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U-Shift IV: Innovations and challenges in autonomous urban mobility

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Abstract

The U-Shift IV represents the latest evolution in modular urban mobility solutions, offering significant advancements over its predecessors. This innovative vehicle concept introduces a distinct separation between the drive module, known as the driveboard, and the transport capsules. The driveboard contains all the necessary components for autonomous driving, allowing it to operate independently. This separation not only enables versatile applications - such as easily swapping capsules for passenger or goods transportation - but also significantly improves the utilization of the driveboard. By allowing a single driveboard to be paired with different capsules, operational efficiency is maximized, enabling continuous deployment of driveboards while the individual capsules are in use. The primary focus of U-Shift IV was to obtain a permit for operating at the Federal Garden Show 2023. To achieve this goal, we built the vehicle around the specific requirements for semi-public road operations which includes narrow streets and pedestrians. This involved integrating necessary modifications across multiple domains, including the e/e-architecture, sensor setup, software stack, and even the design of the driveboard and capsule. By utilizing systematic methods to address regulatory and safety challenges, we ensured that the vehicle met the standards required for autonomous driving in semi-public environments. In this paper, we explore the methodologies employed to achieve regulatory compliance, focusing on sensor integration, software- and e/e-architecture. We discuss our multi-modal sensor setup, which combines camera, lidar and radar to archive redundancy and enhanced environmental perception. Additionally, we provide an overview of our software architecture, emphasizing its role in ensuring safe driving functions and enabling autonomous operations.

Introduction

The U-Shift ecosystem is a multifaceted project that encompasses various development stages and research topics for an urban modular vehicle concept designed for efficient mobility in densely populated environments. At its core lies the innovative driveboard with an integrated capsule changing system, which enables dynamic adaptation on-the-road to meet fluctuating demands. By seamlessly transitioning between passenger capsules during peak hours and cargo capsules during off-peak periods, this concept significantly reduces standby time and increases effective operational hours for an individual driveboard itself [1].

The development of U-Shift I marked a crucial milestone in the project landscape, as it established the foundation for the project's technical specifications and enabled the creation of a functional, real-scale demonstrator with both passenger and cargo capsules seen in the background of Figure 1 [2]. Building upon this success, U-Shift II further expanded on more advanced energy and electric systems. It also incorporated the first perception sensors for an automated driveboard as a research platform [3]. U-Shift III marked a departure from the previous iterations, with a focus on developing an all-electric lifting system and exploring alternative solutions for a Managed Automated Driving (MAD) [4]. This iteration was a collaboration with industrial partners to develop a remote-operated driveboard, further enhancing the project's capabilities. The progression from these iterations laid the groundwork for the latest U-Shift IV concept seen in the foreground of Figure 1, which takes a substantial leap forward in terms of readiness level.



Figure 1 U-Shift IV (front) in lifted state with the new passenger capsule, U-Shift I (background) in lowered state and cargo capsule on the right [5]. © DLR (CC BY-NC-ND 3.0)

The development goal of U-Shift IV was to demonstrate a first iteration of modular automated driving in real-life environments. For that the U-Shift should operate at the Federal Garden Show 2023, an environment with semi-public roads and challenging urban conditions. The track seen in Figure 2 was an ideal testing ground, as it simulated a narrow street scenario with varying environmental factors and shared infrastructure with mainly pedestrian but also other Light Electric Vehicles. To achieve this objective, several considerations were necessary to adapt the vehicle's architectures to these new requirements.

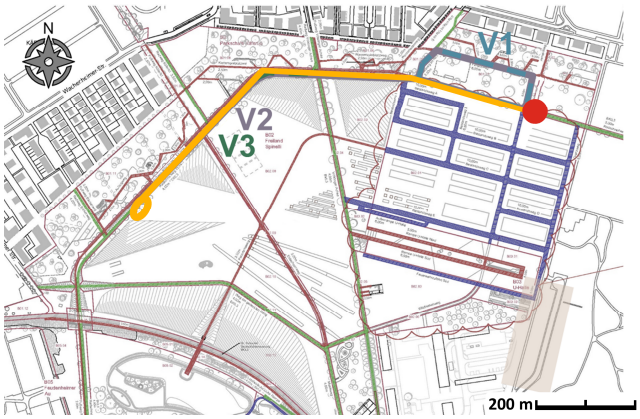


Figure 2. U-Shift test track at the Federal Garden Show with start point (red circle) and the test route (yellow line) inside the park area. The track is approximately 2000 m long.

