APTIV

CES 2024: What You Need to Know

Time to Roll Up Our Sleeves

It's important to dream big. And it's important to have a vision for where technology can take us next. But it's equally important to have a roadmap for getting there.

At the Consumer Electronics Show in Las Vegas, so much of the focus is on the future — from flashy slogans printed on show-floor tchotchkes to conference sessions about where we'll park our flying cars.

Aptiv is looking to the future in our pavilion across Convention Center Drive as well, but we also deeply understand the challenges associated with building that future, and we have the technologies and the tools to work with our customers to make our shared vision a reality.

When you visit the tech theater inside the Aptiv pavilion at CES 2024, you'll see that vision up close — one that goes beyond automotive as we know it, to a world where seamless connectivity and software-defined vehicles open up new possibilities for safety and convenience. You'll be surrounded by the technologies that are necessary to get us to that future — and when you step outside, you'll experience those technologies operating in fully drivable vehicles.

To get the most from your visit, you're going to need some background. That's where this collection comes in.

We start with the software and hardware architecture optimized to enable the software-defined vehicle (SDV) — the abstraction, determinism and updatability over time. The **sustainable SDV architecture** is Smart Vehicle Architecture™ fully realized, and our first chapter covers some key aspects.

With the architecture in place on the vehicle, it's necessary to have an **edge-to-cloud connected platform** to support it. The platform must enable updates that are lightweight and secure and don't interfere with other functions. The second chapter expands on our solution: modular, containerized software supported by open and flexible Wind River technologies.

Chapter 3 examines **intelligent perception.** We'll be showing some exciting applications of Aptiv's intelligent perception capabilities, so you'll want to read our background on radar, cameras and our differentiated approach to automated parking.

There are even more innovations debuting around **high-voltage electrification,** so Chapter 4 is here just to whet your appetite for a few of them: direct contact technology for interconnects, the emerging NACS charging standard and the ultracapacitor technology that underpins the innovative Aptiv Rapid Power Reserve system for backup power. There will be more at the show, I promise.

Chapter 5 closes this year's edition with some good news on **sustainability,** along with more on how Aptiv's approach to sustainability continues to evolve.

We look forward to discussing these topics and more with you at CES — and if you aren't able to attend this year, we hope this gives you some food for thought for continuing the conversation about how we all can move the industry closer to a safer, greener and more connected future.

Jeff Caruso
Vice President, Thought Leadership

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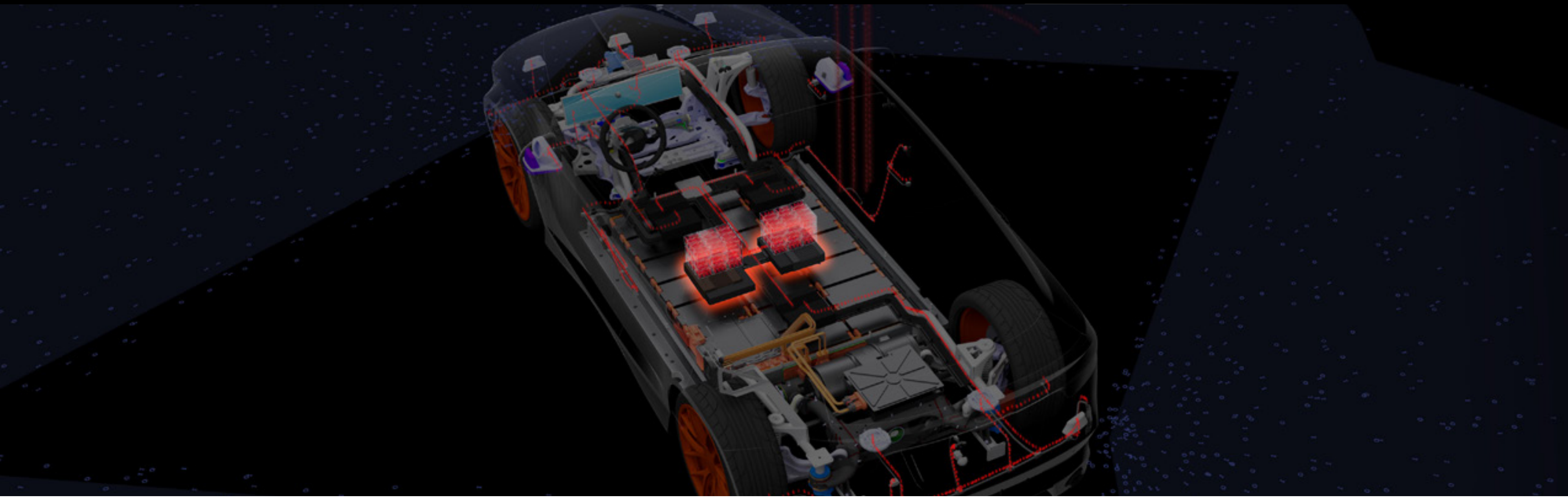
Sustainable SDV Architectures

APTIV AT CES 2024



Open Server Platform Requires Shifts in Hardware and Software

The biggest strength of the software-defined vehicle is that it evolves. A vehicle leaves the factory with a certain set of capabilities, but the OEM is able to leverage usage data and expand those capabilities over the vehicle's full life cycle through over-the-air updates, enabling it to deliver better driving performance, improve the in-cabin user experience (UX), and otherwise make an aging vehicle feel new every day.

Hardware, however, does not evolve. Historically, once the vehicle left the factory, the hardware remained the same.

This dichotomy eventually presents a challenge to the software-defined vehicle. While centralizing and serverizing compute can be a cost-effective solution for sharing workloads, reallocating resources and extending its usefulness, at some point, the compute hardware will be too outdated to take on new software features that require faster processing, more memory or greater storage capacity.

OEMs can address these limitations with the right software and hardware architecture — one that not only has the flexibility to dynamically reallocate resources in real time, but also allows physical upgrades to just the specific compute components that need it the most, well into the future. Done right, the approach will also help them create independent software and hardware ecosystems while greatly extending the life of their vehicles.

BRAIN SURGERY

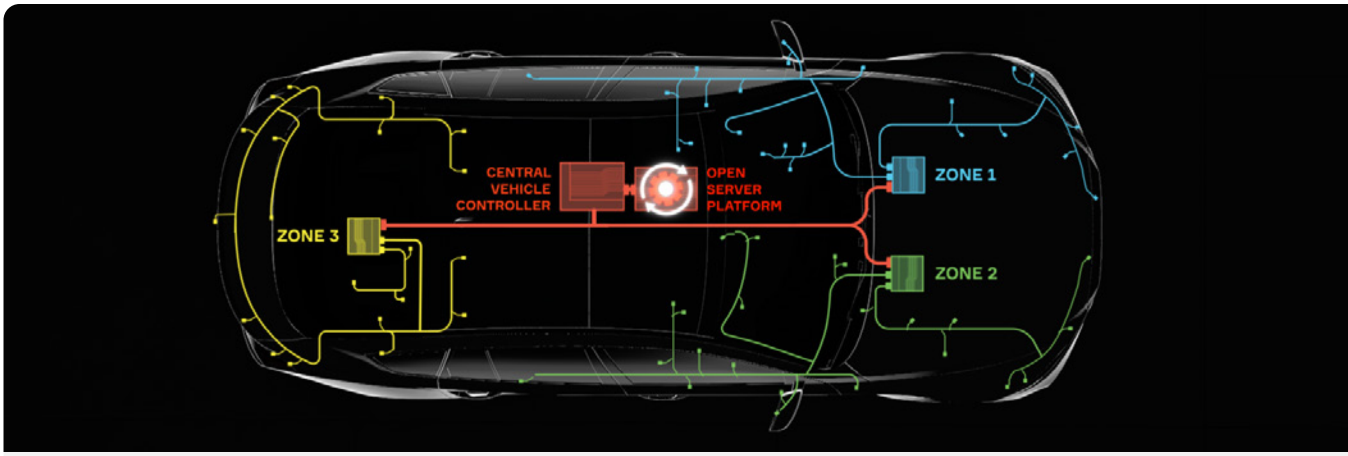
We often think of the compute in a vehicle as its “brain.” After all, just as a human brain takes in information and acts based on that input, the vehicle’s compute platform takes in data from sensors and other outside sources and makes decisions about what to do and what to communicate.

A human brain, however, changes and grows over time. Babies grow into children, and children grow into adults. As their brains physically change, they become capable of greater understanding and more complex reasoning.

In contrast, computers are static, with defined processing limits. As software developers create ever more sophisticated and capable applications, they push those limits until it is necessary to move to the next generation of hardware to enable the functions they create.

In the automotive world, newer hardware could also become necessary to meet evolving safety regulations or to ensure that the vehicle continues to employ the latest cybersecurity measures.

Consumers are used to this upgrade cycle in other contexts. In the mobile phone world, for example, many people upgrade to a new device every two to three years, in part to obtain a processor that can adequately support the latest apps, functions and cybersecurity protections. A key difference, of course, is that the expense of replacing an entire phone is much less than that of replacing an entire vehicle. A vehicle also is obviously far more complex, with hundreds of devices distributed throughout, which are increasingly connected to a central compute unit.



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Hardware architecture

The solution in automotive is to structure the software and hardware architecture so that OEMs can upgrade just the compute needed to execute higher-level functions.

On the hardware side, OEMs are already moving to a zonal architecture, where many of the devices in the vehicle connect to their closest zone controller, which in turn aggregates data from those devices and communicates with a central vehicle controller (CVC). In addition to working with the zone controllers to handle all data communication protocols and signaling with the devices, the CVC handles body control functions, data storage, vehicle access, communication with the outside world, and potentially propulsion and chassis control.

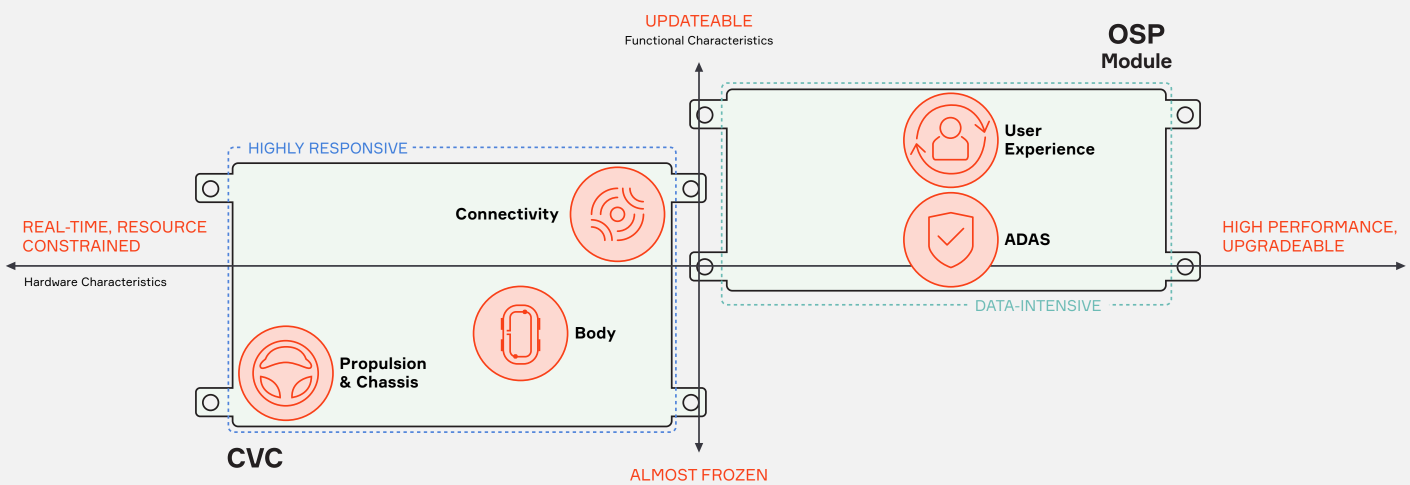
In other words, the CVC and zone controllers manage all of the lower-level functions necessary to run a vehicle. This architecture allows higher-level functions to be supported by a separate compute platform: the open server platform, or OSP.

The OSP is the brain of the vehicle, performing functions that require complex and data-intensive compute capabilities, usually related to advanced driver-assistance systems (ADAS) or in-cabin UX. It might actually be more precise to say that the OSP is the cerebrum while the CVC is the cerebellum, or "small brain," because the CVC translates directives coming from the OSP into actions carried out by the vehicle.

Separating the two architecturally makes a lot of sense. The lower-level functions and communication with vehicle input/output do not change much over the life of a vehicle. But higher-level functions are continuously evolving as developers solve for more use cases or create more innovative UX features. Higher-level functions also require more powerful processing, more memory and a graphics processing unit.

Separate and Unequal

Different vehicle software domains have different needs, so the hardware architecture must be designed to best accommodate those differences. That means running functions either on the central vehicle controller (CVC) or the open server platform (OSP), as appropriate.



Software architecture

The software architecture must also be structured appropriately to support the separation. The key factors are abstraction and interface standardization — that is, presenting a standard, consistent interface to higher levels of software so that those higher levels do not have to be concerned with the details of how the lower levels work.

At the lowest level is the device abstraction layer, or DAL. Devices include everything from sensors (such as radars, cameras and thermal sensors) to actuators (such as seat controls, door locks and window lifters). The zone controllers handle all direct communication with devices, and the DAL presents a standard set of application programming interfaces (APIs) through microservices to higher levels of software for control and diagnostics.

For example, the higher-level software could request through a DAL API that a window be lowered, without having to know how to talk to the window lifter motor; instead, the zone controller would format the appropriate signal through a Local Interconnect Network bus and send that to the window motor. Even sensor data streaming would be standardized.

The next level is the vehicle abstraction layer, or VAL, which abstracts the more complex body control functions managed by the CVC. High-level software would interact with VAL APIs to get data or take actions.

To continue the window-lifter example, abstraction at the VAL level could include a service that manages all aspects of window operation, including user controls, the window lifter motor and so on. Say the in-cabin UX function received a request from a user via the infotainment system to lower all the windows by 50 percent. The UX software would send a command to the window service with those instructions, which would then send individual commands to the DAL APIs for the window lifters on each of the four windows for the duration necessary to lower the windows by 50 percent.

Software containers package together all of the files and libraries with the application that needs them, making the code relatively independent from its host environment.

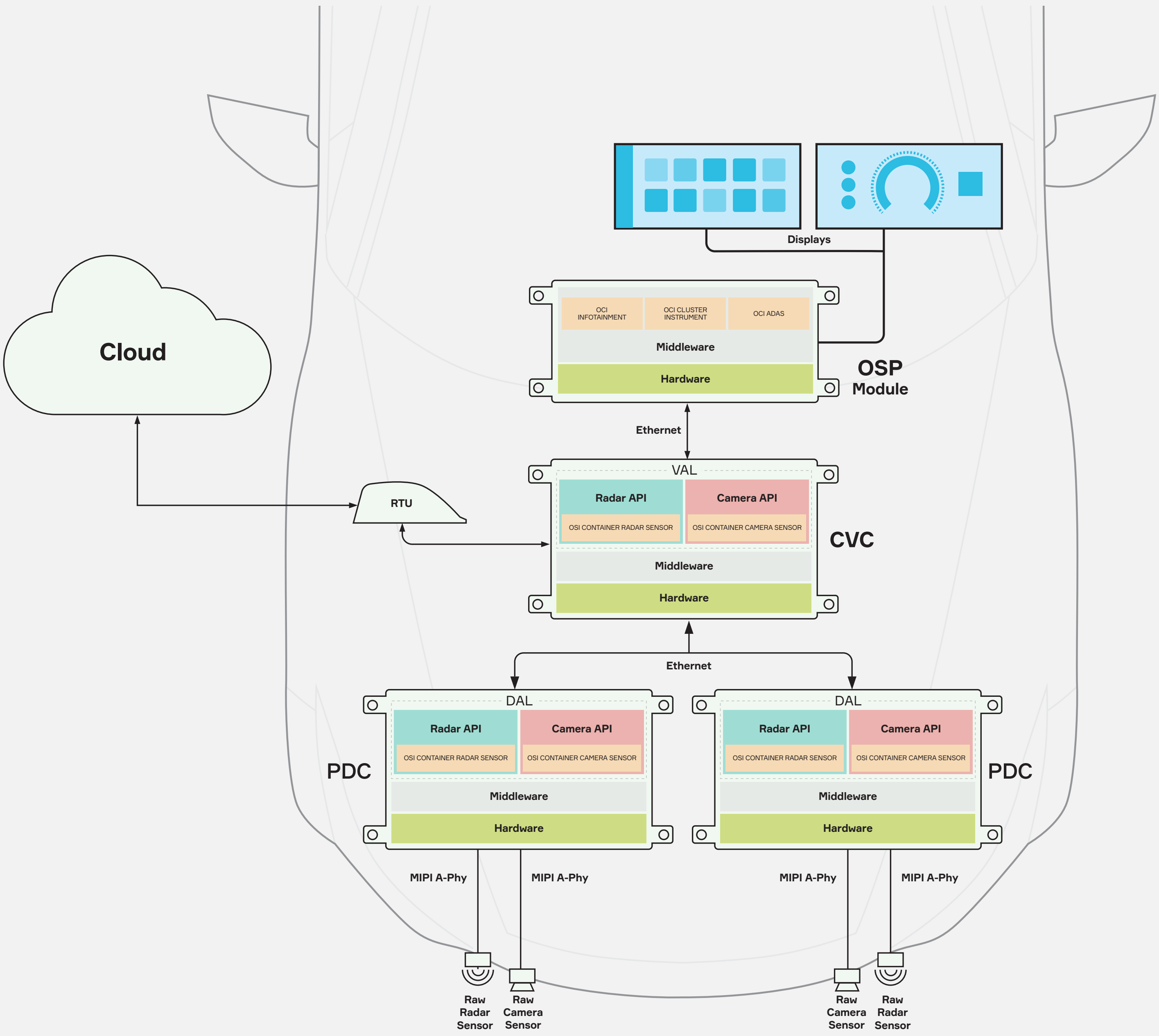
Containerization

Another important piece of the software architecture is containerization. Software containers package together all of the files and libraries with the application that needs them, making the code relatively independent from its host environment. This approach helps to create a service-oriented architecture where individual services, each tied to its own container, can be updated individually without affecting other software.

