ShapeFuture - Technical Progress After Year 1

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***Abstract*— ShapeFuture will drive innovation in fundamental Electronic Components and Systems (ECS) that are essential for robust, powerful, fail-operational and integrated perception, cognition, AI-enabled decision making, resilient automation and computing, as well as communications, for highly automated vehicles.**

The overarching vision of ShapeFuture is to bring ECS Innovation to the heart of Europe's Mobility Transformation, thereby elevating sovereignty by perfecting programmable ECS solutions for intelligent, safe, connected, and highly automated vehicles. In this paper, we detail not only the vision and mission of the ShapeFuture project, but we also showcase the results achieved during the first year.

Keywords*— *Automated vehicles, perception, cognition, HMI, resilient automation, resilient communications

I. Introduction

The global industry has been undergoing radical developments, from human manufacturing processes to industrial digitalization and the introduction of robots, becoming elaborated down to the tiniest detail and entailing deep understanding in complex products.

Industrial developments have been so far heavily influenced by Electronic Components and Systems (ECS). Throughout these industrial (r)evolutions, ECS have evolved from basic vacuum tubes to highly integrated circuits, microprocessors, sensors, actuators, and advanced communication technologies.

In the particular, the area of mobility, ECS have so far contributed to great advancements. Since over a decade, automotive solutions based on perception, e.g. preventing collisions and advancing vehicle automation are available for the mass market. Furthermore, mobility is undergoing a profound transformation driven by a convergence of factors ranging from environmental concerns to technological advancements (see Fig. 1). This shift is crucial to address pressing challenges like climate change, urban congestion, and the need for more efficient and sustainable mobility solutions on the way to zero fatalities.

Given these societal needs, Europe must urgently deliver the right ECS and be instrumental in creating more efficient, convenient, and environmentally friendly mobility solutions for the future.

Furthermore, Europe has to reach an economy of scale for the global competition. It must find the strategic way to gain a prominent differentiating, scalable and stable position in the global ECS industry based on knowledge, competences and capabilities.

The need for European ECS sovereignty and ownership is not just a matter of economic competitiveness, but also a matter of strategic importance for Europe's long-term success and security.

Europe needs to put together a collaborative research and development effort, where all stakeholders along the ECS value chain work together, conducting research in the fundamentals, focusing on the roots of the innovation tree and sharing a common understanding, which is also the firm belief which drives the work presented in this paper, with the results of which, new applications based on ECS advances, will be developed for EU technological leadership in solutions for safe mobility solutions with a resilient supply in ECS.

This paper is structured as follows. Section II details

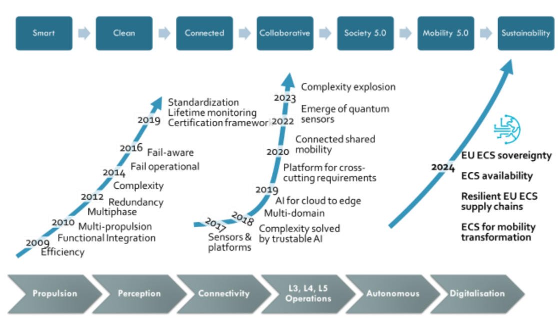

Fig. 1: ECS play a pivotal role in this transformation.

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ShapeFuture's vision, mission, and expected outcomes. Sections III – VI highlight ShapeFuture's Innovation Stream, i.e., the core technical results. Finally, our results are concluded in Section VII.

II. VISION, MISSION AND EXPECTED OUTCOMES AND STRUCTURE

A. *Vision, mission and outcomes*

The work presented herein has the overarching vision that ECS Innovation is at the heart of Europe's Mobility Transformation: elevating sovereignty and manufacturing strategy by perfecting programmable ECS solutions for intelligent, safe, connected, and highly automated vehicles. The work that is carried out in the EU funded project ShapeFuture envisages that:

- Green mobility in Europe is pillared on European supply chains with no more significant dependencies or supply limitations.
- There is a highly competitive OEM-Tier1-Tier2-SME-Academia EU chain
- European ECS supply chains are resilient, able to innovate, and provide competitive products and services in mobility in ECS concepts/architectures, designs, technologies and manufacturing capabilities.

As such, we need to lay the foundations for competitive European ECS solutions to foster manufacturing value chains in mobility. Our mission entails:

- the delivery of a new generation of perfected ECS, for each vehicular subsystem essential to perception, cognition, Human-Machine Interface (HMI), processing and decision-making, as well as resilient operation and communications. Each of these sub-systems unifies the critical components required to realize a specific function – perception, cognition, decision making and secure automation and communications – through vertical integration within an adaptive architectural framework, abstracting internal implementation, enabling portability and facilitating modular development of automation that is guaranteed as safe by design. Further, the adaptivity of the project tangible results enables them to be horizontally integrated with others at the vehicle level, while the decoupling of functionalities into separate groups enables such integration to be performed without rigid system-level architectural constraints;
- pushing and aligning our resources and know how (by activating supply chain teams) to become faster the leading-edge innovators;
- addressing mobility automation, safety, efficiency by focusing on AI, perception, cognition, decision making and communication sub-systems;
- jointly picking up innovation subjects to avoid wasting of engineering energy;
- empowering Europe's engineers to conceptualize, develop, manufacture and support those ECS products, pushing collaboration for education, infrastructure and technology.