The paper presents an overview of the key requirements and challenges for U-Shift IV in regards to its hardware and software in the context of the Federal Garden Show, as well as our approach to addressing these challenges. This provides a foundation for the technical exploration that follows, which delves into the detailed architectures of the driveboard, including its Powertrain and electric/electronic architecture (e/e-architecture), as well as the sensor setup. The final section will examine the software architecture that enable the safe autonomous driving capabilities of the vehicle.

Goals, Requirements and Challenges

While the Federal Garden Show is a private property, which does not require an approval other than from the event management, the project focused on acquiring an approval following TÜV Süds AV-Permit process to satisfy safety requirements. Paper [6] provides a detailed insight into the key considerations addressed for the U-Shift IV concept.

The Operational Design Domain (ODD) of the Federal Garden Show, as shown in Figure 2, represents a unique scenario for autonomous vehicle operation. The route is a 2000 m long, 4-5 m wide asphalt road shared with other users. There is no room to maneuver alongside the road. However, the space offers an open layout with minimal obstructions between the route and the start point.

In addition to the "first on the road" goal for the U-Shift IV, several other objectives were defined. The vehicle should incorporate a fully multi-modal sensor setup, which will support highly autonomous driving functions beyond the scope of the Federal Garden Show. Furthermore, the 400V high-voltage battery, previously used in the U-Shift III concept, should also be adopted to the new concept. The selection of other components is mainly limited by space constraints of the concept and their availability due to the strict time schedule.

Building on the environmental constrains of the ODD and the goals for the U-Shift IV, a hazard analysis and risk assessment were conducted [6]. From this, the primary safety goal for the U-Shift IV architecture was derived: the ability to perform a controlled full stop in case of an emergency. Three major safety requirements for the hardware and software architecture can be deduced from the safety goal. Firstly, it necessitates the presence of a trained safety driver who can monitor the entire system and intervene as needed in emergency situations. Secondly, the braking and steering systems of the vehicle must be certified for safe operation on public roads. Finally, it must be ensured that the hardware and software architecture is designed in such a way, that other components cannot compromise the integrity of the safety-critical functions.

These requirements pose several challenges, including the need for a dedicated safety driver space within the vehicle with an unobstructed view to the front and mirrors on each side. Additionally, it must be ensured that the hardware is reliable and that the overall software architecture does not conflict with any safety functions. Furthermore, a challenge arises from the modular design of the U-Shift concept that does not allow for a mechanical-linked steering wheel, braking or gas pedal system to a driver seat.

The safety driver position requirement is accomplished through a redesign of the passenger capsule. As shown in Figure 3, the new design includes a dedicated area for the safety driver in the front left section of the capsule. This space allows the safety driver to store the remote control and monitor the vehicle's status and surroundings. Additionally, the redesign incorporates a dedicated joystick for manual control, ensuring the safety driver can effectively intervene in case of an emergency.

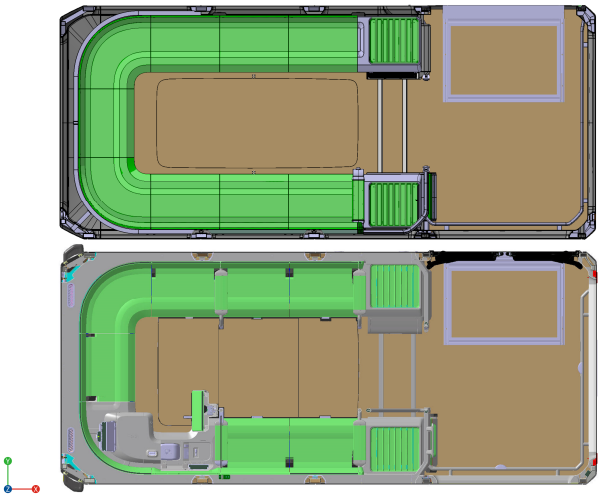


Figure 3 Comparative CAD interior layout of the initial passenger capsule (top) and the redesigned passenger capsule (bottom). The lower left corner highlights the newly integrated safety driver area, enhancing operational safety.