Containerization also helps disconnect software development from the hardware it runs on. That means that containerized services could potentially be moved from one compute platform to another. It also means that containerized applications are not tied to the hardware they run on, so the hardware that comprises an OSP could be changed — from one system-on-a-chip to another, for example.

Layers of Abstraction

Each device in the architecture uses software abstraction to enable higher levels of functionality. Power Data Center (PDC) zone controllers handle communications with devices and present a Device Abstraction Layer (DAL) to the central vehicle controller (CVC), which in turn presents more complex functions to applications running on the open server platform (OSP).



A FLIPPED SCRIPT

With those major architectural elements in place, the OSP becomes swappable. The hardware is structured so that the higher-level functions are isolated on the OSP. The software is structured so that any applications on the OSP communicate to the vehicle through standard interfaces. And software containerization abstracts the applications' access to compute on the OSP. As the OSP ages and becomes unable to run the latest applications or receive the latest operating system updates, the owner can take it to a dealership to exchange it for a newer and more capable OSP — without disturbing the rest of the vehicle architecture.

The ramifications go well beyond the OSP, however. Taken together, these factors enable independent software and hardware ecosystems.

- **Machine ecosystems:** The hardware can be developed and certified independently of any application software. Performance can be characterized by standard benchmarks such as processing speed and memory capacity. Development cycles can be 18 months or less.
- **Device ecosystems:** All devices in the vehicle will combine proprietary hardware and software but will be aligned to a standard API. They will connect via standard buses. Their development will not be connected to any particular machine or application.
- **Application ecosystems:** Containerized applications can move from one hardware platform to another without a software change. Standard UX and ADAS stacks with well-defined APIs can help scale. And all applications can be developed in a cloud environment.

Because these ecosystems are independent, vendor lock-in becomes obsolete. Devices, applications and machines can all be replaced without disturbing the other ecosystems.

Having swappable OSPs also allows OEMs to easily differentiate among models or trim levels. Two models with the same devices and CVC could have different ADAS or UX capabilities, just by connecting different OSPs with hardware that correlates with their software capabilities.

When a vehicle is built with these hardware and software foundational elements, the way is clear for realizing the true potential of software-defined vehicles, ensuring that they have the most up-to-date capabilities for years to come.

THE VIEW FROM SVA™

Aptiv's Smart Vehicle Architecture™ technologies take all of these factors into account as they lay the groundwork for future enhancements.

From a hardware perspective, our OSP modules can be designed to either stand alone or install directly atop a CVC, with a liquid cooling plate between them to keep temperatures down. The configuration further optimizes hardware cost and makes the OSPs easy to swap out when an upgrade is needed.

Automotive Ethernet and PCI Express connect the OSPs to the CVC. Current versions of ADAS-focused compute solutions connect directly to some sensors, but future versions will route all of those sensor connections through the zone controllers and CVC. However, some UX-focused OSP implementations may continue to connect directly to high-definition displays to support their high bandwidth requirements within the cost constraints of the architecture.

From a software perspective, we are moving toward signal-to-service abstraction, and our acquisition of Wind River gives us access to its VxWorks® real-time operating system and support for Open Container Initiative-compliant containers in safety-critical environments.

As SVA™ technologies evolve, our approach will provide for the fail-operational redundancy needed for Level 3 and above automated driving. With the flexibility that comes from containerization, applications can move from one OSP to a second OSP for redundancy, which the OSP modules installed atop the CVC are ideally suited to support.

When a vehicle is built with these hardware and software foundational elements, the way is clear for realizing the true potential of software-defined vehicles by ensuring that they have the most up-to-date capabilities for years to come.

Built for Exchangeability

Ideally, open server platform (OSP) modules should be designed so that a technician can easily change them out when an upgrade becomes necessary.

MULTI-FUNCTIONAL

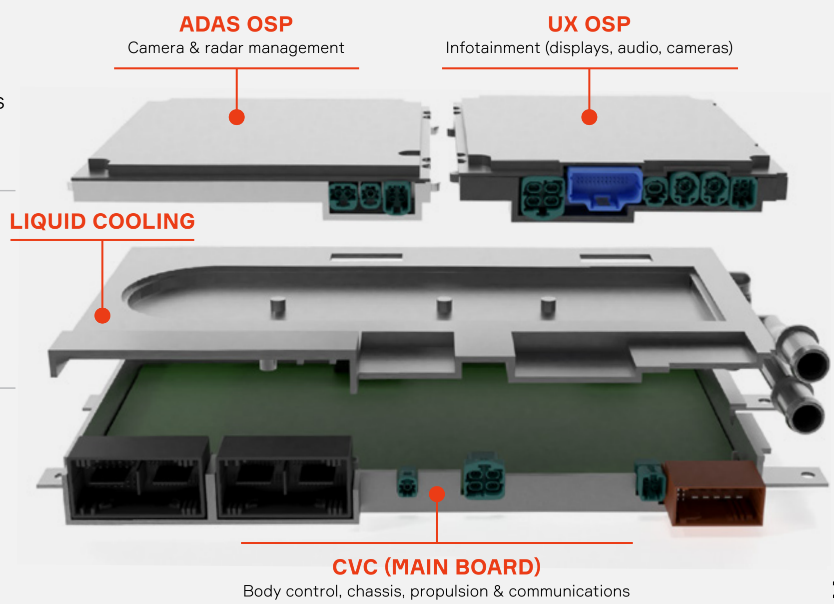
Handles ADAS & UX or provides additional data-acceleration features such as AI/ML, gateway routing, etc.

MODULAR

Exchangeable OSP modules cooled by the CVC unit

EFFICIENT THERMAL MANAGEMENT

Liquid cooling designed to last vehicle lifetime



ABOUT THE AUTHORS

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Martin Bornemann is responsible for the advanced technology and architecture development in Aptiv's CTO office. He has been with Aptiv for more than 20 years, holding positions in innovation management, project management and hardware development. Before joining Aptiv, he designed telecom equipment for Ericsson and conducted wireless LAN research for Bosch.

Benjamin Gould
Product Management Director, Compute
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Benjamin Gould is responsible for defining Aptiv's next generation of compute, the brain of the software-defined vehicle. Benjamin joined Aptiv in 2021 as chief customer engineer, and prior to that he was senior project manager at Mobileye. Benjamin started his career at Intel, where he spent 20 years in industrial engineering, application engineering, technical marketing and product marketing management. Benjamin has a bachelor's degree in electrical engineering and applied physics from Case Western University.

Cezary Klimasz
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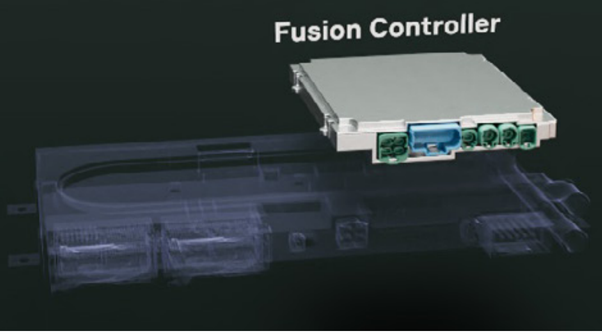
Global Product Organization

Cezary Klimasz leads the design and development of Aptiv's central vehicle controllers and open server platforms. His team is working on next-generation computing platforms leveraging high-performance hardware with state-of-the-art software solutions. Cezary began his career with Aptiv in 2012 as a hardware engineer. Since then he has held various roles in product and technology management.



The Next Step in Mixed-Criticality Processing

With consumers increasingly expecting vehicles to have advanced features, OEMs are looking for new ways to meet demands while optimizing compute resources and costs. Fusing ADAS and the cockpit domain on a single high-performance compute platform through mixed-criticality processing can help OEMs achieve that goal by improving efficiency and simplifying vehicle architecture — allowing OEMs to optimize costs while enabling a feature-rich system.

However, such fusion comes with unique challenges beyond current mixed-criticality processing.

Mixed-criticality processing today

To understand mixed-criticality processing, it is essential to first understand the automotive safety classification system. ISO 26262, the automotive functional safety standard, outlines a classification system known as the Automotive Safety Integrity Level (ASIL), which includes four risk levels: ASIL-A, the lowest level, through ASIL-D, the highest level, which is the rating given to advanced safety applications. A fifth level, Quality Management, or QM, is assigned to features for which no risk reduction is required because standard quality management practices are deemed sufficient. In mixed-criticality processing, a single compute platform is used to support applications with different safety levels.

Automotive OEMs currently employ mixed-criticality systems — using virtual machines to provide dedicated resources — in scenarios where the underlying hardware requirements of the features are the same. Take, for example, the integrated cockpit controller (variants of which have been on the market since 2018): The instrument cluster applications are classified as ASIL-B, while the Android infotainment system has a QM designation. Both require a graphic processing unit (GPU) to display information, so they are able to run on a single chip and share that resource — helping to reduce the system cost by 20 percent.

However, ADAS and the cockpit domain have very different underlying hardware and software needs, with the ADAS feature set requiring a fail-safe design and access to more accelerators, such as a neural network processing unit. These differences can make fusing those functional areas in a mixed-criticality scenario more complicated.

The building blocks for fusing ADAS and the cockpit domain

Several building blocks are essential to successfully fusing ADAS and the cockpit domain onto a single high-performance compute platform: a hypervisor, a real-time operating system (RTOS), containers and middleware.

Hypervisor

A hypervisor is software that uses virtualization technology to create, run and manage virtual machines. A key benefit of hypervisors is that multiple operating systems with very different characteristics can run at the same time, sharing the same virtualized hardware resources without interfering with each other. Without this capability, only one operating system could run on a hardware system.

Embedded systems, such as those in automotive applications, have strict resource usage limits that the hypervisor must operate within while communicating rapidly and with low latency. An RTOS is essential for enabling this fast communication.

RTOS

An RTOS is a specialized operating system that processes data and performs operations within specifically defined time constraints. RTOSes have two key features: predictability and determinism. In an RTOS, repeated tasks are performed within a tight time boundary — meaning each task must take the exact same amount of time to execute every time and must always produce the same result.

Containers

Software containers are essential to enable RTOSes to perform targeted updates. This is especially critical when you consider that systems rated ASIL-D require retesting every time an update is deployed. Without software containers, any update to the cockpit domain would necessitate retesting the entire system. Containerized microservices also help break down complex software systems into small, independent services, which reduces the size of updates.

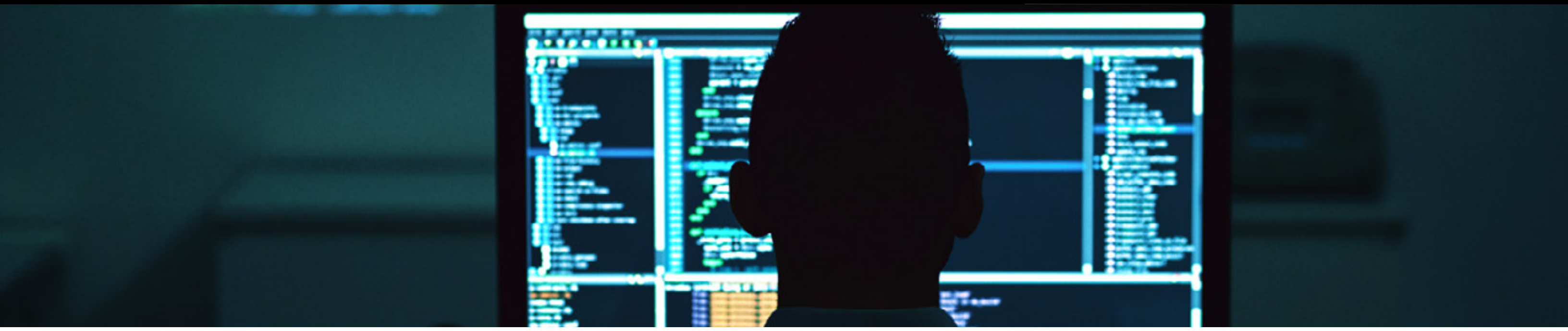
Middleware

In a true software-defined vehicle architecture, middleware is the glue between the hardware, operating system and application software — providing common services across vehicle domains and allowing domain-specific developers to build on those capabilities. The middleware also allows the application to be hardware agnostic through a modular, service-oriented approach.

A system-level approach maximizes benefits

Fusion provides the ideal trade-off between price and performance while facilitating the scalability and modularity of ADAS and the cockpit domain. However, many of the benefits of fusion, such as reduced costs and faster development times, are achieved only by sourcing an all-in-one solution. If OEMs source the hardware separately from the software, there is a greater burden on the development team to integrate the solutions. By bringing together an RTOS, middleware and a hypervisor in a single, scalable, integrated solution, OEMs can focus more on developing brand-differentiating features.

As a system integrator, Aptiv is well suited to help OEMs get the most benefit from fusing ADAS and the cockpit domain. In 2022, we acquired Wind River, a global leader in delivering software for mission-critical intelligent systems. Wind River's Helix hypervisor platform simplifies, secures and future-proofs designs by consolidating multiple operating systems and mixed-criticality applications onto a shared system. Wind River's VxWorks® is the industry's only RTOS to support application deployment through containers that are compliant with Open Container Initiative standards, ensuring compatibility and ease of use across different platforms and environments. Together, Aptiv and Wind River can help OEMs develop an all-in-one solution that reduces costs, improves development times and meets their unique needs.



What Is a Real-Time Operating System?

A real-time operating system (RTOS) is a specialized OS that processes data and performs operations within specifically defined time constraints.

The automotive industry relies on RTOSes to enable advanced driver-assistance systems and autonomous-driving features that need to perform with a high degree of reliability without input from the driver. However, RTOSes are becoming even more critical as OEMs consolidate compute and increase integration between domains — requiring improved orchestration between safety-critical and non-safety-critical systems.

How is an RTOS different from a general-purpose OS?

A traditional operating system, such as Windows, Mac OS or Linux, provides a software interface between applications and the hardware. It accepts commands from input devices and executes those commands sequentially.

A general-purpose OS is not designed to meet the demands of embedded or safety critical systems, which require consistent response times to inputs from multiple sources, including cameras, radar and lidar.

What are the benefits of an RTOS?

RTOSes provide a host of benefits for software development teams:

Multitasking: An RTOS needs to be able to run multiple programs concurrently and seamlessly interrupt a scheduled process to shift resources to a higher-priority operation.

Speed: RTOSes are subdivided into “soft” and “hard” real-time systems. Soft real-time systems operate within a few hundred milliseconds and are used in applications like interactive multimedia. Hard real-time systems provide responses within tens of milliseconds or less and are used in the automotive, factory automation, robotics and aerospace industries.

Predictability/determinism: RTOSes are designed to deliver a predictable response that falls within the desired time frame, and to deliver the same result in response to the same input every time.

Safety and security: RTOSes are frequently used in critical systems where failures can have catastrophic consequences. They are built with higher security standards and more reliable safety features than a traditional OS.

Aptiv and Wind River

In 2022, Aptiv acquired Wind River, a leading provider of intelligent-edge software solutions. Wind River's VxWorks® is the first and only RTOS to support application deployment through containers. This enables software developers to efficiently deploy targeted updates to safety-critical systems without compromising a system's high-performance requirements.

Visit Wind River's website for more details on the characteristics of an RTOS and the benefits of the VxWorks RTOS.

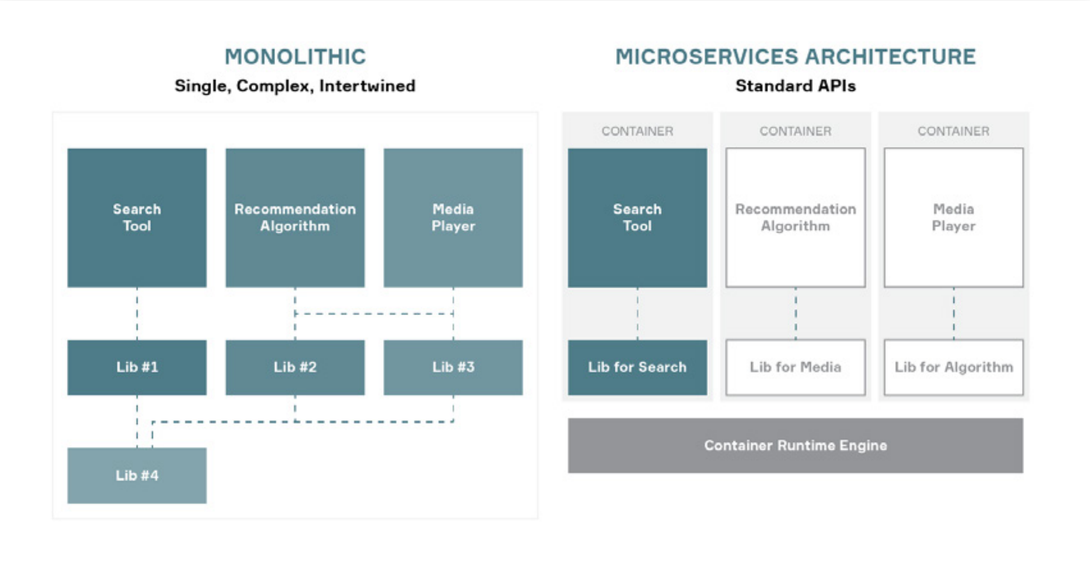
What Is a Microservices Architecture?