The before and after such an initiative is presented in Fig. 2. By carrying out such a mission, we will:

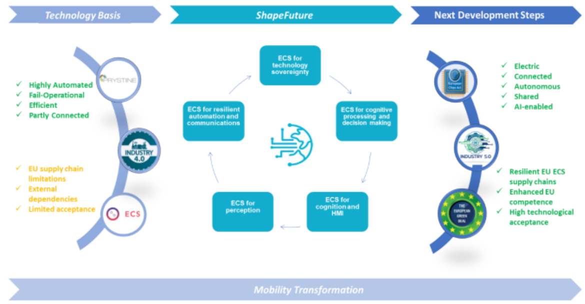

Fig. 2: Before and after the ***ShapeFuture*** initatve.

a) enable Europe to focus on its differentiating elements. This will translate in manufacturing commodity (not to be blocked, keep knowledge and in case needed, decide to ramp up), as well as in further strengthening the differentiating technologies (fail operational, zero-defect, high-quality),

b) enhance the competence along the whole value chain, all developed in a framework of trusted, fail operational, secure supply,

c) guarantee a thorough analysis and very deep understanding of the roots / fundamentals of ECS, so as to bring Europe in a sovereign position in the global ECS landscape.

All in all, the tangible outcomes of the work presented herein consist in the fundamental technical components (ECS, hardware, software, systems, competences and practices) required to perfect ECS and provide numerous innovations that will yield significant benefits to the European ECS industry and give them a prominent position inside the digitally transformed domain of transportation.

B. *Vision, mission and outcomes*

The work presented herein is centered around the development of ECS for intelligent, safe, connected, and highly automated vehicles. From a wide technology perspective, it aims to address the challenges and opportunities presented by the global industrial evolution and digital transformation. It recognizes that advancements in ECS have played a significant role in the automotive industry's transition towards automation and safety features. From a business perspective, the work aligns with the strategic goals of Europe to gain a prominent position in the global ECS industry and secure the region's supply of semiconductors.

The overall workflow is described as follows:

- As shown in Fig. 3, in order to bring the overarching vision into reality, the consortium has a dedicated mission, i.e. to enable the provision of novel, competitive ECS, so as to empower the European manufacturing supply chains.
- To carry out this mission, the consortium has defined a set of 5 objectives (Obj.1 – Obj.5) that will need to be achieved.
- In order to achieve each of the stated project objectives, we define a set of Innovation Streams (INN.1 – INN.5), which also reflect the set of pillars, in which the vision was distilled in, as shown in Fig. 3. In other words, each

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Fig. 3: Overview of the methodology and flow of work.

objective will be achieved through working in the respective Innovation Stream.

- To validate the achievement of each objective through working in the respective Innovation Stream, the consortium has defined several KPIs, with a particular focus on a set of demonstrations that reflect the results of work in the respective Innovation Stream (INN).

In this sense, each innovation stream is the logical/virtual combination of partner activities fitting together within a specific topic leading to a combined result, such as a demonstrator, for the technologies developed. Each innovation stream addresses a specific objective, and its results are used as input to other innovation streams and project activities. Thus, the result of each INN. (usually more than 1 demonstrators) showcases the achievement of the respective objective. This methodology is based on (i) clear and differentiated objectives per task/grouping, (ii) recognition, analysis, management and mitigation of risk and (iii) complementary objectives pulled together and used in the overall project.

III. ECS FOR PERCEPTION

ShapeFuture's Innovation stream "ECS for Perception" aims to fundamentally advance perception systems, moving beyond current limitations to achieve unparalleled accuracy and robustness. *Our overarching vision is to create perception technologies that redefine how machines understand and interact with their environment, demonstrated through key applications ranging from autonomous vehicle calibration to advanced driver assistance and beyond*. This chapter details the progress made in the first year towards realizing this vision, focusing on the foundational steps taken in the development of advanced sensor technologies and their integration into holistic perception systems.

A. Development of a MIMO FMCW Radar Sensor with Extended IF Bandwidth for Enhanced DDM

A key advancement within the ShapeFuture project concerns the development of a cutting-edge MIMO (Multiple-Input Multiple-Output) FMCW (Frequency Modulated Continuous Wave) radar sensor. A significant focus lies on the substantial expansion of the receiver's Intermediate Frequency (IF) bandwidth. This step is crucial for significantly improving the performance of Doppler Division Multiplexing (DDM) in automotive applications [1].

During the first year of the project, significant effort was dedicated to establishing comprehensive requirements and detailed specifications for this advanced radar sensor. Building upon this foundational work, subsequent years of the project will see a targeted increase in effort dedicated to enhancing and expanding the intellectual property (IP) blocks of the receiver section. A particular emphasis will be placed on the integration of a high-performance Analog-to-Digital Converter (ADC).

DDM leverages the inherent Doppler space sparsity in the automotive context to multiplex the signals of multiple transmitting antennas (Txs). This is achieved by adding a virtual Doppler component to each Tx, causing each target to appear multiple times – specifically N_{tx} times – in the Doppler space.

A challenge with DDM lies in the statistical spread of the peaks generated by each Tx in the Range-Doppler (RD) map [2]. To minimize overlaps of these replicated peaks, radar system designers define a "minimal DDM Doppler distance" between the Tx peaks, as dictated by the DDM pattern used. Multiplying this minimal Doppler distance by the number of multiplexed Tx yields an estimate of the minimum required maximum unambiguous speed V_{max}. Thus, the scalability of DDM faces limitations with restricted receiver bandwidth. As the number of multiplexed Tx increases, so does the demand for Doppler space. This ultimately necessitates an increase in the maximum measurable velocity V_{max}. Vmax is directly linked to the chirp repetition interval. This interval is limited by the chirp duration itself. To cover the same radio frequency bandwidth (e.g., 1 GHz) in a shorter time, the chirp rate must be increased. This, in turn, leads to higher IF frequencies, particularly at the maximum detection range R_{max}. Consequently, maintaining the maximum unambiguous range requires an expansion of the receiver bandwidth. The development within ShapeFuture addresses this challenge through the realization of a radar sensor with an extended IF bandwidth, facilitated by advancements in its receiver IP blocks, including a high-performance ADC. This progress enables the multiplexing of a larger number of Tx in the DDM scheme, thereby significantly enhancing the resolution and robustness of environmental perception without compromising the maximum range. In essence, the ability to utilize more DDM-multiplexed Tx in the automotive context is directly coupled with higher receiver bandwidth requirements, and ShapeFuture is making a vital contribution to overcoming this limitation through focused development on key receiver components.