In regards to the component selection, significant emphasis was placed on control hardware. Due to the modular concept of the vehicle an X-by-Wire system is required. While Drive-by-Wire systems, which control throttle, are common in electric vehicles, fully electrical Steer-by-Wire and Brake-by-Wire systems without any mechanical connection to the driver are not yet widely adopted in the industry. We opted for an automotive-grade closed system, which is tested on public road, and developed our hardware and software architecture around that components. For the selection of additional hardware components, primarily off-the-shelf parts were chosen that are certified for the automotive industry.

Driveboard Powertrain

To achieve the safety requirements and design goals for the U-Shift IV, the powertrain of the driveboard was designed with automotive-grade components and redundant power supplies for the safety critical systems. This ensures safe braking and steering operation of the vehicle, even in the event of a primary power failure.

The U-Shift IV main battery system utilizes a 400 V high-voltage architecture identical to that used in the U-Shift III [4]. However, this time, the 35 kWh battery pack is positioned vertically in the front area of the driveboard, resulting in a more compact and shorter overall packaging of the vehicle. The high-voltage battery provides advantages such as faster charging, increased power output to the drivetrain, and higher energy density; however, it introduces a more complex architecture and necessitates low-voltage power supply for other components. Because of that two lower voltage power rails are also deployed: a 24 V and a 12 V rail.

To maintain reliable operation and mitigate voltage fluctuations, two 12 V batteries are connected in series with a capacity of 100 Ah. A DC-DC converter, coupled with a Battery Management System (BMS), charges these batteries during operation, ensuring a stable 24 V power rail. Additionally, a secondary DC-DC converter is used to supply the 12 V rail from the 24 V rail.

In addition, the Steer-by-Wire and Brake-by-Wire systems include a 12 V backup battery that is isolated from the main power rail for increased safety and reliability through redundant design.

The rear axle features two electrical in-wheel motors, each capable of delivering a continuous output of 25 kW and reaching peak values up to 60 kW. The permanent-magnet synchronous motor (PMSM) paired with a suitable inverter enables regenerative braking.

Electric/Electronic-Architecture of Driveboard

The U-Shift IV employs a domain-centralized e/e-architecture as shown in Figure 4, necessary due to varying safety requirements for certain functions. Within this architecture U-Shift IV features four main components that control the driving functions: Brake-by-Wire, Steer-by-Wire, Vehicle Control Unit (VCU) and the High Performance Compute Unit (HPCU). The two most safety-critical ECUs (Electronic Control Unit) are the Brake-by-Wire and Steer-by-Wire system. These systems can operate independently in emergency situations, ensuring the vehicle comes to a safe stop by being directly wired to the emergency stop relays. The selected components are ECE-compliant systems, approved for certain vehicles to be used on public roads.

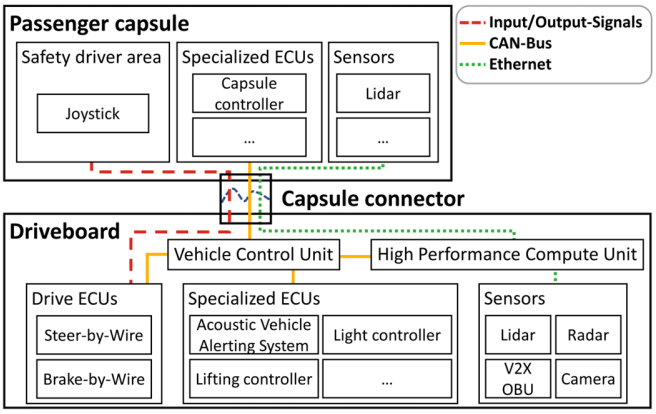


Figure 4 E/E-Architecture of U-Shift IV. The network topology consists of CAN-Bus and Ethernet. The communication between the safety driver area and the X-by-Wire systems is directly wired.

The automotive-grade VCU serves as the central ECU for planning and executing driving functions. It also acts as a body management controller, sending commands to specialized ECUs, such as the Acoustic Vehicle Alerting System (AVAS) or light control ECU. In addition, the VCU receives guidance from the HPCU, which runs a Linux distribution.

The HPCU processes perception-related sensor data, providing advisory inputs to the VCU. However, it cannot control the vehicle directly. The HPCU is an industrial-grade system designed for high-performance computing applications, such as computer vision tasks, that the VCU would not be able to perform.

The CAN-Bus standard is used as the communication channel between all ECUs, as it is well proven and adopted in the automotive industry. To ensure fault isolation and prevent system failures, multiple CAN busses are deployed to separate safety-critical systems from non-safety-critical ones. The VCU acts as a central hub for all CAN-bus communication, aggregating and forwarding data between the various ECUs and systems, as Figure 4 shows.