In software development, a microservices architecture — also known simply as microservices — refers to an architectural approach where complex software systems are broken down into small, independent services.

To understand microservices, it is essential to first understand what is meant by services. A service is a software functionality or a set of functionalities that performs a task automatically, reacts to events or fulfills data requests from other software.

A video streaming website, for example, employs a variety of services. The site's search tool is a service that connects to a database with titles and relevant keywords to return the most relevant results. The site's media player is a separate service that enables high-quality video playback and provides the viewer with various options, such as their preferred language. The algorithm that recommends other videos to watch is another service that analyzes customer actions to improve the user experience.

In a microservices architecture, these services are independently deployable and flexibly managed — allowing developers to make changes to the search tool, for example, without affecting the media player, and vice versa.



Are microservices just small services?

Despite what the name suggests, a microservice is not just a smaller service. Microservices takes the concept of services and integrates it into software development. Instead of the traditional, monolithic approach, where all deployable parts are contained within a single electronic control unit or application, a microservices architecture can use standardized software packages called containers — built independently using software development kits (SDK) — to enable segmentation which allows pieces of the functionality to be independently deployed, updated and managed as services would be. And application programming interfaces (APIs) connect the services by enabling applications or parts of applications to talk to each other.

Microservices in automotive

A microservices architecture provides numerous benefits in the automotive world by standardizing software development and helping OEMs continuously integrate and continuously deploy new software — which is essential to enabling the software-defined vehicles of tomorrow.

From windshield wiper speed to radio controls to automatic emergency braking, every feature and function within a vehicle represents a service or group of services working together. Software independence is essential in automotive environments, where updates to safety-critical and non-safety critical systems must be kept separate. As manufacturers integrate legacy systems, they must ensure that they do not invalidate existing safety functions and that they keep in line with the ISO 26262 industry standard for automotive functional safety.

When designed correctly, a microservices architecture can help OEMs achieve functional safety more quickly and efficiently. Testing and debugging each service independently of the others improves overall software quality, safety and reliability. This approach also enables faster software updates by making it easier for OEMs to fix bugs and address security vulnerabilities.

Additional benefits of a microservices architecture

In traditional vehicle architectures, the software and hardware are tightly coupled, which makes it difficult to upgrade components. Strong dependencies between software parts also make it challenging to exchange parts of the code without breaking existing functionality. With a microservices architecture, the software is abstracted from the hardware and other programs — while hardware-dependent pieces are encapsulated independently — allowing OEMs to replace the software without affecting the underlying hardware or other software functionality.

A microservices architecture improves communication between programs by providing well-defined APIs for services to communicate with each other. Segmentation makes it easier to develop and deploy new features through over-the-air updates, even after a vehicle has been sold — providing OEMs with additional revenue streams and improving customer satisfaction.

Another benefit of a microservices architecture is that it opens up new opportunities for innovation by making it easier for third-party developers to build applications. With a standardized set of APIs available from the SDK, third-party developers can independently build and integrate with the vehicle's software without needing to understand the intricacies of the underlying hardware.

In 2022, Aptiv acquired Wind River, a global leader in delivering software for mission-critical intelligent systems, allowing us to take advantage of their proven solutions which are ideally suited to support next-generation vehicle architectures through software abstraction and a cloud-native approach. A microservices architecture is complex and requires a suitable integrated development environment to manage — such as Wind River Studio. As the only provider of an integrated vehicle brain and nervous system, Aptiv is well equipped to help OEMs adopt a microservices architecture that meets their safety requirements and deliver the best possible experience for their customers.

Edge-to-Cloud Connected Platforms

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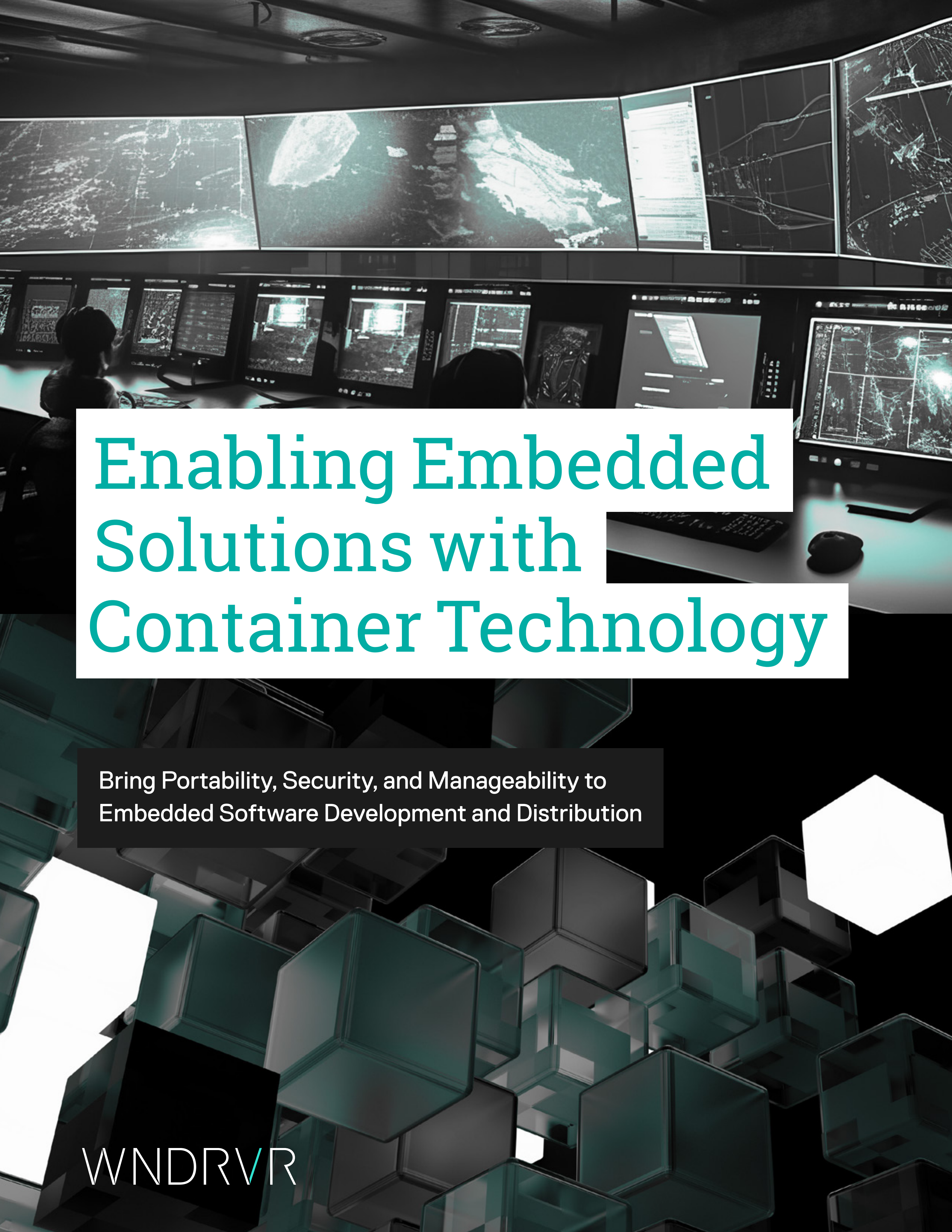
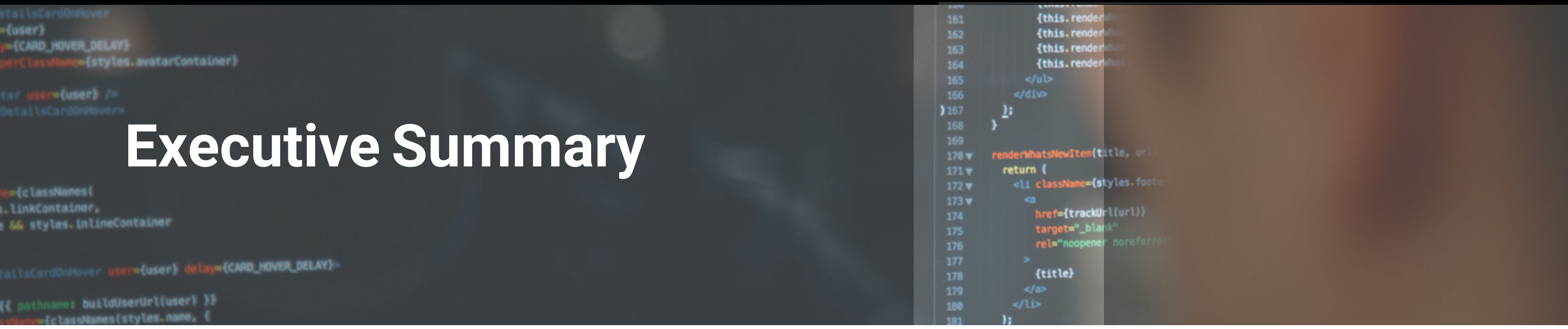


Enabling Embedded Solutions with Container Technology

Bring Portability, Security, and Manageability to Embedded Software Development and Distribution

WNDRVR



Executive Summary

Monumental changes to embedded software development practices are underway to address the complexities of ongoing software lifecycle maintenance and critical security concerns. These challenges have captured the attention of many industry leaders who strive to enable and secure streamlined development and deployment methods.

Complementary technologies have spurred these changes. Such technologies have been driven by the growing adoption of edge computing, autonomous vehicles, medical devices for remote diagnosis and treatment, robotics, aerospace advances, and increasing 5G technology demands as mobile broadband and mmWave microcell installations proliferate.

Adopting cloud-native tools for development empowers teams to collaborate from around the world. Containers make this possible by sharing a common environment with reusable configurations for developing and deploying code. One of the advantages of using containers is that they can be adopted for both existing embedded applications and for new designs. Application developers, whether creating embedded or enterprise-focused programs, can deploy software written in Rust and Python using tools familiar to them. Think of it as a write-once, deploy-anywhere approach.

Real-time operating systems (RTOSes), VxWorks® in particular, are fundamental to embedded systems. The introduction of support for containers in VxWorks to systematically deliver and update software is transformational. Support for containers that can respond dynamically in a real-time, deterministic way to events in the environment is a critical and innovative element for creating a software-defined world. This is especially important for automated manufacturing lines, autonomous vehicle operation, aerospace applications, and medical devices, as digital transformation advances in these sectors.

Adoption has lagged to some degree due to a lack of awareness in the embedded industry of the benefits of container technology. Also, the consolidation of existing solutions around virtualization (virtual machines) implementation as standard has impeded adoption. Another impediment is concern over security issues related to a shared kernel causing a generalized breach among those applications connected to the same host. Finally, adoption has been hampered by a lack of skilled technicians and developers with the tools and expertise to implement container solutions for embedded use cases.

As discussed in this paper, these issues have been addressed in numerous ways, and the multiple benefits of containers enabling innovative embedded applications offer a promising future for the evolving software architecture that supports their creation and distribution.

Demystifying Container Technology

Containerization enables the creation of a standardized bundle of software components — including a collection of all required configuration files, libraries, and utilities — allowing an application to run in a specified environment. Containers for Linux and VxWorks can be confidently deployed across different hardware environments and kernel versions. Containers stay lightweight and manageable by sharing the kernel of the operating system. This simplifies management and updating of code, since the latest iteration of the operating system doesn't need to be distributed each time a container is deployed into a system.

Container Formats and Orchestration

Docker popularized the use of containers with tooling that made it easy and simple for anyone to build and distribute images. Released as open source in 2013, the original creators worked with the community to standardize the specifications based on their work.

Standardization has advanced container adoption, expanding interoperability across multiple architectures. The Open Container Initiative (OCI) lists three specifications for container developers to follow:

1. **Image specification:** Defines the container images, which are basically file system bundles stored in a registry from which they can be retrieved by a host
2. **Distribution specification:** Provides a means to locate images in the registery and download them
3. **Runtime specification:** Establishes the rules for unpacking the image contents, the file system bundle that will be used by the container when running

VxWorks supports these specifications, enabling use of common formats and tools for developing and deploying containers. VxWorks containerized workloads can even be controlled by Kubernetes to orchestrate containers across devices.

Through Wind River® Studio, orchestration of containers can be extended to manage a large fleet of devices running VxWorks. For example, software upgrades of applications in VxWorks can be configured within Kubernetes and applied automatically.

> "Container technology is opening the world to you, while enforcing security and enabling reuse of components. Containers also foster adoption of DevSecOps and make your software modular and flexible."

—Nicolas Chaillan,
founder, Ask Sage; former U.S. Air Force and Space Force Chief Software Officer

What Is Inside a Container?

Typically, containers are associated with deploying microservices in the cloud. However, containers can also be used for deploying traditional services and applications. Wind River takes this one step further by extending support for containerizing embedded software on VxWorks.

By definition, containers consolidate the vital elements of a set of modular, interlinked applications into a cohesive solution. The concept is based on building large software applications from many smaller, independent blocks, as shown in Figure 1 (page 5). This approach takes advantage of proven open source tools, frameworks, and software to speed software development time and reduce costs. It also breaks free of the legacy practice of building monolithic, inflexible software applications that are difficult to create and update. Instead, this modular approach favors portability, lightweight operation, and agility. These attributes are essential for supporting modern architectures, including cloud-native and service-oriented architecture as used in automotive designs. Wind River supports containers in both VxWorks and Wind River Linux to build next-generation architectures based on cloud-native principles across multiple industries.

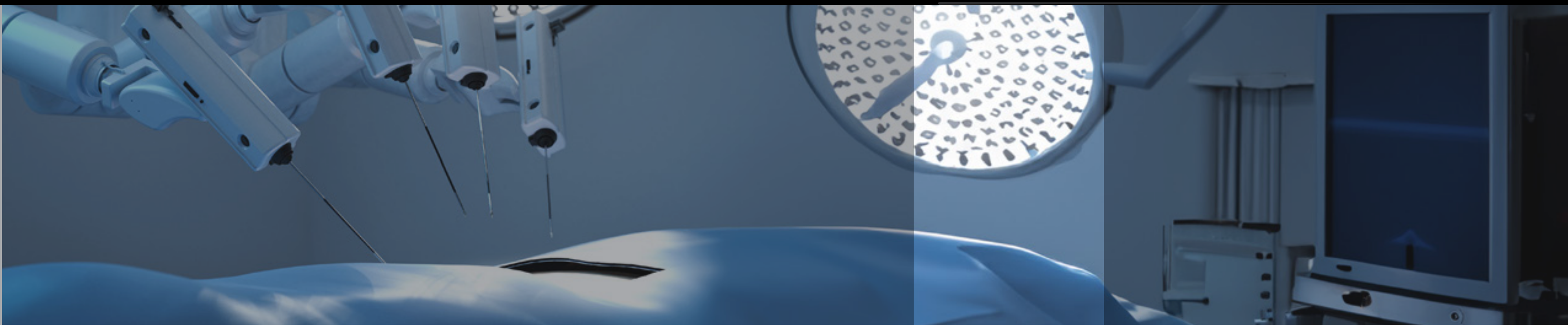
Where Are Containers Being Used in Different Markets?

Containers are ideally suited for applications in many vertical markets in which embedded software plays a significant role, including:

- **Avionics:** For commercial and military avionics companies looking to optimize space, weight, and power (SWaP), containerization is transformative. Being able to run applications in their own containers, independent of the underlying stack, enables greater portability and even reusability of legacy software packaged as containers deployed on a newer system. Examples of prime use cases are flight data analysis, flight management systems, 3D cockpit displays, user interfaces, in-flight entertainment systems, and aircraft system monitoring.
- **Automotive:** Automotive applications for container technology are among the most promising developments in the field, particularly as they support autonomous driving and software-defined vehicles. This new approach virtualizes vehicle equipment and consolidates various functions on a single hardware system. Due to modularity

> "Containerization brings three things to the industry that are desperately needed. First, it allows you to manage software, which today is monolithic. Secondly, it lowers development costs. The third thing is that containers unlock new monetization models with software-related revenues."

—Glen De Vos,
Senior VP of Transformation and Special Projects, Aptiv



and compatibility, the concept of containers is used for updating and upgrading features over the air both faster and more securely. Containerized workloads can also support other use cases, such as in-vehicle infotainment, connected car services, real-time diagnostic alerts, predictive maintenance, fleet management, analytics, and telematics data.