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B. Mobility-aware asynchronous edge-assisted perception DDM

Latency and perception quality are critical in achieving reliable perception for Connected Autonomous Vehicle (CAV) functionalities in fast-changing scenes and challenging illumination conditions. The work on Mobility-aware asynchronous edge-assisted perception aims to address these challenges through the integration of event-based cameras (EBCs) and asynchronous sensor fusion. Unlike regular frame-based vision systems, EBCs offer better temporal resolution and dynamic range (DR), providing low-latency, high-contrast visual feed [3]. A suitable tradeoff between DR, frame rate, and resolution is especially critical in challenging scenarios such as high-speed driving, strong opposing sunlight, tunnel exits or low-light conditions—situations where traditional cameras often suffer from motion blur, saturation, or insufficient contrast.

Current COTS automotive frame-based active pixel sensor (APS) cameras provide high-resolution imaging at high frame rates (5MP at 60–90 FPS), capturing fast-moving scenes without distortion. However, this performance comes with a DR tradeoff, typically limited under 70dB, which lowers performance in scenes with high contrast. On the other hand, high dynamic range (HDR) cameras can reach dynamic ranges of up to 120dB but typically operate at lower frame rates (around 30 FPS at 3-5MP). Meanwhile, even deep learning (DL) models optimized for inference speed, such as YOLO series models often used in Autoware or Apollo perception stack, struggle to maintain inference time below 40 milliseconds at full sensor resolution [4]. Event cameras offer a compelling alternative, by producing sparse data streams that reduce latency (as low as 10 microseconds) and ensure very high-dynamic range (over 120dB) at the same time. Driven by these advantages, recent studies have explored the use of EBCs for key autonomous driving tasks, including stereo event vision for 3D scene reconstruction [5]. Since EBCs capture only pixel changes instead of full image frames, they are particularly effective for moving object detection (MOD) and segmentation (MOS), reducing inference time by a factor of 6 [6][7]. However, static regions in a scene also contain valuable information that event cameras alone cannot capture. In practice, a hybrid combination of APS, HDR, and EBC cameras is necessary, which has been shown to assist regular frame sensors in hybrid fusion models for reliable perception under extreme lightning or motion [8]. Nonetheless, handling purely event-based or mixed data poses substantial challenges due to its irregular structure, driving ShapeFuture's demonstrator investigations dedicated to asynchronous event-frame fusion.

To complement stereo event vision and frame-event fusion, ShapeFuture's demonstrator builds environmental representation with occupancy grid map (OGM), which is particularly suitable for path planning and obstacle avoidance. To supplement the ego vehicle perception a cooperative perception can be used, using C-V2X communication with CAM and/or CPM messages defined by ETSI. CAM messages must be broadcasted at a frame rate of 1 - 10 Hz, and CPM has the same frame rate recommendation. In the worst-case scenario with network congestion by many traffic participants, message latency can increase due to package collision increase [9][10]. Therefore, relaying on obstacle detection by cooperative system might lead to collision for the ego vehicle due to latency, which highlights the necessity for internal obstacle detection. However, cooperative obstacle detection and map generation can nevertheless provide additional benefits such as improved driving condition and reduced collision risk, e.g., reduced abrupt breaking by predicting adverse obstacles beyond line of site of the ego vehicle. Furthermore, it can lead to overall driving efficiency gain, e.g., speed adjustments for standstill traffic jam reduction and cooperative maneuvers. To benefit from this, a cooperative obstacle avoidance (CoCa) approach is to be adopted. Therefore, OGM sharing between traffic participants and roadside units (RSU) will be implemented.

C. Safety-compliant body motion controller with high-performance data fusion capabilities

Fatigue is a major concern for road safety. Powered two-wheelers riders [11] are also affected from this issue, as described in some sleep-medicine paper considering both the relation between sleepiness and risk of accidents [12]. Considering the diffusion of at-home delivery services, which mainly employ riders, developing a solution can contribute toward increasing road safety, especially in case these solutions are adopted by companies providing such services. While in the past monitoring the fatigue level was a challenge, requiring use of special-purpose devices [13], nowadays, thanks to the availability of COTS devices capable of monitoring the physiological parameters Heart Rate (HR), Heart Rate Variability (HRV), and Respiration Rate (RR) [14], enable the implementation of solutions for addressing this issue. These systems can complement or substitute those based on body balance such as [15].

Between the commercial devices available in the market, and capable of measuring HR, HRV, and RR, the most promising for this solution can be smartwatches and smart band, based on PhotoPlethysmoGraphy (PPG) sensors. Both present advantages and disadvantages. Smartwatches can be worn all day and allow for monitoring the person during the whole day, allowing for the measurement of the fatigue level, while the smart band sensors, on the other hand, can be easily integrated within a rider glove, providing a seamless experience. In any case, with both solutions, it is possible to determine the drowsiness level of the rider in real-time, enabling the possibility of alarming him/her in case of early signs of drowsiness are detected.