For high-bandwidth applications like perception sensors, localization, and wireless communication devices, which require low latency and high data transfer rates, we deploy an Ethernet network to provide a reliable and efficient communication channel. Once all sensors are operational, the Gigabit connection to the HPCU is utilized at 90% capacity, far exceeding the capabilities of a regular CAN-Bus. The HPCU analyze and processes all that data from the sensor systems via Ethernet and advice the VCU via CAN-Bus accordingly.

To establish a connection with the capsule's systems, the U-Shift IV is the first driveboard to deploy an automatic capsule connector. The connector is located on the left inner side as Figure 5 shows. When the capsule is properly docked in the driveboard, the driveboard's capsule connector can be extended and automatically connect the capsule data busses. The redesigned passenger capsule is the first capsule featuring this connector system. If a connection is established, CAN-Bus, Ethernet and I/O-signals are transmitted.

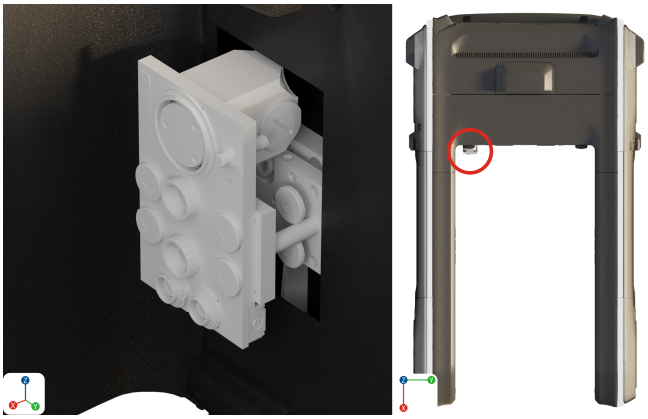


Figure 5 Close up of the extended capsule connector of the U-Shift IV. The connector on driveboard side can be extended and connect automatically after the capsule was successfully docked with the driveboard.

Sensor concept

The U-Shift IV features a comprehensive sensor setup to gather information from its surroundings. This includes perception sensors, localization sensors, and communication interfaces for Vehicle-to-everything (V2X) communication.

In terms of perception, the driveboard uses a multimodal sensor setup with overlapping fields of view as Figure 6 shows. The setup consists of lidar, radar and camera.

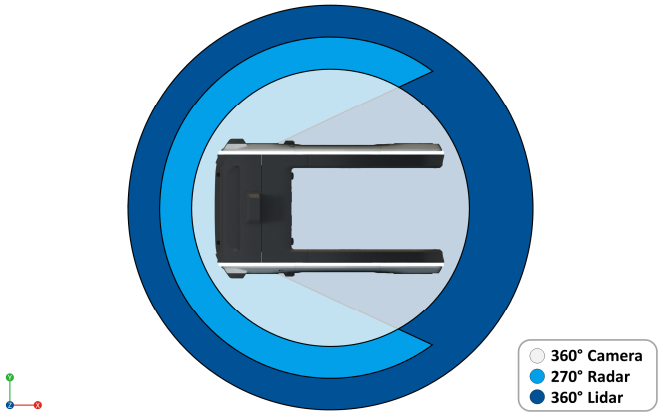


Figure 6 Coverage of different sensor modalities. While camera and lidar allows a 360° view around the vehicle, radar is only deployed in the front of the vehicle.

Eight solid-state lidars are mounted around the vehicle, achieving a 360° field of view (FOV). Two of the front-facing lidars have a squinting arrangement, as can be seen in Figure 7 and Figure 8, to minimize blind spots in front of the vehicle. Each individual lidar sensor has a 60° horizontal field of view with a range of 60 m (at 10% reflection).



Figure 7 Front view of U-Shift IV with marked sensors. The radar sensors sit behind the bumper and side panels.

The sensor facing the inner of the driveboard is occluded if a capsule is docked, creating a blind spot directly behind the U-Shift. This issue can be addressed by installing additional lidar sensors on the passenger capsule. While the passenger capsule has two more lidars installed at the back, the cargo capsule does not have further sensors installed, which in turn leads to more restricted ODD.