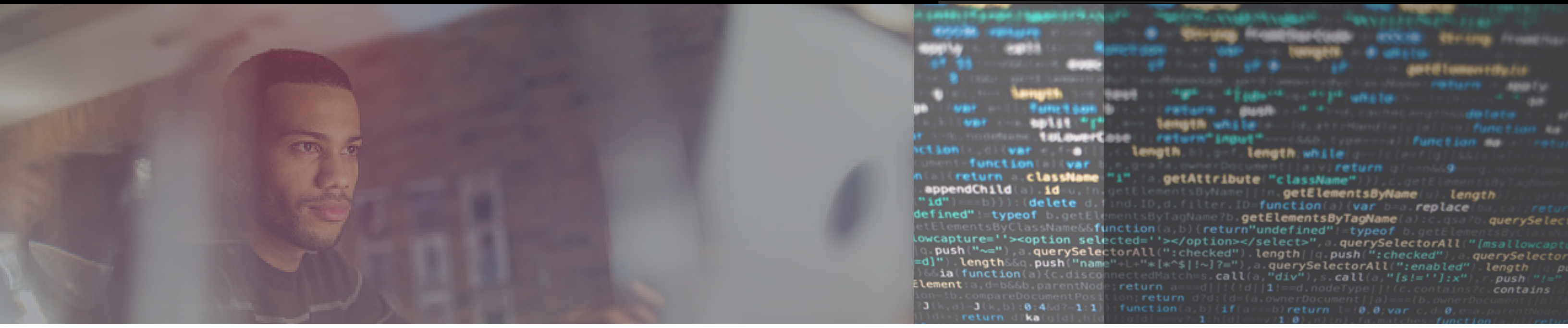
- **Industrial:** Transformation is underway as Industry 4.0 changes are sweeping through markets. By running secure, isolated containers on single or distributed systems, industrial applications can be consolidated into fewer systems, improving scalability, simplifying deployment, and enhancing system update capabilities. It also ensures update- and upgrade-ready forward-looking architectures including predictive maintenance, AI-enabled robots and cobots, manufacturing-line automation, supply chain operations and logistics, augmented reality, virtual reality, and control systems.
- **Telecommunications:** Containers enable top service providers to deploy and securely update 5G and upcoming 6G networks. A world-leading telco equipment manufacturer is implementing initiatives using containers for 5G network slicing to support applications with differing performance requirements, such as augmented reality and virtual reality. 5G base stations equipped with mmWave capabilities use containers to distribute software in smart city environments and to ensure that current software patches are installed. Network utilities such as firewalls and load balancers can also be implemented through containers.
- **Medical:** In a highly regulated environment where device high availability is a matter of life and death, containerized workloads on underlying safety-certified operating systems enable critical environment separation of applications and data. Use cases enhanced through containers include remote patient care, health monitoring, imaging systems, infusion pumps, and surgical and robotic systems. These applications can utilize containers to deliver security patches and critical software updates. Surgical robots are being developed that are fully automated and can perform complete operations without human intervention.

As container technology matures, potential use cases are essentially unlimited.

Isolation of Applications Increases Security and Reliability

Containers isolate applications and their runtime operations for security, conflict avoidance, and management control. Common isolation techniques include the use of namespaces to control access to system resources and capabilities and to place limits on how much can be allocated. Containers sometimes use an overlay file system to share common files but keep any local changes private.

VxWorks has granular control over how its real-time processes (RTPs) can access kernel objects, view files and directories, and interact with kernel resources. By restricting access to system calls, applications can be isolated from each other and given a private sandbox to run in. The file system namespace provides a unique view of the file system to allow containerized applications to manage their libraries and configuration independently. Its overlay file system allows reduced footprint size through reuse of containers with a common base image without interfering with each other. The extensive network functionality in VxWorks — stemming from its history in telecommunications — also makes it possible to control the network interface provided to applications and the endpoints they can communicate with.



Containers provide additional hardening, particularly when features are combined with other security provisions. This can be valuable in embedded environments where container security is essential. For example, a secure boot technology establishes a chain of trust by validating the full range of software components, from the hardware root of trust through the bootloader and kernel, right down to the signed container and the application itself. Combining container security with secure boot provides an end-to-end chain of trust for software running on the device.

Integration of Mixed-Criticality Components

In some cases, containers deploy software developed with higher-level programming languages or open source software that cannot be certified. This results in containers with varying levels of criticality. Successful integration of these components, identifying certifications that have been met or compliance that has been granted, can help avoid the need to redo certain certification processes. To take full advantage of agile development practices and DevSecOps workflows, isolating components according to the level of criticality can retain the advantage of streamlined development while maintaining existing certifications for specialized components.

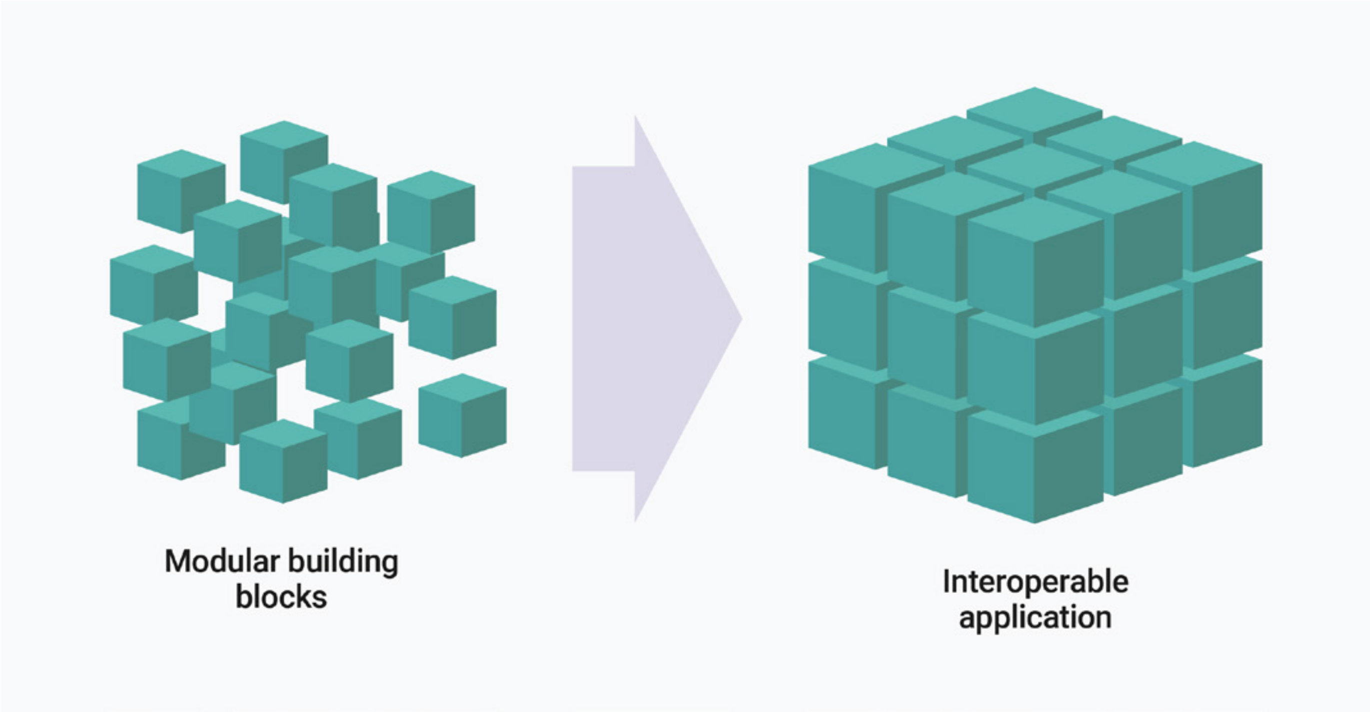
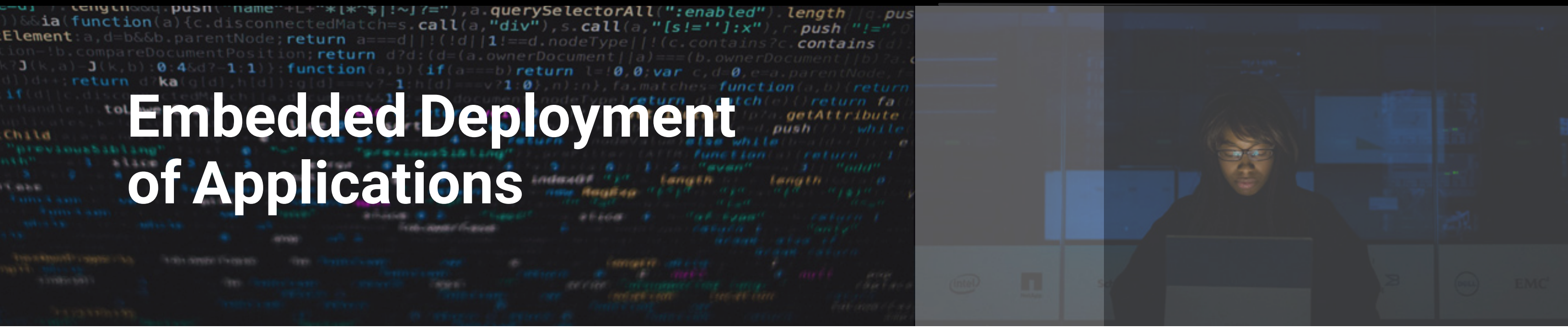


Figure 1. Modular building blocks make it easier to rapidly deliver advanced capabilities



Embedded Deployment of Applications

The challenges of effectively deploying embedded applications that comply with the rigors of vehicular, medical, or edge computing use cases are well suited to container technology. Rob Woolley, principal technologist at Wind River, summarized the benefits in his paper, "Deploying Embedded Applications Faster with Containers." He notes, "Embedded developers can benefit from the infrastructure-agnostic, scalable execution environment enabled by containers. Imagine a design process — from development to test to deployment to production to management — in which developers can share resources, pipelines, and results across the team. Instead of being limited by the number of development boards available, companies could exploit the elasticity of the cloud to set up multiple instances of a system on demand."

Embedded use cases often require low-latency, responsive, deterministic behavior. VxWorks has been engineered to provide an RTOS for these types of deployments, with OCI-compliant container support for enabling small-footprint embedded solutions. It has a long history of use in products that require rigorous security compliance with specialized certifications. VxWorks suits demanding use cases in industries such as medical, aerospace, transportation, and Industry 4.0 robotics and automation.

The charactertistics of containers are ideal for continuous integration and deployment (CI/CD), ready for producing new software updates quickly from new source code changes. Their modularity means they can be leveraged in a DevSecOps workflow with automated orchestration (as shown in Figure 2). Containers built for VxWorks are highly portable across environments that value security and frequent urgent software patches to address cybersecurity concerns.

- Compliant with OCI
  - Image format
  - Runtime specifications
- Runtime
  - Image parsing/validation
  - Instantiation of the container
  - Execution of the application
- Manager
  - Logic for pulling containers from registry
  - Command line tools for development/testing

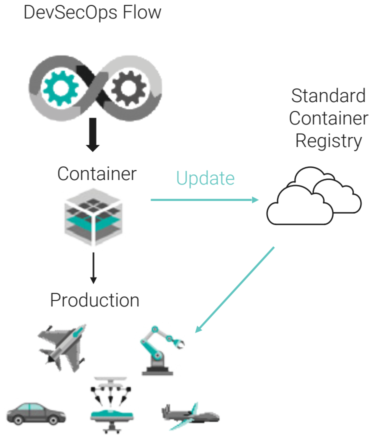


Figure 2. Creating and distributing VxWorks containers

Developing the CAPS Framework

To streamline software development and fend off potential security breaches and malware, Collins Aerospace developed the Containerized Application Platform System (CAPS). A recent whitepaper describes the approach in these terms:

"Based on an easy-to-use, mainstream technology stack, CAPS ensures reliable operations for a collection of containerized microservices in an embedded avionics environment where power is pulled after each flight and the system is never connected to an IT network for maintenance."

Developing and Testing Containers with Wind River Simulation

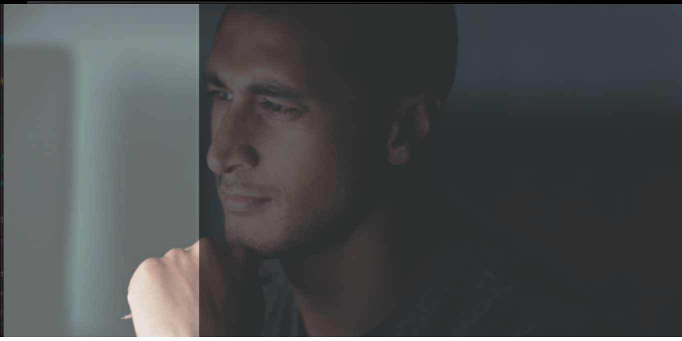
Wind River advanced simulation software offers an effective way for developers and system architects to test containers to identify and resolve software defects before deploying to the physical device. As the DevSecOps model becomes more widely adopted, containers can be engineered to minimize embedded solution issues, probing for potential problems at the earliest stages of development.

Simulation software can effectively detect and ensure that safety vulnerabilities don't go unnoticed and can be eliminated before a container goes into large-scale distribution. This simulation technology makes it possible to test effectively on virtual hardware, an important capability when exploring potential attack vectors that are difficult or impossible to check on a live system.

Creating a digital twin of a container-enabled system is increasingly important to long-term operation and upgrades. Nicolas Chaillan, founder of Ask Sage and former U.S. Air Force and Space Force chief software officer, commented, "A digital twin is essential when it comes to modeling and simulation. It empowers teams effectively to know exactly how the system is going to behave before bending metal. And a lot of people look at software agility and forget that you can do a lot of that. You don't have to always be in a waterfall universe in hardware. I think you can easily now swap hardware, swap compute with a rack or some type of easily replaceable hardware, compute, or storage capability — on jets, on ships, you name it."

> "A digital twin is essential when it comes to modeling and simulation. It empowers teams effectively to know exactly how the system is going to behave before bending metal. "
>
> —Nicolas Chaillan

Prospects for Container Technology



Rethinking the design of an existing embedded system to embrace a software-defined architecture is not a trivial pursuit. However, momentum is building throughout the industry to embrace containers as a logical evolution of modern development practices. Commenting on the direction in which design is proceeding toward a software-defined model at Aptiv, Senior VP of Transformation and Special Projects Glen De Vos said, "We went through all of these proofs of concept and studies with the automotive OEMs to [say], 'This is why this works.' We're now in the next phase, the software equivalent of that: We're going to show you smart software architecture with containerization and the DevOps environment, and that's the process for now. We think the math is very compelling. In fact, the technology has gone from being unsustainable to being profitable."

Container technology for embedded solutions is still in the early stages of adoption. However, it is part of an industry-wide transformation of how software is designed using modular components, built with DevSecOps practices for increased agility, security, and ongoing maintenance. The shift to cloud delivery of software patches and upgrades can, in the long term, save companies substantial cost and efficiently open new opportunities to reliably meet customer demands and industry requirements.

As awareness of the benefits of embedded container technology grows, and the containerization skills of software developers keep pace with this growth, the technology holds the promise of a bright future.

AI and Container Technology Are a Winning Combination

Container technology combined with artificial intelligence (AI) and machine learning facilitate powerful capabilities. Examples include:

- **Predictive maintenance:** Machine learning models within embedded solutions can assess the probability of parts failure, triggering timely maintenance procedures and preventing unexpected downtime. This is particularly important in the aerospace industry, in which safety and fail-safe operation are paramount.
- **Identifying and combating security threats:** The dangers of security breaches — including malware and unauthorized access to systems — can be lessened by employing AI to monitor the behavior of embedded applications and block intrusions.

> "When it comes to containerization in the future, one important point is that it is going to streamline the adoption of artificial intelligence and machine learning, which is dependent on containerization and the scalability of containers."
>
> —Nicolas Chaillana

- **Balancing resource use:** AI makes it possible to intelligently allocate resources within embedded container applications, creating an optimal balance of processor, memory, and storage resources as well as delivering dynamic scalability to meet application requirements.

Expect AI to provide value and benefits in a host of emerging technologies as containers are widely adopted, encompassing (but not limited to) autonomous vehicles, avionics, smart grid installations, smart city infrastructure, and intelligent agricultural equipment.

Conclusion

As the embedded industry tackles the challenges and complexities of software lifecycle maintenance and critical security concerns, support for containers in VxWorks provides a solution for regular, reliable, and large-scale deployment of updates.

The adoption of container technology in VxWorks opens the door for innovation by leveraging existing industry standards and tools for existing and next-generation designs. Container use provides modular software that can be reused across projects, resulting in cost savings and faster time-to-market.

Containers provide agility to contend with the accelerated pace of change in technologies, map to diverse use cases, and create business opportunities. Visit www.windriver.com/containers to learn more about how Wind River can help you adopt containers.