The designed system will be composed of (i) a wearable device, (ii) a smartphone, (iii) a wireless (Bluetooth or Wi-Fi) to Controller Area Network (CAN) bridge, and (iv) the Integrated Body Motor Controller (IBMC). The IBMC is an ISO 26262:2018 compliant ECU that manages both the body loads (light, buttons, horn, etc.) and the motor by integrating a 48V power inverter. It targets light-weight vehicles, ranging from L1e to L7e [16] categories, where a single ECU providing both function results in easier integration. Moreover, being developed as a Safety Element out of Context (SeooC), the platform can be adopted on several vehicles. A detailed block diagram is shown in Fig. 4. The wearable device measures the physiological parameters and transmits them in real-time to the smartphone, which collects and processes them to determine

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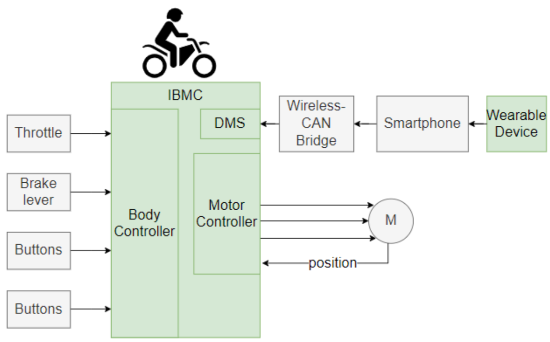

Fig. 4: Block diagram of the proposal for Safety-compliant body motion controller with high-performance data fusion capabilities.

fatigue and drowsiness levels. The fatigue level comes from the historical analysis over the entire day and contributes when available to improve the drowsiness level computation. The drowsiness level is then transmitted every second to the IBMC through the wireless-CAN bridge. The computation is performed all locally on the smartphone, to make the system available regardless of the availability of internet access and to preserve the privacy of rider's physiological data. Upon receiving the drowsiness level, the IBMC can warn the driver in case of an indication of a high risk of a sleep onset. The driver can be warned by audio, video, or haptic signals.

D. Autonomous and Tele-operated Machines with Enhanced Sensors and Haptics

For years, autonomous and mobility technologies have been centered on transportation, especially passenger cars. In ShapeFuture project, we have taken a new approach by integrating these advancements into smart construction and construction vehicles. We aim our automated vehicles to achieve superhuman decision-making performance by enhancing both safety and efficiency. The automated construction vehicles will reduce collisions with vulnerable site workers by 50% compared to human operators. Additionally, these vehicles improve efficiency by reducing energy consumption by 10% through optimal trajectory planning in complex construction environments, minimizing misjudgments in critical scenarios.

In ShapeFuture, we are focused on perception of precise systems that transform the way machines interact with and understand their environment. Our work will be showcased through the demonstrator Autonomous & Tele-operated Machines with Enhanced Sensors and Haptics. To achieve this vision, an autonomous excavator and a cabinless truck are developed and transforming them into fully autonomous operation. These vehicles will seamlessly collaborate on construction sites without human intervention as depicted in Fig. 5. Ensuring precise and intelligent navigation is critical for full autonomy, with advanced perception playing a key role. At this stage the project is leveraging from enhanced LiDAR technology, enabling accurate environmental perception and smart navigation. In addition, the activities on autonomous operation of the vehicles, development on a Human to Machine Interface (HMI) system for the beyond vision line of sight teleoperation of the excavator and haptics for immersing the tele-operators of machines at off-

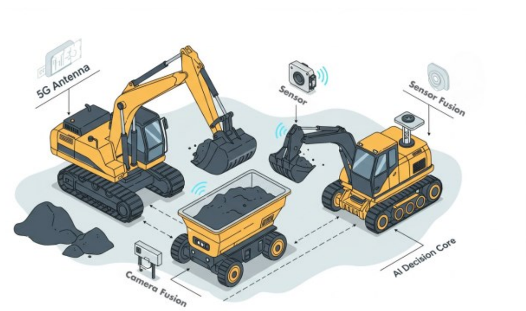

Fig. 5: Autonomous and Tele-operated Machines with Enhanced Sensors and Haptics in collective action.

site locations are done as a part of the ShapeFuture's Innovation Stream on ECS for Cognition and HMI of the project.

In this pioneering collaboration between leading research institutions and industry partners, as depicted in Fig. 6, a transformative effort aims to revolutionize the construction and farming industries through the integration of cutting-edge technologies. This effort will lead to significant improvements in efficiency, safety, and digitalization across traditionally low-tech sectors, with real-world deployments expected to validate the systems' effectiveness. As the technology is scaled for broader applications—including mining, logistics, and disaster response—industry partners will continue refining these systems, paving the way for a more automated, sustainable, and connected industrial future.

E. Reliable Multimodal Virtual Sensing for Vehicle Dynamics

Cyber-physical systems are becoming increasingly important in various domains, such as autonomous driving, robotics, and industrial automation. These systems are characterized by the tight integration of computational and physical components, which interact with each other to achieve a common goal. In such systems, sensors play a crucial role by providing the necessary information about the physical world to the computational components [17]. One common application field of machine learning in cyber-physical systems is virtual sensing for state estimation [18]. The goal is to substitute one or more physical sensors with a machine learning model. Virtual sensing has several

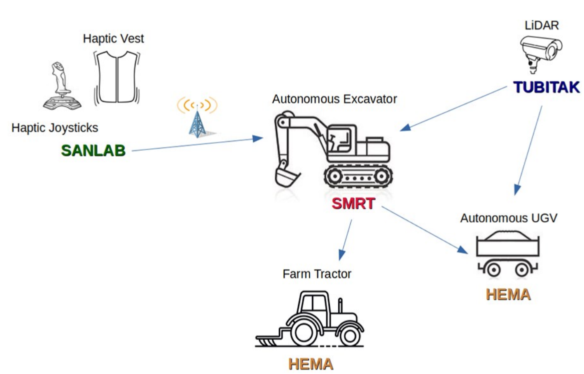

Fig. 6: Partners and their collaborations on Autonomous and Tele-operated Machines with Enhanced Sensors and Haptics.

