Interface
HPC	High-Performance Computer
IDS	Intrusion Detection System
IoT	Internet of Things
IPC	Inter-Process Communication
IVN	In-Vehicular Network

ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
OEM	Original Equipment Manufacturer
OMG	Object Management Group
OS	Operating System
OTA	Over-The-Air
QoS	Quality of Service
ROS 2	Robot Operating System 2
S2S	Service-to-Signal
SDN	Software-Defined Network
SDV	Software Defined Vehicles
SM	State Management
SOA	Service-oriented Architecture
SOME/IP	Scalable service-Oriented MiddlewarE over IP
TCP	Transmission Control Protocol
TSN	Time-sensitive Networking
UCM	Update and Configuration Management
UDP	User Datagram Protocol
ZCU	Zone Control Unit

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