Additional Resources

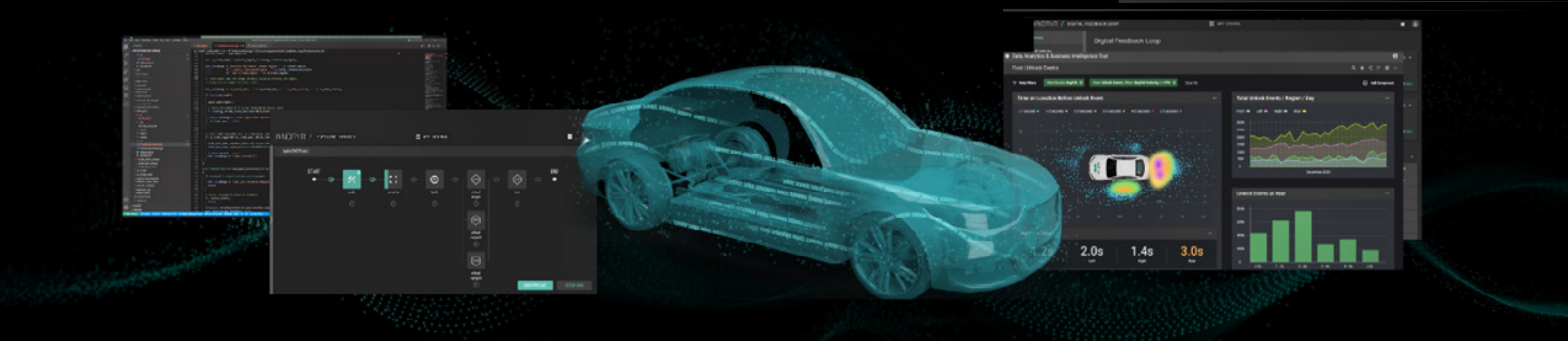
What Are Embedded Containers? Discover the ways in which container technology is bridging the divide between enterprise and embedded systems.

Hype Cycle for Container Technology, 2023: Get insights from Gartner on the benefits of container technology to enable digital business strategies.

Container Technology Energizes Edge Computing: See how manufacturers, medical organizations, energy providers, aerospace firms, and others can take advantage of the container support included with VxWorks.

About Wind River

Wind River is a global leader in delivering software for mission-critical intelligent systems. For 40 years, the company has been an innovator and pioneer, powering billions of devices and systems that require the highest levels of security, safety, and reliability. Wind River software and expertise are accelerating digital transformation across industries, including automotive, aerospace, defense, industrial, medical, and telecommunications. The company offers a comprehensive portfolio supported by world-class professional services and support and a broad partner ecosystem. To learn more, visit Wind River at www.windriver.com.



What Is a DevOps Platform?

A DevOps platform is a development interface that combines development and operations to provide software developers with a common toolset to code, deploy and test software and analyze data.

Before DevOps principles were adopted, developers would write an application in isolation and then deliver it to the operations group for deployment. DevOps platforms are particularly important in the automotive industry, where OEMs need multiple software-based systems to work together seamlessly. DevOps platforms help enable the over-the-air connectivity capabilities needed to perform continuous integration and continuous deployment, as well as continuous testing.

There are many benefits to using a DevOps platform, including better performance monitoring, easier troubleshooting, continuous certification, higher customer satisfaction and improved compliance with regulatory requirements. A DevOps platform makes it easier for teams to collaboratively plan, develop, build, secure and deploy software while lowering costs by reducing the number of engineering tools that developers must buy, integrate and maintain.

The mobility industry's transition to software-defined vehicles requires a purpose-built DevOps platform to speed up software development, streamline deployment and enable complete lifecycle management.

Improving safety and performance

The transition to electric vehicles and the rising demand for autonomous driving capabilities puts pressure on the entire mobility value chain to adopt the fastest, most efficient and most cost-effective methods for developing and deploying new features.

But developing new applications in the automotive industry requires extensive testing to ensure adherence to stringent safety and performance standards, such as those outlined by the ISO 26262 automotive functional safety standard and the ASPICE (Automotive Software Process Improvement Capability dEtermination) industry standard guideline for evaluating software development processes. Achieving ASPICE compliance requires full traceability: Developers must be able to link each written line of code to the requirements provided by the OEM and conduct testing to verify that the software meets the requirements. It is ordinarily a very time-intensive process, but a DevOps platform can save developers time by automating major portions of the traceability and testing procedures.

Simulation tools that mimic real-world driving conditions — particularly rare or challenging corner cases — improve safety performance and reduce the costs of validating vehicle safety. There are several types of simulation tools, including software-in-the-loop, hardware-in-the-loop and vehicle-in-the-loop. One method of software-in-the-loop testing employs virtual electronic control units (vECUs), which allows engineers to test portions of their code on standard desktop computers instead of relying on physical ECUs. By building software-based test environments, developers can conduct tests cost-effectively and quickly, using data that is received in mere minutes. An end-to-end DevOps platform can seamlessly integrate these testing tools and improve collaboration between OEMs and suppliers.

Enabling full lifecycle management

In 2022, Aptiv acquired Wind River, a global leader in delivering software for mission-critical intelligent systems, allowing us to take advantage of their proven solutions which are ideally suited to support next-generation vehicle architectures through software abstraction and a cloud-native approach that modernizes software development, deployment and operation over the life cycle of the vehicle. We are integrating our Smart Vehicle Architecture™ technologies with Wind River Studio which will help OEMs create value for consumers across the lifecycle of the software-defined vehicle.

Positioning Automotive Cybersecurity for the Future

Software-defined vehicles open up tremendous possibilities, allowing end customers to enjoy many of the very latest safety, comfort and convenience features available on the market through software updates, even as their vehicle models age. Protecting that software throughout deployment and operation is critical.

Well-structured cybersecurity management must go hand in hand with the development of software-defined vehicles. Developers must bake security into every layer, making no assumptions about the safety of a particular application or any of the supporting software.

In short, developers must manage risk, draw lessons from other industries, and push forward with comprehensive cybersecurity management systems that provide a framework for handling whatever risks come next. Working with our customers, suppliers and peers through industry organizations, Aptiv is actively helping to raise the bar.

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THE SECURITY CHALLENGE

Cybersecurity is a relatively new concern for the automotive industry. As automobile manufacturers began to include electronically controlled steering and brakes in their vehicles, the risk increased, but connectivity opened the door to much more risk.

Observers often point to vehicles' direct connections to the internet as a source of risk, but they tend to overlook indirect connections, such as through a cellphone via USB or Bluetooth. Even a vehicle that otherwise does not appear to have any connectivity could have a wireless tire pressure monitoring system or an onboard diagnostic module that allows access to vehicle information.

Connectivity without robust enough security led to a widely publicized incident in 2015 in which researchers were able to remotely control certain functions of a vehicle. Despite being a painful experience for many, the incident forced the automotive industry to more deeply consider what a systematic approach to vehicle cybersecurity might look like.

Of course, other industries have had similar journeys, so security management practices from a variety of industries have helped shape the framework for automotive cybersecurity. While one might think of business IT and its high-profile ongoing defense against malware, there is a closer analog: the aerospace industry.

That industry has long supported the idea of having very sensitive code running next to less sensitive code. In fact, it classifies software by Design Assurance Level, or DAL, a risk classification system that is similar to the automotive industry's Automotive Safety Integrity Level, or ASIL.

Other industries' experience with cybersecurity provided the basis for new regulations that specify how to create a comprehensive cybersecurity management system in automotive, such as Regulation 155 (R155) from the United Nations Economic Commission for Europe (UNECE). The demand for hardware-backed security has created economies of scale in specialized microprocessors from which the automotive industry benefits. And defense-in-depth strategies developed for other industries provide a clear path for ensuring security at multiple layers throughout a vehicle.

SECURITY AT EVERY LAYER

A cybersecurity management system represents a systematic approach to defining processes and governance with security in mind — from the start of development through the maintenance of the software over time — and it allows an organization to apply that approach at every layer of the automotive system. Here are some of the key areas of focus in automotive.

Secure updates

To ensure that consumers have the most capable features and functions available, today's vehicles download software updates over the air from the cloud, and those updates must be secure.

Most people are familiar with the lock icon in their web browsers indicating that an encrypted connection has been established with a server that has been authenticated. The cryptographic verification of the code being downloaded to a vehicle follows similar principles.

Public key infrastructure (PKI) is the mechanism that allows manufacturers to digitally sign their software in such a way that the receiving system can verify its authenticity. Using a secret digital key, the manufacturer encrypts the software before making it available. When a vehicle downloads the software, it uses a different, publicly available digital key to validate the content. A complex algorithm ensures that only content signed with the secret key can be validated with the public key.

Secure boot

Even with secure update mechanisms like PKI in place, manufacturers should not assume that all software on the vehicle is harmless, because some might have gotten there by other means.

That is why manufacturers must also provide for secure boot. When a vehicle starts up, the system should verify the authenticity and integrity of software before it starts running. That is, the system must ensure that the code was made by the manufacturer rather than by an attacker.

Secure vehicle networking

As vehicles become more software-defined and complex, the many software applications running on them will use the same processors and the same networks to transfer data among various processing nodes. For example, some infotainment applications might require vehicle speed and navigational data, while other applications might need information on battery management.

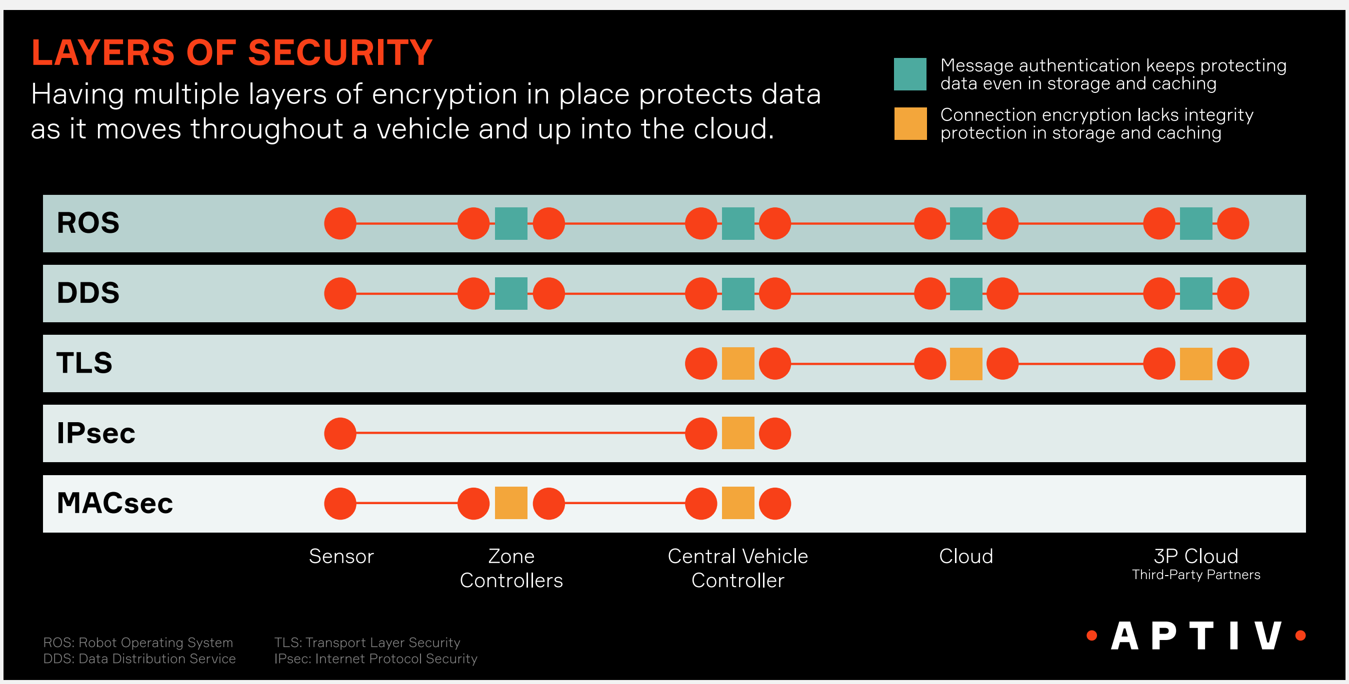
Having a network within the vehicle — and a connection out to the cloud network through cellular and Wi-Fi — requires that vehicles secure those connections at multiple levels.

The lowest layer is Media Access Control Security (MACsec), which establishes a bidirectional encrypted link between two directly connected devices. MACsec can work extremely quickly, encrypting and decrypting information at line rate using specialized hardware.

The next higher layer is Internet Protocol Security (IPsec), which works at the network layer to authenticate and encrypt packets of data between network nodes with IP addresses. Using the IPsec mechanism can help protect data as it flows throughout a network — through a router, up to a cloud and so on — and not just on a physical link between two points.

Moving up the stack, manufacturers can use Transport Layer Security (TLS), which operates at the level of the network where processes communicate without being tied to IP addresses, so the security mechanism is more flexible. TLS is used pervasively in internet-based communication today, and vehicles are likely to use TLS when communicating with the cloud.

While Aptiv has implemented MACsec, IPsec and TLS in our products, we are also exploring message integrity protection — such as that found in some Data Distribution Service



implementations and in Secure Robot Operating System 2 (SROS2) — to actually bind the protection to the information. This protection can hold even as the information is cached and stored between TLS connections, and even for relays spanning many TLS connections within a vehicle and between the vehicle and clouds and smartphones.

Advanced communications

As autonomous driving becomes more common, implementing security at even higher layers for encrypting messages could become increasingly important. For example, a consumer may send a message to a vehicle requesting that it pick her up at a certain address. That message should be signed cryptographically and delivered securely. New protocols can help with this, even across multiple clouds, if necessary.

In addition, as automotive companies start to bring in more developers to build different features in software, it is becoming important to ensure noninterference among the applications by using hypervisors, containers and other technologies to keep the software separate, even on shared hardware.

A STRUCTURED APPROACH

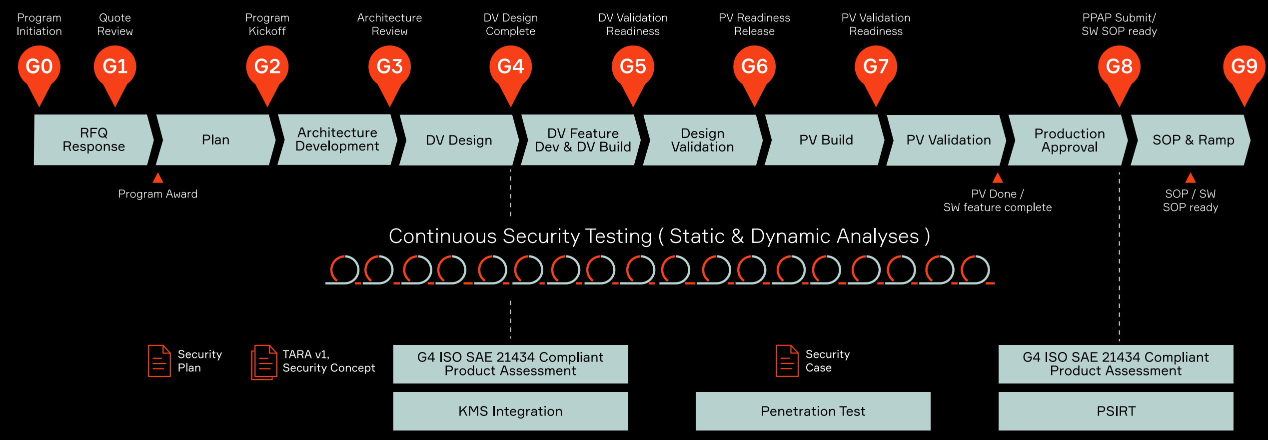
Getting all of these cybersecurity technologies in place in the right way requires structure, which can come from best practices, automated testing, audits or regulations.

The United Nations has established regulations that provide guidance for cybersecurity in the automotive industry. One is UNECE R156, which drives all of the requirements for secure update, secure boot and other technologies. The other is UNECE R155, which calls for cybersecurity management systems governing how security is engineered into vehicles and provides a framework for thinking systematically about risk to a vehicle, through a threat analysis and risk analysis.

UNECE R155 cites the international standard ISO/SAE 21434, which, among many other valuable contributions, helps set guidelines for gauging risk that are based on the feasibility of

CONTINUOUS TESTING

Security testing should be continuous throughout the development process.



•APTIV•

an attack occurring and the potential impact if a threat were realized. The standard also introduces the concept of the cybersecurity assurance level (CAL), which can convey how critically a system must be protected from attacks.

An organization can scale its cybersecurity activities — that is, it can use more or less rigor — based on the CAL.

Automotive companies are currently preparing for the UNECE regulations to become mandatory in the European Union in mid-2024 by auditing their engineering processes to ensure that they are in compliance. Once the regulations are in effect, regular audits can ensure ongoing compliance.

Compliance is not enough, of course. Automated testing is also essential to maintaining a high level of security resilience. Aptiv has already built continuous security testing into our continuous integration and continuous deployment (CI/CD) infrastructure and is adding more forms of testing.

Aptiv uses several ways to test code as it moves through development. Static application security testing (SAST) inspects source code for flaws, and dynamic application security testing (DAST) runs simulated attacks. Going beyond SAST and DAST, fuzz testing or "fuzzing" tools can help security-test code as it matures throughout software development, instead of waiting until the end of the process when time is short on deadlines. Fuzzing covers a very wide range of potentially unexpected inputs; it generates inputs automatically and in large numbers, quickly giving developers the feedback they need, sometimes nightly, to harden their code against everything from malformed packets to random data.

NEXT STEPS

Many of the risks in automotive are not unique to one company but rather are shared by the entire industry. As automotive cybersecurity evolves, automakers and suppliers will need to speak openly about risks and work together to develop best practices to address them. They will have to share information about what is happening in the threat landscape and collaborate to recognize when threat actors might be targeting automotive. Much of that collaboration can happen through existing bodies, such as the Automotive Information Sharing & Analysis Center (Auto-ISAC).