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advantages, such as cost reduction, increased flexibility, and the ability to measure quantities that are not directly observable. However, virtual sensing also poses several challenges, such as the need for robustness, safety-critical requirements, and the necessity to ensure that the virtual sensor provides accurate measurements under various conditions [19].

Robustness in machine learning encompasses the capacity of models to maintain reliable performance under a variety of adversarial and non-ideal conditions, a factor that is critical for cyber-physical systems operating in dynamic environments. It involves ensuring resilience against adversarial perturbations, sensitivity to noise, and variations due to distributional shifts, all of which can lead to significant degradation in predictive accuracy [20]. This multifaceted challenge demands rigorous validation techniques and theoretical guarantees to safeguard against failures in safety-critical applications, reinforcing the necessity for robust algorithmic designs that can accommodate both expected and unforeseen disturbances.

Over the course of this research endeavor, we are going to address two key aspects of robustness critical to automotive virtual sensing: (i) improving generalization to rare or underrepresented driving scenarios, aligning with the domain of deep imbalanced regression, and (ii) enhancing resilience to non-adversarial input perturbations arising from sensor failures. In the upcoming work, we will focus on the estimation of the Vehicle Sideslip Angle (VSA) as a representative use case to demonstrate the benefits of robust virtual sensing. The VSA is a critical parameter in vehicle dynamics, quantifying the deviation between the vehicle's actual trajectory and its heading direction [21].

Our aim is to highlight the potential of robust virtual sensing techniques to enhance VSA estimation, addressing key challenges such as sensor limitations and extreme driving conditions, with results that are generalizable to other applications, thereby contributing to broader advancements in vehicle safety and control.

IV. ECS FOR COGNITION AND HMI

This innovation stream of the ShapeFuture project is predominantly aimed at improving the capabilities of ECS when it comes to vehicular perception and interaction with end users. In a market dominated by the constant addition of complex technologies for vehicular perception, connectivity, and control, this innovation stream is spearheading the development of devices that will effectively improve user experience, allowing people both inside and outside the vehicle to better understand and interact with them.

A. Laser beam scanning

One of the core activities of this Innovation Stream, is the research and development of laser beam scanning (LBS) technologies. LBS is a content projection approach that uses a 2D oscillating Micro-Electro-Mechanical Systems (MEMS) mirror to deflect RGB laser light into the scenery. While sense and drive electronics actuate the MEMS mirror and monitor its position, a picture-generation unit (PGU) decides when to trigger the RGB lasers with a defined color setting.

LBS is currently regarded as the most promising content projection technology in the automotive environment, because it is low-cost, it is automotive qualified, supports high ASIL-levels, and can project bright and high-contrast content even during challenging sunlight conditions. Fig. 7 depicts potential applications in the automotive context. ShapeFuture's LBS solution fully addresses these uses-cases. In particular, the dynamic ground projection (DGP) use-case is currently generating a huge market momentum and represents ShapeFuture's main demonstrated use-case.

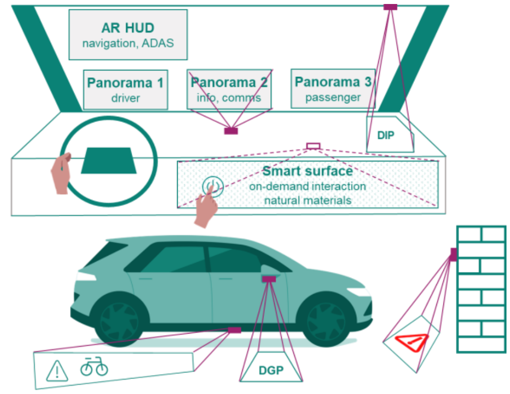

Fig. 7: Laser beam scanning (LBS) applications in the automotive context.

During the ShapeFuture project, the partners will develop a full-blown LBS demonstrator with all the required components. The core of the LBS demonstrator is made of a 2D MEMS mirror (oscillates along two axes) and drive&sense electronics. The very first LBS demonstrator version will be available already mid of the project exploiting the availability of older components. Iteratively, until the end of the project, the demonstrator's components will be exchanged with novel versions researched and developed during ShapeFuture. As an example, a novel 2D MEMS mirror is currently being developed and manufactured featuring higher oscillation frequencies, larger deflection angles, improved optical parameters (such as optical reflectivity) and a higher Q factor. This novel MEMS mirror device will then replace the former MEMS mirror of the LBS demonstrator in a plug-and-play manner. The LBS demonstrator will also feature a PGU, lasers, and laser drivers specifically targeting the DGP use-case, to keep the bill-of-material as competitive as possible. Other use-cases, such as augmented reality head-up-displays (AR HUD), require more sophisticated PGU and optical/laser solutions.

Summarizing, ShapeFuture's LBS approach represents with its partners' semiconductor manufacturing capabilities the technological spear head of the future's automotive content projection solutions.