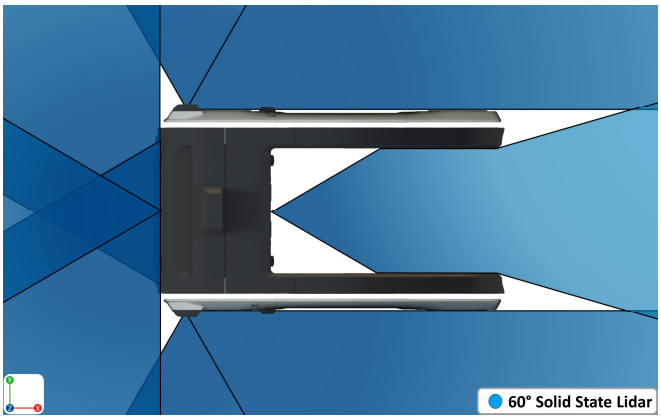


Figure 8 Sensor coverage of the lidar setup. The squinting arrangement in the front minimize the horizontal blind spot.

The five radars shown in Figure 9 can be switched between three scanning modes: long range, mid-range, and short range. In low and mid-range mode, all five radars have a 130° field of view around the front of the vehicle, resulting in an overall field of view of approximately 310° degrees. The radar system's range varies depending on the scanning mode, ranging from 20 m to 120 m. If the sensors are used in long range mode, the field of view decreases to 100°.

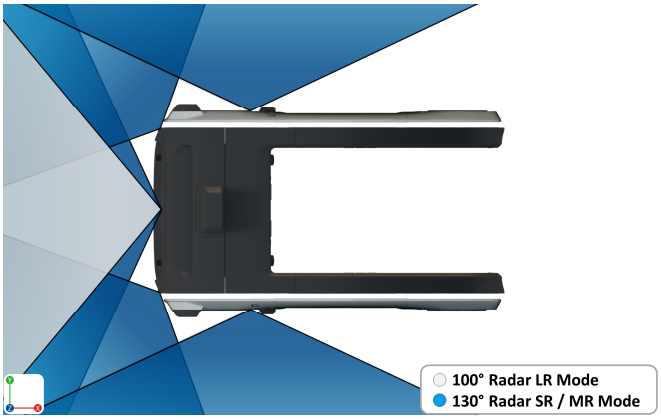


Figure 9 Sensor coverage of the radar setup. The radar has a more focused FOV in long range mode compared to short and mid range.

The camera setup consists of nine GMSL2 cameras and three higher-resolution Power-Over-Ethernet (POE) cameras on the front side. The arrangement allows for a 360° field of view around the driveboard. The two cameras in the inner part of the driveboard assist with alignment during capsule docking.

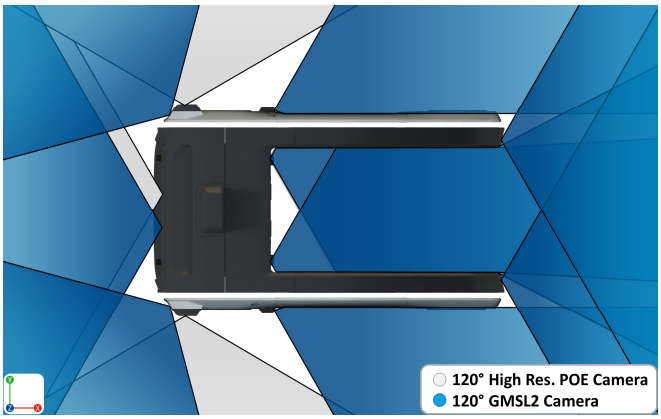


Figure 10 Sensor coverage of the camera setup. It utilizes a nearly 360° FOV with GMSL2 cameras. Higher resolution cameras are deployed for the front side to enhance the effective range.

When compared to a standalone driveboard, the addition of a non-overhanging cargo capsule only expands the blind spot area behind the U-Shift slightly. However, as Figure 11 highlights, the passenger capsule produces an obstructed rear view, which is due to the overhang of the capsule. To mitigate this issue, an additional camera is placed on the passenger capsule.