Aptiv is proud to be very active in Auto-ISAC, and we will continue to work closely with our customers, partners and industry colleagues as we all strive to create cybersecurity management systems that enable the next generation of software-defined vehicle innovation.

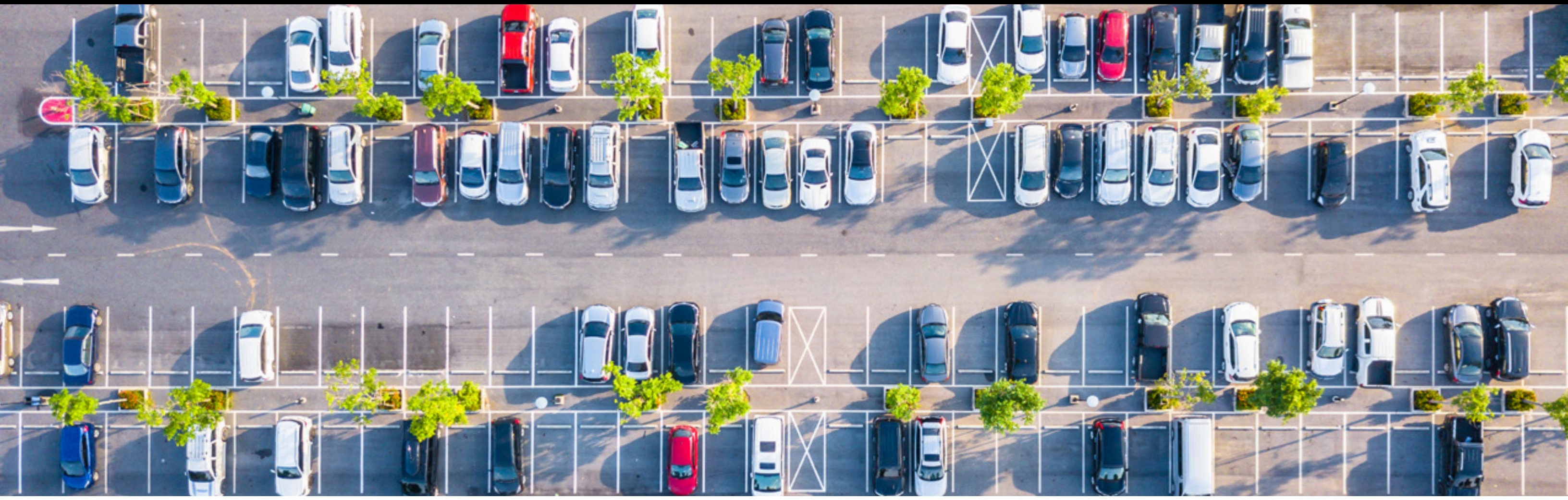
ABOUT THE AUTHOR

Brian Witten
Vice President & Chief Product Security Officer

With more than 20 years of cybersecurity experience ranging from consumer electronics to military aerospace systems, Brian Witten has global responsibility for product cybersecurity at Aptiv. He oversees cybersecurity policies and processes, planning and leading the development of diverse tools and infrastructure for the company. Prior to joining Aptiv, Brian held engineering and research leadership roles at the Defense Advanced Research Projects Agency (DARPA), Symantec, United Technologies Corporation (UTC) and Raytheon Technologies, and served in the U.S. Air Force. Over the years, Brian has helped build security into millions of cars and billions of devices.

Intelligent Perception

APTIV AT CES 2024



Intelligent Approach Expands Possibilities for Parking Automation

Parking assistance features like proximity warnings and driver-monitored hands-free parking have become common conveniences across most vehicle classes.

But as consumers increasingly demand more advanced parking features, it is becoming clear that autonomous parking systems must be designed as safety-critical technologies, not just as mere conveniences. A vehicle that is parking itself must be fully aware of nearby pedestrians, cognizant of all the available space around it and intelligent enough to use that information to execute the maneuver safely and efficiently.

That means that technologies used in advanced driver assistance systems (ADAS) for driving on local streets are critical to ensuring higher performance and safety when it comes to parking assistance. The same sensors and machine learning intelligence that power ADAS in complex urban driving scenarios and in difficult lighting and weather conditions will play key roles in automated parking as it evolves.

THE UNIVERSAL CHALLENGE

Parking is the expected conclusion of every vehicle trip, but the conditions under which this occurs can be as varied as an empty, well-lit parking garage, a driveway at night or a crowded parking lot in a rainstorm. Whether nosed in, backed in or parallel parked, every vehicle is expected to safely come to rest.

Automating that function across all conditions starts with robust sensing and perception capabilities. While many parking automation features rely primarily on ultrasonic sensors and cameras, state-of-the-art radar enhanced with artificial intelligence and machine learning (AI/ML) has significant advantages over other forms of sensing. Using radar to interpret a parking environment transforms the way in which a vehicle can plan and carry out parking tasks.

Enhanced radar data, fused with inputs from cameras and ultrasonic sensors, enables safe, reliable parking features with increasing levels of vehicle automation. For example, vehicles can use radar to identify an open parking space from a sufficient distance to pull into it directly, without going so slowly as to frustrate nearby drivers. Other sensing modalities often require the vehicle to first drive past the space when traveling at typical parking lot speeds. Intelligent systems can also map a parking area and be trained to navigate it later, and radar will let Level 4 autonomous cars safely drive away to park themselves in a garage and return on demand.

EFFICIENT, ROBUST PERCEPTION

Radar has significant advantages over both vision and ultrasonic sensors, creating more robust 360-degree sensing under a wider range of conditions. Because of these advantages, radar is increasingly becoming foundational for a wide range of ADAS features, but radar's advantages also enable OEMs to create parking features with greater capabilities over a broader operational design domain.

Compared with ultrasonic sensors — core components of many parking assistance systems — radar offers much longer range: potentially five to 10 times farther. This extended range significantly improves collision avoidance and enables new parking actions. For example, ultrasonic sensors can measure the size of a parking space only when directly in front of it, forcing the vehicle to drive past the space, back up, and return to enter it. Radar detects a suitable space between two parked vehicles from a farther distance, allowing the vehicle to directly maneuver into it.

In addition, recent advances in radar have expanded its field of view vertically so it can detect overhanging obstacles, such as tractor-trailer rigs or objects extending from the bed of a pickup truck.

Radar has key advantages over vision systems for accurately perceiving distance and distinguishing among objects. Radar detection inherently provides the distance to an object, while vision systems are limited by cameras' 2D perception. Vision systems have to rely on triangulation techniques while moving past objects to determine the distance to a given object in its field of view, such as a parked car, and the perception of distance with these systems declines at longer ranges. Radar is also better at distinguishing between one or two partially overlapping objects, such as pedestrians.

High availability

In addition, radar works in certain conditions, such as rain, fog and darkness, that make other sensors less reliable. Front-facing cameras rely on windshield wipers or headlights to keep their view clear, but cameras elsewhere around the vehicle lack those features. A buildup of salt, dust and grime, which may be a constant presence during severe weather, can degrade the performance of cameras and ultrasonic sensors, even triggering proximity alarms when ultrasonic signals bounce back from a heavy buildup of material on the surface of a sensor.

These conditions have much less effect on the transmission of radar waves, so radar units mounted around a vehicle can provide reliable 360-degree sensing in the widest possible range of driving scenarios.

INTELLIGENT PERCEPTION

Innovations in radar hardware and signal processing are building on the technology's inherent strengths, thus enabling new applications across the full range of vehicle automation, from parking to high-speed ADAS and autonomous driving.

Sensing gains precision

Emerging 3D air-waveguide technologies for radar antennas allow for the use of special radar beams tailored to specific applications. These technologies efficiently illuminate the environment with radar signals and receive the faint echoes that return with low loss, enabling higher precision while keeping costs down and sensor size the same. With 3D air waveguides, radar sensors receive more of the data needed to identify where objects are, how fast they are moving and even what they are, by feeding the data to machine learning systems to classify objects.

The latest generation of radar also adds a fourth dimension, sensing elevation. This allows the system to create a radar point cloud to model the surrounding environment in high definition, with important details such as low curbs, overhead signs and parking garage gates.

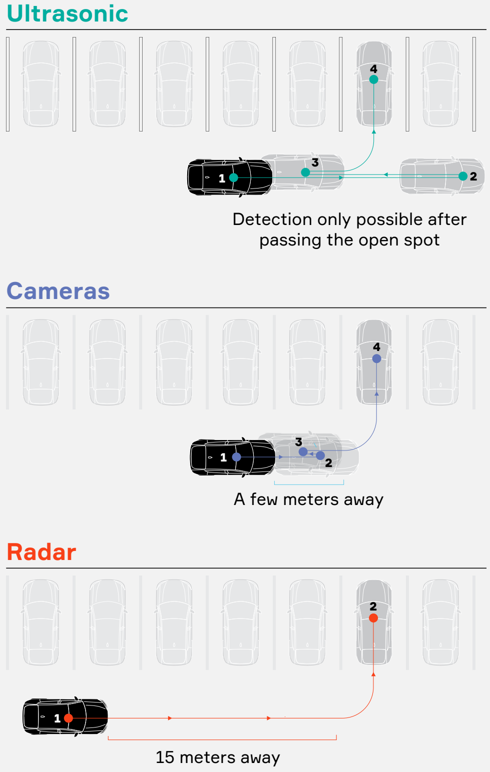
AI/ML: A force multiplier

Artificial intelligence and machine learning are doing the most to transform the capabilities of radar. The growing power of flexible, centralized onboard computing platforms and the rapid development of pattern-recognition algorithms are helping to make this possible.

Radar has been used primarily to detect the location, direction and speed of vehicles and other highly reflective objects, especially for high-speed ADAS applications such as adaptive cruise control. Now, machine learning techniques like those used to train in-vehicle vision systems to distinguish among vehicles, pedestrians and roadside infrastructure are being applied to radar signals.

Better at Spotting Parking Spots

Several different sensing technologies can detect open parking spaces, but radar excels at detecting those spaces sooner at conventional parking-lot driving speeds.



Enhanced resolution, trained neural networks and more powerful radar reception algorithms give these intelligent systems greater ability to correctly identify stationary and less-reflective objects. In parking applications, the combination allows vehicles to analyze all potential obstacles in the environment, including partially occluded objects such as pedestrians walking behind cars.

Sensor fusion adds value

Vision remains essential to many parking applications for uses such as reading signs and identifying lane markings, and such data can be merged with radar inputs through sensor fusion. Readings from ultrasonic sensors, which provide low-cost short-range sensing, can also be merged with this data. Sensor fusion helps to build the best possible picture of the surrounding environment.

Radar is especially well suited to AI/ML processing compared with other sensing technologies. Unlike ultrasonic sensors, radar captures enough detail to be used for object classification. But it generates less overall data than vision systems, which take in unnecessary details such as vehicle color, so identifying hazards requires less computing power in the vehicle's core computing platform. In-vehicle preprocessing of data from radar sensors can further reduce computing requirements.

ADVANCED PARKING BREAKTHROUGHS

Several next-generation parking assistance features benefit from advances in sensing and perception including AI/ML signal processing, for increased automation, availability and safety. Aptiv has developed four such applications.

Auto Parking Assist

Auto Parking Assist allows a vehicle to automatically find, enter and exit a parking spot. It controls the steering, speed, brakes and gearbox while the driver monitors the process from inside or outside the vehicle. Radar sensors scan a parking lot and identify a suitable space. The vehicle can then go directly to it and maneuver into it — and later leave the space — with no driver input. A neural network processes radar data using AI/ML to detect, track and identify all types of hazards while integrating vision to read signs and road markings.

As an SAE Level 2 automation feature, Auto Parking Assist can operate only when the driver is paying attention and ready to take control, either in the vehicle or at a distance with a key fob or smartphone app that can stop the vehicle. This allows owners to park in spaces that are exposed to weather or too tight for the doors to open.

Memory Parking

This feature, first demonstrated by Aptiv at CES 2023, allows a vehicle to record the process of parking in a given location and later repeat it automatically with the driver present.

The first time a driver parks in a given location and instructs the system to record, Memory Parking detects and classifies all stationary objects in the environment, exclusively with radar enhanced with AI/ML. It uses this data to build a virtual map that remains in the vehicle, and the data recorded on subsequent trips is aggregated to keep the map current. If there is a major, permanent change in the area, Memory Parking will instruct the driver to retrain it.

Memory Parking models the scene using an occupancy grid, in which a radar reception algorithm classifies any stationary object in a given quadrant, such as a garage pillar, to a high degree of certainty. The virtual map, along with real-time sensor inputs, enables the vehicle to situate itself within the learned environment through simultaneous location and mapping.

Memory Parking self-maps the area without referring to any existing map, but it can also be aligned to a commercial map of the surrounding area when one is available. This feature — also known as home zone parking — is designed for navigating to a space or garage on private property, such as a home driveway. A Level 2 "summon" feature is possible using the same technologies without any further training.

Though designed initially as an SAE Level 2+ feature that requires driver monitoring from either inside or outside the vehicle, Memory Parking could be implemented as Level 4 — allowing vehicle autonomy within a limited domain — with enough redundant sensing and computing systems to ensure safety.

Auto Park Valet

This Level 4 parking feature on the Aptiv road map will enable a vehicle to drop off passengers, find a suitable parking space and return when summoned, all without driver monitoring or control. It will provide full autonomy within an operational design domain limited to parking.

Auto Park Valet will use high-definition digital maps from outside sources for localization and navigation within parking areas. In real time, it will use combined radar and vision to find suitable parking spaces from a distance and enter them directly. Auto Park Valet is designed for parking in public lots and garages without training and will rely on high-definition large-area maps that are expected to become commercially available in parallel with the on-vehicle capabilities.

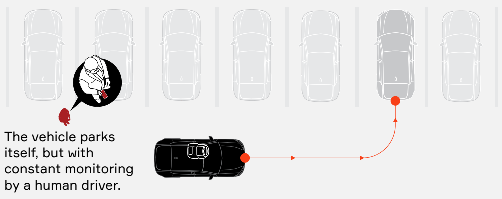
Surround View

This feature uses sensor fusion to combine data from radar, vision and ultrasonic sensors in a view of the vehicle's surroundings shown on the in-cabin display. It stitches together images from multiple surround-view cameras and can provide multiple viewing angles. Other information, such as the current steering path and distance warnings, can be overlayed onto the video image.

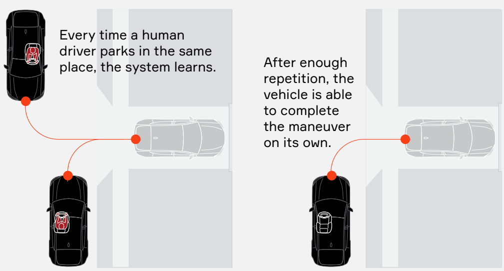
Advanced Parking Options

Advances in sensing and perception enable several parking applications.

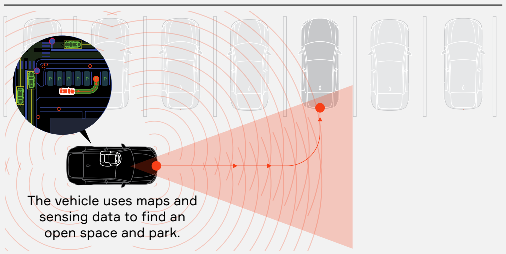
Auto Parking Assist: Operates with human oversight



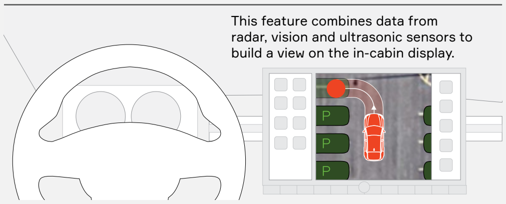
Memory Parking: Learns frequent parking patterns



Auto Park Valet: Performs fully autonomous parking



Surround View: Creates comprehensive view



A SYSTEM APPROACH

Parking assistance is increasingly not just a convenience feature but a part of the continuum of vehicle automation, subject to all the real-world safety demands imposed on this technology. As parking assistance features evolve from Level 2 to Level 4 and beyond, unlocking increasing degrees of autonomy, the most capable and cost-efficient parking automation solutions will be those that combine ADAS cruising innovations with the power of AI-enabled radar.

An end-to-end ADAS platform provides a complete safety package, including features such as forward collision warning and automatic emergency braking, that can be extended into parking automation features with proven effectiveness and reliability. In addition, comprehensive ADAS development and testing generates a wealth of knowledge on nearly all types of driving scenarios, adding to the robustness of parking capabilities.

Parking assistance is a critical component of Aptiv's Gen 6 ADAS platform. The next-generation parking features described above, which were introduced with the platform, build on Aptiv's deep experience developing and manufacturing industry-leading automotive radar systems. Together with our Satellite Architecture, this platform allows OEMs to implement scalable, integrated ADAS capabilities in a modular, flexible and cost-effective way for increasingly intelligent real-time sensing and decision-making.

Aptiv's system approach to vehicle automation, which spans parking, ADAS cruising and ultimately autonomous driving, brings together a full safety package, a comprehensive sensor fusion platform, and access to extensive driving data. With a detailed road map and proven solutions on the market, we are able to partner with OEMs for parking automation and beyond.