B. Ultra-wideband for Secure Car Access

In addition to the LBS approach, another development within this innovation stream focuses on improving security in combination with HMI, more specifically, the security of car access systems. To counter the security vulnerabilities of previous technologies which were attacked through relay attacks, the Car Connectivity Consortium (CCC) [22] introduced a new standard for car access using UWB as secure ranging technology for touchless car access. UWB is using an impulse radio (IR) principle for communication between two UWB transceivers and ranging is performed by calculating the time-of-flight (ToF) of the signal which results in high accuracy (+/- 10cm) ranging of current UWB

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systems. More recently, the CCC added the combined use of a hardware secure element or trusted execution environment to enable an improved secure-ranging technology for car access. Therefore, within this project, the consortium will optimize its UWB chip- and system-design for using hardware-based security mechanisms for the critical key and security operations in parallel to the UWB ranging. This also includes redesigning existing hardware-security parts, in order to match UWB-related timing and protocol constraints.

V. ECS FOR COGNITIVE PROCESSING AND DECISSION MAKING

This Innovation Stream is dedicated to pioneering Enhanced Cognitive Systems (ECS) equipped with advanced cognitive processing and autonomous decision-making capabilities. The overarching ambition is to empower ECS by embedding sophisticated intelligence, transforming machines into intelligent decision makers capable of adapting and operating seamlessly within complex environments.

The focus is on the development of cognitive ECS systems that replicate human-like cognitive functions enabling autonomous machines to perceive, analyze, reason, learn, and respond dynamically to evolving situations. Leveraging cutting-edge AI and cognitive technologies will allow these systems to make real-time, data-driven decisions, enhancing their resilience, robustness and readjustment to complex environments. This innovation stream represents a transformative leap in autonomous cognition, paving the way for safer, more reliable, and sustainable mobility solutions.

A. Enabling AI Integration for Connected Vehicles

This demonstrator presents a framework enabling deterministic integration of AI workloads into automotive safety-critical embedded platforms. It combines real-time GPU scheduling, kernel preemption, deterministic hardware accelerator management, and automated SPIR-V kernel tuning, ensuring robust and predictable AI execution in connected vehicles. The framework introduces advanced GPU scheduling techniques that overcome limitations of traditional approaches such as NVIDIA MPS, providing more precise preemption capabilities and real-time guarantees. Additionally, kernel-level preemption combined with time-partitioning ensures reliable real-time execution and effective resource isolation. Deterministic scheduling of hardware accelerators further guarantees consistent performance for critical automotive applications. AI-driven automated kernel optimization, utilizing SPIR-V intermediate representation and Python-based tuning frameworks, significantly enhances GPU performance and predictability. In the demonstration, realistic connected vehicle simulations incorporate widely used platforms like Carla, Autoware, Zenoh, and TTTech's Safety Software Platform. The framework consistently achieves inference latency under 10 ms, significantly enhancing real-time performance. GPU utilization improvements exceed 30% compared to traditional static scheduling methods. Moreover, compliance with automotive safety standards, particularly ensuring freedom from interference between AI-based and conventional software components, is clearly demonstrated.

Key research challenges addressed by this work include achieving uniform kernel optimization across diverse GPU APIs such as Vulkan Compute, OpenCL, and SYCL. Further investigation is required into the effectiveness of kernel preemption within high-level AI inference frameworks. Additionally, a comparative assessment of deterministic scheduling against existing GPU scheduling solutions remains essential for comprehensive validation.

Overall, this framework significantly advances deterministic AI execution for automotive systems, establishing benchmarks aligned with the objectives from this Innovation Stream of ShapeFuture (Obj.3).

B. Autonomous vehicle with enhanced in-out and out-in perception

This demonstrator is an autonomous vehicle integrated into a connected smart city, where real-time environmental data enhances in-vehicle decision-making capabilities retrieved by driver monitoring systems. Unlike traditional sensor fusion approaches that rely on raw data, this system processes high-level metadata, providing a more intelligent and efficient way of interpreting the environment. The vehicle is deployed within the Modena Automotive Smart Area (MASA), where it receives crucial information about road conditions, obstacles, and pedestrian activity. This enables more informed, safe, and efficient decisions.

One of the key challenges addressed by this demonstrator is the need for computing power, required for autonomous navigation. To achieve this, the system relies on the AISDF platform, a sophisticated automotive computing platform developed within the AI4CSM project. It integrates FPGA-based programmable logic, ARM cores for generic computation, and Infineon's TC4 safety processor to ensure robust, fail-safe execution.

The proposed system features an AI-driven decision-making process (Aggregator) that operates on pre-processed data from the vehicle's sensors. This primary decision-making system, accelerated using FPGA technology, enables high-speed computations that enhance responsiveness and ensure reliable autonomous operations. In parallel, a more lightweight rule-based decision system, running on an Aurix microcontroller, operates using pre-determined lookup tables. This secondary system is designed to take over in case of a failure in the primary AI-based system.

The overall architecture of the demonstrator is designed to highlight the interplay between different components. The sensors and computing units form the core hardware infrastructure, while the aggregator system acts as the central intelligence, processing data from various sources such as physiological-based Driver Monitoring Systems, behavioral analysis modules, and the city's own obstacle recognition system. The MASA cloud infrastructure serves as the backbone of the connected environment, continuously feeding real-time information to the vehicle.

C. ODD-aware modelling and decision making

This demonstrator features a modular architecture designed to improve autonomous vehicle (AV) decision-making through modeling that adapts to Operational Design Domain (ODD) conditions and real-time changes in the driving environment. At its core, the system enables semantic-aware decision-making by fusing real-time data from multiple sources—such as traffic conditions, vehicle health, and environmental sensors—into a unified and continuously updated understanding of ODD boundaries. A novel methodology systematically maps degradation scenarios (e.g., sensor malfunctions or adverse weather) to Restricted

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ODDs (RODs), ensuring robust vehicle behavior and smooth transitions to Minimal Risk Conditions (MRCs) when needed. The demonstrator brings together several key components:

- perception and prediction modules that provide continuous situational awareness
- a decision-making engine that generates safe and interpretable path plans, and
- a supervisory module that oversees system status, detects degraded conditions, and activates Human-Machine Interface fallback strategies. Additionally, a Driver Monitoring System supports safe and timely handovers, maintaining human-in-the-loop control when automation approaches its limits.