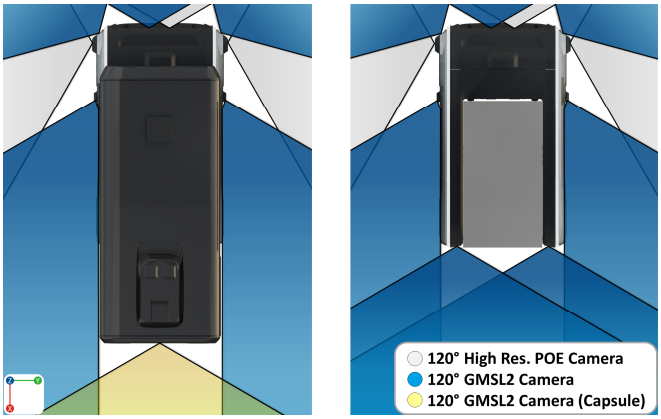


Figure 11 Blindspot comparison between the passenger capsule and the cargo capsule. Due to the overhang of passenger capsule another camera is installed.

For localization the driveboard uses a GPS sensor with an integrated inertial measurement unit (IMU). In conjunction with the passenger capsule a more precise real-time kinematic GPS (RTK-GPS) module with a triangular antenna configuration on the capsules roof is used. The more precise RTK-GPS is placed on the capsule as the antennas on the driveboard would be highly obstructed by the capsule itself. The approach builds upon the utilization of perception sensors for an enhanced localization of the driveboard's ego-position estimates if no capsule is docked. This will ensure robust localization performance in the future.

The driveboard employs a V2X On Board Unit (OBU) for communication with other vehicles and infrastructure, which is particularly valuable in urban environments. By leveraging this technology, the vehicle can utilize an additional perception channel, enhancing its situational awareness. In contrast to U-Shift III with a managed automated driving approach, the primary focus in this generation shifts to collective perception where information about object positions and states is shared among road users and infrastructure. This collaborative approach extends the perception range beyond traditional line of sight capabilities, improving safety around the vehicle [7].

Software Architecture

The U-Shift IV is accommodating three distinct modes: manual, remote-controlled, and automated. These modes are prioritized from highest authority to lowest, with the safety driver able to intervene at any time via an emergency brake. In manual mode, the safety driver is situated in the passenger capsule with the wireless emergency stop button and a joystick for control, directly wired to the Brake-by-Wire and Steer-by-Wire system as shown in Figure 4. The remote-controlled operation mode enables the safety driver to remotely control the vehicle from outside, provided the current situation permits it. Automated mode requires the safety driver again to remain within the passenger capsule, with the remote located in a designated holder. Upon verification of all parameters, the vehicle begins its predefined route.

The manual mode serves as a backup and testing solution, enabling manual movement of the vehicle from within the passenger capsule when necessary. This mode is intended for situations where the vehicle

needs to be manually operated, like maneuvering around non-moveable objects.

The same goes for the remote-controlled mode. Further it is used for capsule change maneuvers, which are only performed in designated closed areas without passengers. The operator can switch between cargo and passenger capsules using this mode. As the capsule change is requiring precise maneuvering and vision on the mounting rail, this operation is best carried out from outside. The capsule needs to be precisely maneuvered onto the rails of the driveboard. Currently, manual operation is required due to the high precision requirements involved.

In contrast, the autonomous mode is initiated from the designated safety driver seat and leverages a high-accuracy GPS point follower and lidar-based braking assistance. As the ODD does not allow for evasive maneuvers, the vehicle will brake in case of an obstacle. The vehicle's ego position is determined using RTK-GPS data from the capsule, which follows a predefined route. This route includes multiple GPS points, speed profiles for different road sections and bus stops along the way.

The calculation of the drive strategy and controlling of the drivetrain happen on the VCU. Concurrently the HPCU processes lidar perception data to create an occupancy grid. Despite autonomous operation, the safety driver retains the ability to override vehicle speed or perform a full emergency brake at any time.

From a safety perspective, the U-Shift IV's driving functions and hardware architecture are inspired by an onion architecture visualized in Figure 12. The innermost layer, with the highest safety requirements, features the Brake-by-Wire and Steer-by-Wire system. This system itself meets the "safe stop" safety requirement through its redundant hardware design and direct connection to the emergency stop relay via a safety relay. The interfaces between this inner layer and the outer layers of the architecture are carefully defined to prevent any interference with the Brake-by-Wire and Steer-by-Wire systems. This ensures a high level of reliability and fail-safeness.