Parking assistance is increasingly not just a convenience feature but a part of the continuum of vehicle automation, subject to all the real-world safety demands imposed on this technology.

ABOUT THE AUTHORS

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Walt Kosiak has spent his career at Aptiv innovating in the fields of integrated circuit design, passive safety systems, active safety and driver assistance, and automated vehicles. His areas of expertise include ADAS/AD feature/function algorithms, threat assessment and warning algorithms, radar and radar-vision fusion, adaptive cruise control systems, vehicle-to-everything communication, map-based electronic horizon technology, and rapid prototyping systems for automotive systems development. Walt is an inventor on 24 U.S. Patents and was a member of the team that completed the first U.S. coast-to-coast automated drive in 2015.

Gürhan Gümüssu
Parking Core Systems Lead Architect

Gürhan Gümüssu is responsible for leading and coordinating systems activities of Aptiv's parking feature development in the Global Product Organization. He has been with Aptiv for four years, contributing to system teams on various projects and supporting business pursuits. Before joining Aptiv, he worked at a global automotive manufacturer as systems engineer.

Kamil Ostrowski
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Dr. Kamil Ostrowski leads the software development activities for parking at Aptiv. In his seven years at the company, he has helped successfully launch products related to radar, vision and features for multiple customers. Previously, he worked for a U.K. OEM and in the railway industry. Kamil holds a doctoral degree from the University of Liverpool, U.K., with a research focus on advanced control algorithms for the powertrain domain. He is currently pursuing an executive MBA at Poznan University of Economics and Business.

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Motional Builds Radars Into Perception System

Driverless-vehicle maker Motional uses an array of high-performance radars to create a more complete model of the environment around a vehicle in a cost-effective manner that maintains high performance standards.

Motional develops and deploys autonomous vehicles for ride-hailing and delivery services. Because its vehicles operate at Level 4 — fully autonomous driving — they require extremely robust sensing and perception capabilities. To make the most informed driving decisions possible, the vehicles must have a very clear sense of what objects are around them, and how fast and in what direction they are moving.

Stretching further

Traditionally, lidar has provided much of the object detection data for highly autonomous vehicles. However, Motional was looking to expand the range of its vehicles' sensors while achieving higher reliability and ensuring high performance during adverse weather conditions — all of which are radar's strengths.

Plus, lidar costs five to 10 times as much as radar. Motional says the lidar sensors are the most expensive externally purchased components it includes in its second-generation robotaxi, which is based on the Hyundai Ioniq 5.

Lidar systems use pulsed lasers to detect objects and their distance from a vehicle. The lasers require line of sight to make those detections, which can be hampered by rain, snow or fog. Motional was also looking to leverage sensors with fewer moving parts to keep maintenance costs down. Radar uses solid-state electronics, which have no moving parts. While the industry continues to make progress on solid-state lidar, there is not yet a suitable alternative that meets Motional's demanding requirements.

But perhaps the biggest requirement for Motional is extending its vehicles' sensing range. Its vehicles need to be able to detect objects with high fidelity at longer distances than lidar can provide.

CHALLENGE

- **Sense the environment around the vehicle under more conditions**
- **Achieve a consistent sensing range of 200 meters**
- **Keep costs and maintenance down**

SOLUTION

- **Implement Aptiv FLR4+ long-range radars**
- **Configure the radars for 360-degree coverage**
- **Fuse the radar returns with lidar points and camera images**

RESULTS

- **Expanded operational design domain**
- **Reduced reliance on lidar**
- **Lower costs to meet requirements**

Introducing radar

Motional continues to employ long- and short-range lidar sensors so that the vehicle can clearly detect the shapes of objects that are within their range in fair weather conditions, but it complements those devices with twice as many radars.

Motional uses Aptiv FLR4+ long-range radars in a configuration that provides 360-degree coverage around the vehicle. In contrast, a vehicle that operates at Level 2 or Level 3 might include a single long-range radar in the front, with short-range radars providing coverage from each corner.

The vehicle uses a neural net to perform sensor fusion between the lidar point cloud and the radar point cloud, which enables it to preserve more data than if each point cloud were processed separately. The vehicle then further fuses that data with images gathered through an array of cameras, using a technique called point painting, which projects the merged point cloud onto the camera images.

A better view

The radars provide a more complete picture of what is going on around the vehicle. The 360-degree coverage allows the vehicle to see behind itself for any overtaking traffic, which is especially important for lane changes. The radars are able to provide returns from 200 meters away from the vehicle, including the distance and speed of any objects.

The automotive-grade radars also expand the operational design domain, working more reliably in rain, snow and fog. Combined with lidar sensors, they are able to provide a more complete picture in low light conditions, when cameras are more challenged.

Overall, the radars help the system to be more confident in its assessment of the environment, which in turn allows it to take safe driving actions with higher confidence.

A joint venture between Aptiv and Hyundai Motor Group, Motional is working with Aptiv to continue to improve the AI and machine learning capabilities of radar, enabling the system to use radar to more accurately classify objects as vehicles, pedestrians, bicyclists or something else.

Motional is looking to employ radar for localization in the future, to help a vehicle establish exactly where it is on a high-definition map. Today, this function is carried out by lidar.

The end result is that radar is helping Motional provide autonomous vehicles with smoother, more confident movements that will yield a better mobility experience for passengers.

Flexibility Is Essential for Vision Systems

To meet emerging regulations and get lifesaving active-safety features into the hands of more drivers, OEMs need one thing above all else in their sensing and perception systems: flexibility.

Safety regulations around the world — such as the European Union's General Safety Regulation 2 (GSR2), which will roll out new requirements in 2024 — are mandating certain advanced safety features across vehicles. When features like automatic emergency braking and emergency lane keeping are incorporated into new vehicles, they will go a long way toward reducing accidents and fatalities.

Many of these safety features can be built into vehicles by adding a minimal number of sensors, which means that the cost of vehicles that include them should remain within reach of most consumers. For example, the features mentioned above can be implemented with a vision system consisting of a single camera, either alone or in conjunction with forward-facing radar.

The challenge is that some vision-based perception solutions on the market bundle a wide range of capabilities into their systems without providing the flexibility to optimize the capabilities for required features. That means an OEM could have to pay for capabilities such as free-space detection or high-beam controls even if they are unrelated to the safety features the OEM wants to offer on a particular model. In addition, some vision solutions are tied to a specific system-on-a-chip (SoC), so the OEM has no latitude to decide which provider's SoC is included in its vehicle.

When OEMs have limited ability to specify the system design or software functions that would meet their requirements, they face challenges scaling safety capabilities across their product lines.

A fresh approach

The answer is to move to an open and flexible platform of software and systems — one that is SoC-agnostic, does not force the OEM into set bundles of software capabilities, and can scale from vision-only safety features related to GSR2 compliance to a Level 2+ or above automated driving solution that fuses 360-degree sensing from multiple sensing modalities.

Aptiv's Gen 7 Vision solution meets all of those criteria. It fulfills GSR2 requirements while supporting NCAP 2025 up to a 5-star rating. It enables vision implementations that are optimized for specific requirements, resulting in the best overall system cost without sacrificing performance, and allowing OEMs to affordably scale their vision systems from entry-level vehicles through premium models. OEMs also have flexibility when it comes to selecting software capabilities and an SoC for the system.

The forward-facing camera itself is available in two primary versions: a smart 3-megapixel camera that would most often be used for Level 0 to Level 2 automated driving, and an 8-megapixel satellite camera most commonly used for Level 2+ and beyond.

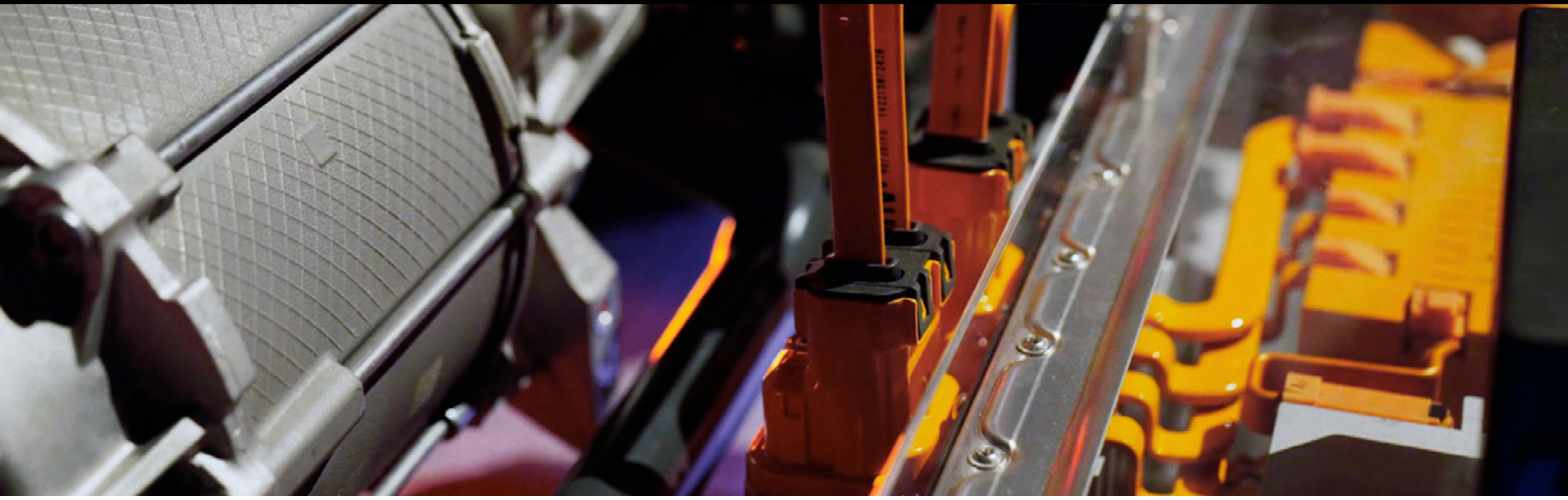
As OEMs look ahead to greater functionality and higher levels of automation, the system can easily integrate vision data with radar data for sensor fusion, providing a comprehensive model of the environment around the vehicle. Radar performs in all weather and lighting conditions, with improved object detection and packaging flexibility, while maintaining low power and compute requirements.

Flexibility is key to innovation. To develop highly optimized, high-performance perception systems, OEMs will need solutions that meet the specific needs of their customers today while providing opportunities to scale to more robust features in the future.

Gabor Vinci
Senior Manager Product Strategy, Perception

High Voltage

APTIV AT CES 2024



Direct Contact Technology Needed to Meet Future EV Needs

As automakers unveil one battery-electric vehicle (EV) platform after another, high-voltage (HV) interconnects are emerging as one of the most important automotive components. They enable power delivery from chargers to batteries and from there to inverters, electric motors, power distribution systems and auxiliary devices such as air conditioners.

Because of their central role, well-designed HV interconnects can be key differentiators for EVs. OEMs need connectors that conduct electricity efficiently, save space and last a long time — while also streamlining manufacturing and adapting to a range of applications.

Direct contact technology can produce interconnects with all of those attributes, helping OEMs to achieve their ultimate goals of greater reliability, range and performance.

TERMINAL DESIGN IS KEY

To ensure that their EVs are able to charge quickly and deliver power to major elements of the vehicle, OEMs incorporate larger and heavier busbars and cables that are capable of handling high current. But these new conductors demand new approaches to connector design.

An ideal connector would be able to maximize conductivity, keep resistance low and perform reliably over long periods. It would also be manufacturing-friendly — flexible enough to work in a variety of electrical architectures and easy for OEMs to incorporate into their processes.

Direct contact technology meets those needs. Its simplicity is a breakthrough in HV connector design that will have a significant effect on the performance, compactness, flexibility, reliability and other attributes of the connector system as a whole.

Conductivity

In conventional terminal designs, electric current is transferred from a conductive copper female terminal to a conductive male blade via a separate contact spring commonly referred to as a lamella. This spring must perform both the electrical function of carrying current from the harness terminal to the device terminal and the mechanical function of generating normal force at the terminal interface. To meet the requirements of both tasks, the contact spring is typically made from a copper alloy that is less conductive than the main copper elements of the connector but has stronger mechanical properties than copper alone. Because it needs to perform both electrical and mechanical functions, this component cannot be optimized for perfect performance in either area.

Direct contact technology brings together the harness terminal and device terminal in a simplified design that allows current to flow directly from one conductive element to the other, minimizing the bulk resistance and contact resistance by eliminating the lamella and the contact interfaces on either side of it. The work of securing the terminal to the busbar is performed by the terminal body using a separate component made of stainless steel, the optimal material for this task. The steel terminal body provides higher contact force and durability than a copper alloy contact spring.

Simplicity saves space

Every component in an EV must take up as little space as possible in addition to being optimized for light weight. Compact parts are essential for design flexibility as OEMs seek to incorporate larger batteries and more electrical components. All of these elements must coexist with enough space to be positioned for minimal electromagnetic interference.

There are several ways to optimize space in HV interconnects and cables. Design options such as right-angle or axial orientation, and bolts or levers to secure harness connectors to devices, are essential to achieving optimal space efficiency. Connectors that can accommodate busbars — flatter, more rigid alternatives to round cabling — provide other space-saving opportunities. Busbars have a lower profile than cables and can be formed with a tighter bend radius.

The simplicity of direct contact technology allows for packaging flexibility, and designs can take advantage of this attribute. For example, the terminal body can be moved to the header, which allows for a smaller connector on the harness side.

Longer life

HV interconnects that link charging systems, batteries, drive motors and other essential EV components require high reliability for safety and maximum performance over the life of the vehicle. EVs are expected to last longer than internal combustion models and require less servicing, and the long-term reliability of HV connectors will play a major role in this outcome. In the future, autonomous EVs may be used more heavily, resulting in many more miles driven during a vehicle's life span. The HV connectors and terminals must be able to meet this expectation.

The weak point in conventional terminal systems is the conductive spring that both provides contact force and conducts current between terminals. Even if a terminal initially exhibits low contact resistance, over time a copper spring will experience stress-induced relaxation. This will result in increased resistive heating in the connector and decreased current-carrying capability over the life of the vehicle.

Direct contact technology improves reliability by replacing the copper spring with a high-conductivity copper terminal and a stainless steel terminal body. The direct flow of current generates low and stable resistance over the life of the vehicle and thus less heat, while the stainless steel spring in the dedicated terminal body can achieve a higher contact force for a longer duration than a conductive spring can. As a result, the operational life span of a direct contact terminal is at least 100 times that of a conventional terminal system.

Adaptation without reinvention

When it comes to HV interconnects for EVs, one size does not fit all vehicles or applications. The best possible connector design for any given device depends on its function, location, power requirements and other variables.

For example, for power conversion devices such as DC chargers and drive motors, OEMs need scalable connector options to accommodate increasing cable sizes and amperages, from $25mm^2$ to $120mm^2$ cabling and up to 400A of current. Those requirements will expand as charging levels and battery sizes increase, and all such connectors also need the physical clearance required for 1,000V operation.

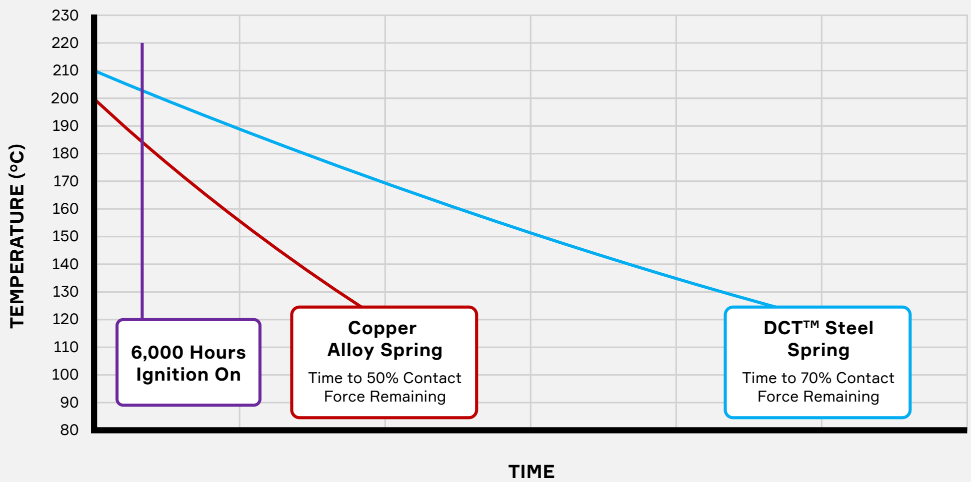
In addition, optimal designs to fit a growing number of high-voltage devices into vehicle interiors may require a wide range of connector types and configurations, including two-way and

Direct Contact Advantage

Based on reliability testing of the two types of terminals at a range of typical operating temperatures, the contact force of a copper alloy conductive spring would decline much more quickly than a non-conducting steel spring.

Terminal Contact Spring Contact Force Remaining vs Time

(Arrhenius formula based on 3,000 hours of test data)



three-way connectors and axial or right-angle orientations for harness connections facing right or left. Harness assemblies may need to be locked down using levers or bolts.