To evaluate system-level ECS integration, this demonstrator is tested in complex peri-urban scenarios, including roundabouts, construction zones, rural segments, and mixed traffic. It supports both tactical and operational decision-making, emphasizing traceability, adaptability, and safety assurance using metrics such as ODD violation rates, successful MRC transitions, and response time under degradation. By seamlessly integrating automated and human-supervised decision layers, the demonstrator advances the development of safe, resilient, and context-aware AV behavior in dynamically evolving environments.

D. *Distributed target tracking using radar nodes*

In addition to on-board decision making, tracking of automotive vehicles using radar is a fundamental challenge, which is typically addressed in a centralized architecture, which are vulnerable to single points of failure, communication bottlenecks, and scalability issues. With the growing demand for robust, efficient, and scalable sensing in radar networks, there is an immediate need to develop a distributed approach that allows radar nodes to collaborate locally while still achieving accurate target localization [23]. To this end, a novel distributed approach to target localization in radar networks using the Alternating Direction Method of Multipliers (ADMM) [24]. The proposed decentralized algorithm removes the need for a central fusion center, improving the system's scalability, fault tolerance, and energy efficiency. Through simulations, the robustness and accuracy of the proposed method under various network configurations and signal conditions have been demonstrated in the ShapeFuture project.

E. *Virtual testing and validation of automated driving functions*

This demonstrator features a crucial aspect of developing intelligent systems: thorough and efficient testing and validation before deployment into real world.

Real-world testing has inherent challenges and limitations such as inadequate coverage of diverse scenarios within full ODD scope, restricted ability to simulate critical edge cases, and reproducibility of tests. This demonstrator will tackle these hurdles by integrating the system under test (SUT) into a controlled and versatile virtual environment. By incorporating a modular architecture, combining Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL) approaches, this testing environment will expand the scope of testable scenarios, making it possible to rigorously assess intricate and high-risk situations that are impractical or unsafe to replicate with real world tests. Key feature that allows reproducibility and variability of test scenarios is injection of not only collected measurement data but also injection of synthetically generated data. Inclusion of an accurate vehicle dynamics model, aligned with the real test vehicle, and virtual sensor models allows for extension from open-loop testing into a high-fidelity, closed-loop simulation environment that mimics the complexities of real-world environment. To ensure reliability of the testing process, a novel methodology will be developed to assess the correlation between virtual models and real-world counterparts. Correlation of virtual vehicle model and synthetic sensor outputs with real-world data is crucial for guaranteeing model trustworthiness and truthful replication of physical behavior. Advancements achieved within this demonstrator will enable researchers and developers to push the boundaries of innovation while ensuring safety, efficiency, and performance. Furthermore, methodologies integrated into this demonstrator will prove as the essential tools needed to drive the evolution of automated driving technologies.

VI. ECS FOR RESILIENT AUTOMATION AND COMMUNICATIONS

This Innovation Stream focuses on safeguarding automation systems and communication networks from disruptions to ensure mission-critical applications to run uninterruptedly, even under extreme and unpredictable circumstances. The main objective is to create ECS solutions that empower resilient automation, strengthen communication infrastructures, and enhance situational awareness in smart mobility and transportation. The developed technologies will be realized in the following three demonstrators.

A. *Drive situation awareness enhancing image transmission and aggregation*

This demonstrator aims to improve Situational Awareness (SA) of drivers or vehicle operators through the sharing and merging of data from sensors on the ground or other vehicles.

The concept of SA can be defined in simple terms as the perception process of understanding "where am I?", "where are the others?" and "where are they going?" For this demonstrator, a main scenario includes other traffic participants occluded from the view of the driver of the ego vehicle, for instance if a pedestrian intends to walk across the road but is hidden by a truck. With additional roadside units or vehicle-mounted sensors on the truck transmitting information to the ego vehicle, on-board algorithms can identify the danger and alert the driver provided the reasoning can be done quickly enough. To this end, sensor data will be processed with low-power hardware to reduce size, weight and power (SWaP) of the equipment, and will be based on pattern recognition as the conceptual nucleus of the demonstrator.

The demonstrator is planned to be implemented with high-level components as depicted in Fig. 8. The technical setup is divided into the on-board segment and the ground segment, which again can include a (local) cloud-based backend where needed for intensive AI support.

These components and subsystems are selected to make a relevant and demonstrable contribution improving the situational awareness of the driver.

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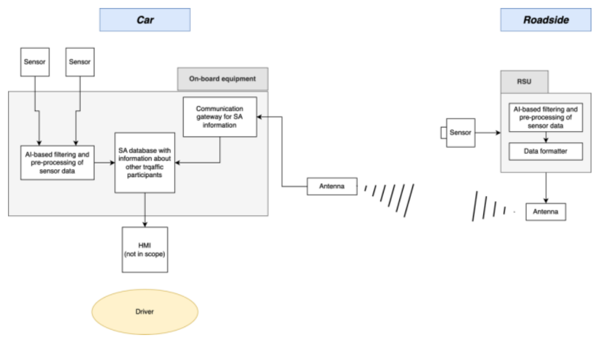

Fig. 8: High-level architecture for Situational Awareness demonstrator.

The demonstrator will be based on radar and LiDAR data obtained from other partners in this Innovation Stream. The technology development can be summarized as depicted in TABLE I.