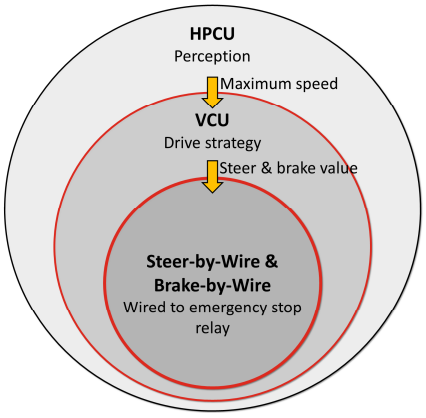


Figure 12 Every layer of the onion architecture restricts the access to the inner layers more. The HPCU is not able of directly communicating with the safety related X-by-Wire ECUs.

The next outer layer in the onion architecture is the VCU, which controls the Drive-by-Wire system, plans the trajectory, and executes driving commands. The VCU's software is aligned with the European Guidelines for Advanced Safety (EGAS) norm, which itself is inspired by the ISO26262 standard.

The outermost layer of the onion architecture describes the Linux-based HPCU. While the codebase is written with best practices in mind, it does not follow a specific safety norm. As the outermost shell, the HPCU has limited control over the inner components. It acts as an advisor to the VCU's path planner, providing suggestions for maximum speed limits but not directly controlling the vehicle.

The Steer-by-Wire and Brake-by-Wire system is an automotive-grade software solution that is only configured by our team, not programmed. This system provides various input options, including a CAN-bus interface, which allows us to transmit braking and steering values to the system. In addition to this, there are multiple routines and sequences in place to actively monitor the health status of both X-by-Wire systems and the VCU bidirectional. This ensures that the safety-critical components are functioning correctly, and it can be quickly identified if any issues arise from the VCU. This triggers an emergency brake.

The VCU software has an application layer that is monitored by an additional safety layer on top. Within the VCU software, the application layer is divided into four main software blocks shown in Figure 13.

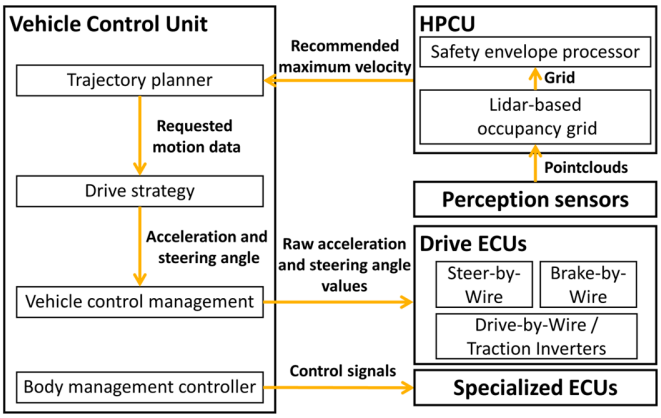


Figure 13 Dataflow of the autonomous stack between the central hardware components and their respective software blocks.

The first block is responsible for the trajectory planning, which analyzes the current position, next GPS point, speed profile, and advisory from the braking assistant.

The second block, known as the drive strategy block, focuses on determining optimal steering and acceleration values based on a parameter set tailored to the vehicle and the instructions of the trajectory planner.

The vehicle control management block acts as the counterpart to the Steer-by-Wire and Brake-by-Wire systems, managing communication and routines with these systems while also controlling the Drive-by-Wire system. It includes the control loop for the Traction Inverters, ensuring smooth and safe operation of the vehicle's powertrain.

The fourth block, called the body management controller block, oversees a range of tasks including battery management, as well as controlling multiple specialized ECUs in the vehicle. This includes ensuring safe operation of the remote-control system, managing docking routines for the lifting mechanism of the driveboard, and coordinating capsule connector operations.

The VCU has an additional safety layer not shown in the figure. The layer lies above these application layer of the VCU and monitors the vehicle's status and hardware health across various systems. This layer also controls switching between different operation modes, ensuring the vehicle remains in a safe state at all times.

The HPCU communicates over CAN-bus with the VCU. To minimize the safety implications of running non-real-time Linux on the HPCU, a highly restricted interface was defined, preventing interferences with the inner layers in regards to the safety requirements. This interface primarily consists of a maximum speed advisory, which is sent to the VCU as shown in Figure 13. However, the final decision over the current speed remain fully controlled by the VCU. In other words, the advisory from the HPCU is a maximum speed limit, but the VCU can set the real speed lower at any time if necessary. A higher speed is only possible if the safety driver actively commands it through their input controls, but still within the defined parameter space of the current road segment.