Separately designing or sourcing connectors for different platforms in order to meet these varied requirements adds unnecessary time and expense that OEMs can ill afford. An adaptable HV interconnect architecture, with a modular design and common components, streamlines the development of connector systems to best serve multiple product lines over time. This type of architecture lets OEMs use the same device in several vehicle platforms. Using common components can accelerate the design process while reducing the cost of sourcing, qualifying and stocking separate components for each connector design.

The relative simplicity of direct contact technology designs can improve design flexibility as well as ease of manufacturing, as described below.

Streamlined manufacturing

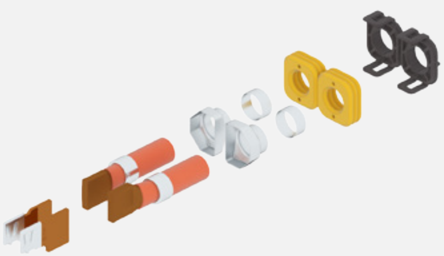
As OEMs migrate to EV platforms to meet growing consumer demand, HV interconnect production needs to scale up rapidly and cost-effectively. Connector systems must provide for simplified manufacturing, in addition to rapid product development. This reduces costs and increases automation, which can ensure more consistent quality. There are several ways in which a connector design can reduce complexity and costs for OEMs, Tier 1 device suppliers and harness builders.

First, suppliers can streamline the manufacturing of HV wiring harnesses by delivering highly integrated connector assemblies. A harness maker supplied with a fully prepared connector housing rather than a bag of parts to be assembled like puzzle pieces can plug leads directly into a finished connector assembly. The OEM receives an assembly that is ready to be mated to the header on a device.

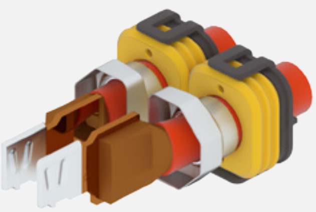
Second, suppliers can provide a header design in which key components, such as electromagnetic shielding, are cast into the device's enclosure. This can simplify manufacturing, reduce the total

DCT™ Harness Connector Assembly

Aptiv's DCT™ solutions leverage direct contact technology and enable pre-integration of components, such as cable leads, to save time and costs when assembling connectors.

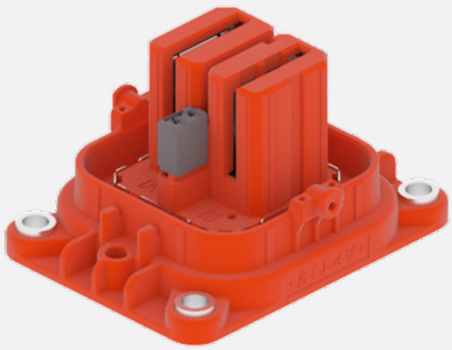


Harness Components



Lead Preparation

Assembled DCT™ Connector



Direct contact terminal designs offer streamlined header assembly in which a header is fastened directly onto the device power bus.

number of components in the bill of materials, and better protect against interference and corrosion. Aptiv's Direct Mate™ technology, which works with direct contact technology, is an example of such a design.

Third, suppliers can design their connectors so that leads can be processed individually. HV cables are large, cumbersome and difficult to position for processing, yet some suppliers force manufacturers to process two at a time, with a single shield covering both. Harness makers need the flexibility to handle leads one at a time.

In addition, because direct contact technology designs use pure copper terminals without lamellas, manufacturers can safely use industry-standard termination technologies — such as ultrasonic welding, laser welding and resistance brazing — on interfaces between terminals and cables without damaging lamella contacts..

MAKING THE HIGH-VOLTAGE VISION REAL

Aptiv embraces the growing importance of HV connectivity in EVs and is already responding to the escalating requirements for design flexibility, economies of scale, reliability and space constraints in HV connector systems. Aptiv also recognizes that different operating characteristics, such as extended vehicle life, reduced servicing and increased usage enabled by EVs and vehicle autonomy, present new challenges.

Aptiv's DCT™ family of HV interconnects uses the breakthrough terminal design described above to help OEMs cost-efficiently implement connectors for the next generation of EVs. The DCT™ family does the following:

- Achieves industry-leading power density and package size, with scalability for various power needs.
- Lasts 100 times longer than conventional copper-alloy terminals.
- Uses a design optimized for harness processing, manufacturing simplicity and automated assembly.
- Incorporates maximum flexibility for device header integration.
- Leverages Direct Mate™ technology to optimize the device interface.

The combination of this terminal design philosophy, material selection, R&D and connector implementation provides a "million-mile solution" to meet future vehicle demands.

The DCT™1400 and DCT™2200 interconnects share a common fundamental design for HV connectivity and work with cables ranging from 25mm² to 120mm². They support up to 1,000V operation and can be adapted for use with busbars or aluminum cables in place of copper cables. Common headers for different connector configurations and orientations, including Aptiv's low-cost Direct Mate™ header, offer maximum modularity and flexibility.

Aptiv is developing applications of DCT™ for use cases across the full range of HV interconnects. As part of our end-to-end approach to in-vehicle electrical architectures, DCT™ products will enable consistently scalable and flexible solutions to emerging EV challenges.

ABOUT THE AUTHORS

Nick Durse
Mechanical Design Lead

Nick Durse is responsible for the development, design and launch of Aptiv's next-gen high-voltage terminals, as well as related metal components, such as shields and busbars. Nick has a wide range of engineering experience in product development, manufacturing and project management. Since joining Aptiv in 2014, he has secured 10 patents across several different high-voltage product lines, while also supporting new business pursuits and production launches.

Patrick Reedy
Staff Product Engineer

Patrick Reedy leads Aptiv's development of high-voltage interconnects used in high-current traction motor inverter and DC fast-charge cable assemblies. Patrick has been with Aptiv for nearly four decades, holding various product engineering positions in both connection systems and wiring. Since 2008, he has been a leader in engineering for Aptiv's high-voltage connection systems for the North America EV market.

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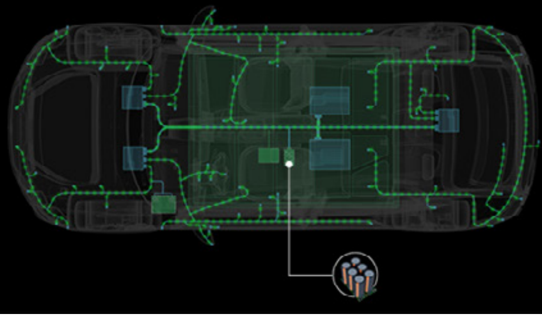


What Is an Ultracapacitor?

An ultracapacitor, also known as a supercapacitor or an electric double layer capacitor, is a long-lasting energy storage device that can store and release electrical energy faster than a battery.

While batteries store energy through chemical reactions, standard capacitors store energy in an electric field between two electrodes — similar to the static charge that accumulates when a balloon is rubbed against someone's hair. However, capacitors have a very low storage capacity because they store energy in the form of electrons, which repel each other.

Ultracapacitors, on the other hand, do not store electrons directly. Instead, they store positively and negatively charged ions and use a liquid electrolyte to facilitate the flow of energy; unlike in batteries, no chemical reactions are involved. This results in much faster charge and discharge times and makes ultracapacitors ideal for automotive applications that require quick bursts of power or quick storage, such as when energy is recaptured through regenerative braking.

Ultracapacitors also have a much longer life cycle than batteries because there are no physical or chemical changes speeding up degradation. A typical battery can handle 2,000 to 3,000 charge cycles, whereas an ultracapacitor can withstand more than 1 million cycles. Ultracapacitors are more stable than batteries, do not contain heavy metals, and have an operating temperature range between -40° C and 65° C.

Replacing the 12V battery

Ultracapacitors lack the storage capacity to serve as the propulsion battery in electric vehicles (EVs), but they are an attractive alternative to the 12V lead-acid battery that powers low-voltage systems such as instrumentation panels, entertainment systems, LED lighting and sensors.

While EVs typically use DC-to-DC converters to step down the power from the primary vehicle battery to supply low-voltage components, traditional 12V lead-acid batteries are still commonly used to provide a redundant power supply. Some EV models use 12V or 14V lithium-ion batteries instead of lead-acid batteries, since the higher energy density of lithium-ion technology allows them to achieve a smaller size while providing the same power. However, they are more expensive and cannot provide the same surge current that lead-acid batteries provide.

Enter ultracapacitors. Weighing about 60 percent less than their lead-acid battery counterparts, 12V ultracapacitors offer a solution to help OEMs optimize mass and provide the required surge current – while lowering costs, thanks to their long life spans. They also help address vehicle reliability; battery trouble is often listed as a top cause of roadside breakdowns.

In 2022, Aptiv was awarded a new commercial program with a major OEM for our ultracapacitor module, Aptiv's Rapid Power Reserve. Part of our ASIL-D-rated 12V power delivery network, the ultracapacitor provides instantaneous backup power to safety-critical systems such as steering and braking.

Aptiv's solution combines battery management control software with power electronics to deliver maximum performance at an optimized cost and power density. As the only supplier of both the brain and the nervous system of the vehicle, Aptiv is uniquely positioned to provide solutions that optimize the entire vehicle architecture.

What Is the North American Charging Standard?

The North American Charging Standard (NACS) is a charging connector interface standard for electric vehicles that Tesla Inc. developed and has made available for use by other charging network operators and automakers.

In 2012, Tesla developed what it referred to as “the Tesla charging connector” as a proprietary charging interface for its own vehicles. The company has used the system on all of its vehicle models since its initial release. In contrast, the majority of automotive OEMs use the Combined Charging System standard—CCS1 in North America and CCS2 in Europe — for DC fast charging.

However, Tesla has expanded its charging network rapidly and now operates about 60 percent of all direct-current fast chargers in the United States.

In November 2022, Tesla changed the name of the Tesla charging connector to the North American Charging Standard and made the specifications available to other manufacturers. Since then, several major OEMs have announced plans to equip future vehicles with NACS-compatible charging inlets. In June 2023, SAE International announced that it would standardize the connector, helping to ensure consistency across the industry.

The most striking difference between NACS and CCS is the size of the charging interface. The NACS interface is much smaller because it uses the same pins for both AC and DC charging. This shift in charging interface affects the system’s architecture and wiring as a whole — not just the charge cord and the inlet. Because AC and DC pins are shared, the power must be managed by control electronics that can safely switch between the two modes via harness splicing, harness fusing, contactors, electrical centers or switching in the onboard charger (OBC). This can also affect the high-voltage wiring systems that distribute power from the inlet to the battery pack via the OBC and other power distribution devices.

A complete charging portfolio

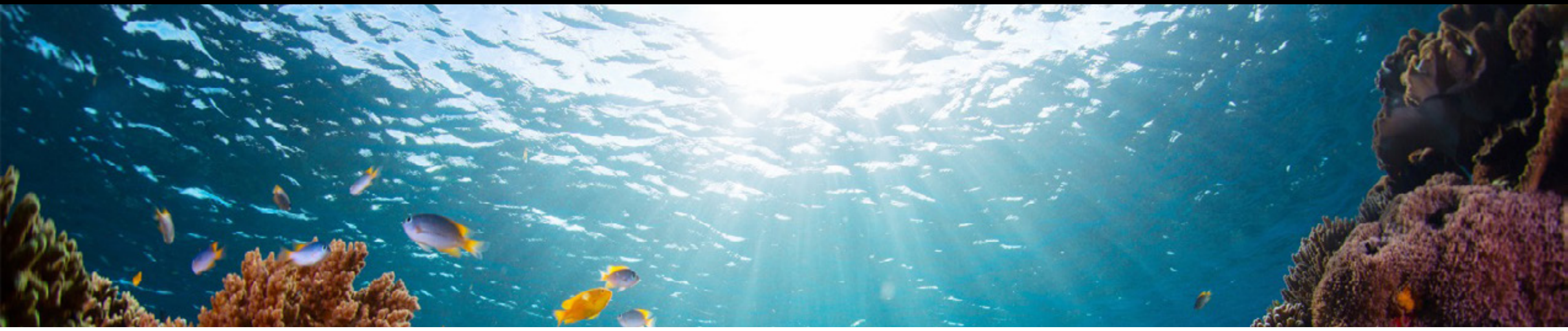
There are a number of safety mechanisms specified in NACS to protect the end user and achieve the functional safety that automotive applications require, such as preventing the amount of heat generated during charging from exceeding safe operating limits.

NACS and CCS use the same communications protocol between the EV and the charging station. This allows the vehicle and charging station to agree on charging parameters and ensure a safe charge.

Aptiv's high-voltage product offerings span charge cords, inlets, wiring, busbars, OBCs and power distribution units to deliver power to the battery. Aptiv's approach to optimizing the electrical/electronic architecture is well suited to delivering flexible, cutting-edge, integrated grid-to-battery-pack charging solutions that fulfill the highest requirements for performance, functional safety, cybersecurity and power.

Sustainability

APTIV AT CES 2024



The First Auto Part Made From 100% Recycled Ocean Plastic

According to the International Union for the Conservation of Nature, more than 14 million tons of plastic end up in the oceans every year — more than a garbage truck's worth every minute. To help reduce the environmental impact of ocean plastic, Aptiv subsidiary HellermannTyton developed a solution with Ford Motor Co. to remove one of the most dangerous types of plastic waste found in the world's oceans: fishing nets.

The fishing industry leaves hundreds of thousands of tons of plastic nets in the oceans every year — nearly enough to cover a land area the size of Scotland. Nylon fishing nets pose a unique danger because sea animals, such as dolphins and sea turtles, can become entangled in them. Given that plastic takes hundreds of years to break down, abandoned fishing nets can devastate countless generations of marine life.

Ford turned to HellermannTyton, a global leader in cable management products, because of its track record of innovation and commitment to sustainability. “When you choose a partner, you choose someone like HellermannTyton,” said Deborah Mielewski, a former technical fellow for sustainability at Ford who worked with HellermannTyton at the time of the project.

The collaboration produced the first automotive part made from 100 percent recycled ocean plastic: a cable lead on the Ford Bronco Sport. The recycled material is cheaper and less energy-demanding to produce than new petroleum-based products and matches their strength and durability — proving that sustainable solutions can also be good for business. The project was so successful that Ford has expanded the product line to include transmission brackets, wire shields and floor side rails.

Having a positive impact on the environment through the products we develop is essential to achieving Aptiv’s mission of creating a safer, greener and more connected future. HellermannTyton’s efforts to create healthier oceans for us all are a testament to that goal.

Sustainability Always Moves Forward

At Aptiv, our business strategy is directly aligned with our sustainability goals. We provide solutions of the highest quality — designed, developed and manufactured responsibly — that enable a safer, greener and more connected world. In doing so, we take care of our people and the communities we operate in while minimizing our carbon footprint.

But sustainability — and how we achieve it — is not static. We put our sustainability strategy "in motion," understanding that its impact is only as good as its implementation. We also recognize that our strategy must be continually evaluated and refined. To that end, in 2022 we updated our materiality analysis, asking key stakeholders — including customers, investors, employees, suppliers, industry associations, and other third-party experts — to rate environmental, social and governance topics in terms of their importance to our business. These insights serve to refine our sustainability strategy and crystallize our priorities. This ongoing dialogue with key stakeholders yields clear context for Aptiv's Board of Directors to provide governance and oversight, and for our executive leadership to evolve our sustainability program across functions wherever it makes sense.

Foundational pillars of Sustainability

What has not changed at Aptiv are the four foundational pillars of our sustainability framework. Each will be discussed at length in this report, but here is a preview:

People: Our changing world requires high-performing, committed and talented professionals who are not only open to innovation but are driven by it. Including diverse experiences and points of view is key to building that kind of team. In 2022, we brought together experts from the United States, China and Europe, across engineering disciplines ranging from software and systems to electrochemistry and mechanical and electrical engineering. This diverse group was tasked to develop a power electronics solution that is already enabling new functionality for electric vehicles, including our first production award 18 months after we began to form the team, for a vehicle that is scheduled to launch in 2025.

Products: Our products have a tangible impact on the environment. In 2022, our HellermannTyton business unit worked with Ford to produce wiring harness clips for the Ford Bronco Sport that are the first automotive components made from 100 percent recycled ocean plastic.

Planet: In our goal to be carbon-neutral by 2040, we need a sustainable business model that addresses every aspect of our production process. In 2022, Aptiv recycled 84 percent of our total waste, exceeding our target of 80 percent and saving more than 35,000 tons from entering landfills globally.

Platform: How we conduct our business is just as important as what products we make, and our Code of Ethical Business Conduct serves as the foundation for putting our values into action. In 2022, Aptiv's senior leadership team engaged with our employees in a variety of ways to promote a culture of speaking up and to educate our employees about ethics, including hosting town halls and live webchats, providing targeted risk- and role-based training, and distributing a monthly newsletter.

This report showcases the advances that we have made in sustainability. We are proud of our work but also recognize that we must continue to progress toward our goals — our customers expect nothing less, and our planet deserves at least as much. Thanks to our 200,000 employees from around the world, I am confident that we will meet the challenge.

Kevin P. Clark
Chairman and Chief Executive Officer

Want to Learn More?

Check out these resources for more insights into the technologies Aptiv is demonstrating at CES 2024.

APTIV AT CES

Get details on the technologies that will be on display. Plus you can take a virtual tour of our pavilion after the show.

https://www.aptiv.com/en/ces-2024

APTIV INSIGHTS

Access white papers, articles, videos and other content throughout the year.

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APTIV SOLUTIONS

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