Formats for the test data to be used in this demonstrator are being developed, beginning with LiDAR. A structure that works with 3D and 2D LiDAR-based environmental perception data is being developed to increase driver situational awareness. Thanks to the 3D LiDAR sensor used in the test area, high-precision 3D point cloud data of the environment is obtained. This data is recorded in .db3 format with ROS-based systems and then converted to .pcd format using PCL (PointCloud Library). This 3D data, aligned with the real-world coordinate system, allows annotation of elements such as roads, pedestrian crossings, parking areas. Thus, the vehicle can understand environmental elements and make decisions appropriate to the situation. A more powerful localization infrastructure is aimed by integrating this data with a detailed 3D point cloud map created in the existing test area.

TABLE I. COMPONENTS/ELEMENTS AND THEIR SA LEVEL

Component or element	SA Level
Radar data (sensor)	Perception
LiDAR data (sensor)	Perception
HW AI processing of sensor data	Perception + Comprehension
Decision algorithms	Perception + Comprehension
Gateway	Enabling technology
Data merging	Projection

B. Enhanced C-V2X communication for the urban area

As Day-2 V2X applications are realized, communication system requirements for latency, reliability, and throughput are increasing. Although the sidelink of 3GPP V2X (C-V2X) does not provide reliable packet transmission, it is becoming more popular [25]. Especially in dense urban areas, the probability of packet collisions increases significantly [26]. Alternatively, cellular-based communication (Uu-link) provides a reliable data link at the cost of increased latency. The concept of hybrid routing can increase the overall resilience of communication, by optimal selection of communication channels. Khalid et al. [27] developed a rule-based channel selection algorithm that enhances latency, reliability and packet delivery rate, by incorporating statistics from received CAM messages.

This demonstrator aims at developing an AI-based channel selection algorithm incorporating Quality-of-Service (QoS) data and packet properties. The AI algorithm will be trained with the help of a digital twin representing a testbed, located at the OTH-AW campus in Amberg, Germany, which is built up and maintained in cooperation with the research project VRUIDFUL [28]. Data obtained from the testbed will be used to evaluate the accuracy of the simulation and minimize the sim-to-real gap. Finally, the AI algorithm will be deployed on edge hardware for practical testing and validation.

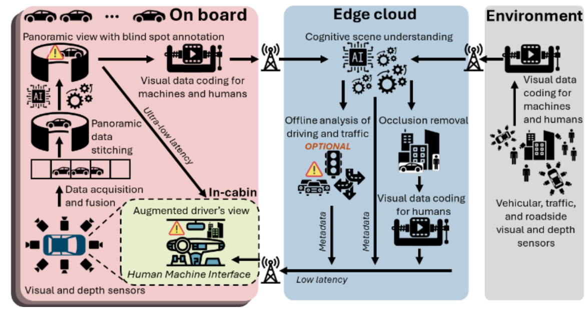

Fig. 9: Augmented situational awareness in driving.

C. Augmented situational awareness in driving

Fig. 9 depicts the basic operating principle of this demonstrator that showcases how vision-based technologies developed in the project improve situational awareness in driving. The main objective is to provide the driver with an occlusion-free panoramic view of the surrounding environment, along with automatic traffic alerts and traffic analysis data. For that, the visual data processing is specified to take place: 1) on board the ego vehicle; 2) in the environment; and 3) in the edge cloud.

The ego vehicle is equipped with multiple camera and depth sensors distributed around its bodywork. Panoramic visual data acquisition of the environment is carried out by capturing individual camera streams, fusing them with depth sensor data, and converting them to 360-degree video format using depth-adaptive panoramic data stitching techniques. Occluded areas in the scene are identified with lightweight saliency detection techniques that annotate video streams with metadata about blind spots. The augmented panoramic view with blind spot alerts is immediately delivered to the cabin occupants of the ego vehicle through a Human Machine Interface (HMI) in real-time and at ultra-low latency. The same video stream is also compressed using hybrid human-machine coding techniques and transmitted to the edge cloud over a wireless 5G network.

The ego vehicle is specified to operate in a local, limited area with other vehicles and vulnerable road users that may be obscured by other traffic participants or buildings. Visual environmental data from roadside units, other vehicles, and traffic cameras is respectively captured, compressed, and transmitted to edge cloud over wireless links.

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In the edge cloud, cognitive scene understanding makes use of the available processing power of the cloud and input data from all sources to refine the panoramic view of the ego vehicle using versatile AI-based machine vision tasks, like in-depth object detection and tracking, object segmentation, and classification. The output of the scene understanding is used for driving/traffic analysis and virtual occlusion removal. The latter utilizes view synthesis to provide the cabin occupants with an occlusion-free panoramic view of the surrounding environment. The synthesis virtually adds transparent objects on top of the view through 3D feature map generation for object location, rotation calculation for different camera angels, and cropping/masking to fit the source object silhouette from the point of view of the ego vehicle. The visual data, with overlaid transparent objects and traffic metadata, is compressed for human consumption and transmitted to ego vehicle. The cabin occupants of the ego-vehicle can see panoramic occlusion-free traffic scenes and related traffic scene information through HMI.
The functionality of the whole system will be demonstrated in a virtual Cithrus2 environment [29]. In addition, selective parts of the system will be tested and validated in a laboratory environment.

Conclusion

ShapeFuture is a key European research project which will drive innovation in fundamental ECS thus advancing Europe's technological leadership and sovereignty. The researched and developed ECS are essential for robust, powerful, fail-operational and integrated perception, cognition, AI-enabled decision making, resilient automation and computing, as well as communications, for highly automated vehicles.

This work highlighted the visions of ShapeFuture's Innovation Streams and summarized the preliminary results achieved during ShapeFuture's first year. Furthermore, the outlook towards the next years' results is sketched.

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