The software on the HPCU uses the Robot Operating System 2 (ROS2) middleware, providing an agile development environment for research purposes. For instance, the emergency brake assistant uses a CAN2ROS-Bridge to communicate with the VCU.

The braking assistant utilizes lidar perception data, which includes raw point clouds from all sensors. These point clouds are fused into a calibrated single cloud and ground points are filtered out. The emergency brake assistant itself is based on an occupancy grid with a safety envelope processor as seen in Figure 13. The safety envelope defines critical zones around the vehicle, shown in Figure 14, according to the safety concept. When an object enters these critical zones, a maximum speed is specified that gets sent to the driving strategy on the VCU. The final vehicle speed is calculated in conjunction with the current speed limit for the route. Again, the ultimate decision-making authority remains with the safety driver by adjusting the maximum speed or initiate an emergency braking at any time.

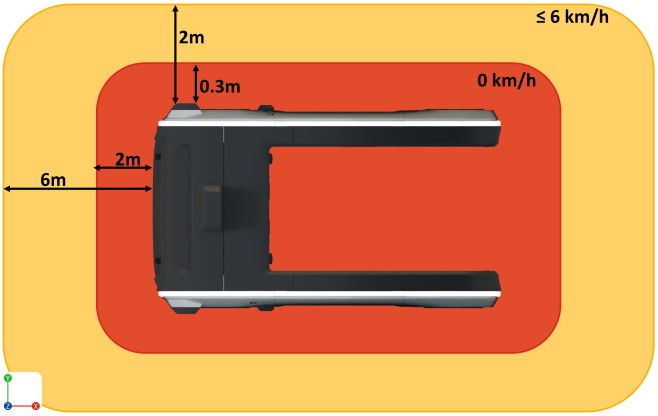


Figure 14 Safety envelope around the U-Shift. Depending on which zone an obstacle is located in, the brake assist system brakes the vehicle.

Conclusions and Outlook

By applying the described architecture to the U-Shift, the team successfully obtained an approval from TÜV Süd for the semi-open space at the Federal Garden Show. Throughout its operational period of six months, the U-Shift IV logged over 2000 km of mileage and facilitated transportation for approximately 10,000 passengers [6]. Notably, during this time, five instances of hard braking events were triggered by the safety driver in response to attempts by road users to test the system's integrity. Fortunately, none of these incidents resulted in a collision or accident [8].

During operation the path follower performed exceptionally well, maintaining a deviation of less than 2 cm from the given points. This performance is likely due to the relatively open nature of the track, which minimized the impact of signal reflections from nearby buildings and other environmental factors. In a more urban environment we expect higher deviation. Unfortunately, some technologies did not mature in time for deployment at the Federal Garden Show, and we will address these gaps next. This includes V2X communication with other road users and infrastructure, as well as autonomous capsule docking.

Furthermore, our current software architecture shows limitations in terms of flexibility for higher automation functions. The primary issue lies in the feature limited interface between the HPCU and the vehicle's control systems, which hinders seamless transition to a full autonomous stack.

To address this shortcoming, our architecture will shift towards a more centralized approach around the HPCU. This will move the planning and trajectory controller to the HPCU, allowing us to directly control the vehicle’s lateral and longitudinal movement. We will further enhance perception capabilities, implementing advanced algorithms that fuse the outputs of all our sensors. These changes will require an extension of the interface between the safety-related systems and the autonomous stack, which necessitates a new consideration of the safety requirements.

Nevertheless, leveraging a safety driver in conjunction with a safe X-by-Wire system provides a promising approach for developing a from ground-up new vehicle concept like the U-Shift.

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Definitions/Abbreviations

MAD	Managed Automated Driving describes a concept, where vehicle functions, like perception, are outsourced to the infrastructure
e/e-architecture	electrical/electronic-architecture
ODD	Operational Design Domain
BMS	Battery Management System
PMSM	permanent-magnet synchronous motor
VCU	Vehicle Control Unit
HPCU	High Performance Compute Unit
ECU	Electronic Control Unit
AVAS	Acoustic Vehicle Alerting System
V2X	Vehicle-to-Everything communication
FOV	Field of View
POE	Power over Ethernet
IMU	inertial measurement unit
RTK-GPS	Real-time kinematic GPS
OBU	On Board Unit for V2X communication
EGAS	European Guidelines for Advanced Safety
ROS2	Robotic Operating System 2 is a middleware for software components which enables communication between them