UNICARagil – New Architectures for Disruptive Vehicle Concepts

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Summary

This paper provides an overview of the research topics of the UNICARagil project with the focus on different architectures, such as the mechatronic, the software, and the mechanic architecture. The main research questions as well as possible solutions, which will be investigated in this project, are described. The project is funded by the Federal Ministry of Education and Research of Germany

In terms of the mechatronic and the software architecture, this paper focuses on the ECU concept: the main tasks of the automated driving process are executed on three ECUs, which are called the cerebrum, the brainstem and the spinal cord. This architecture supports the modular approach regarding functional safety, the ability of future updates and upgrades, and the service orientated architecture (SOA) of the software. The well-known SOA approach is transferred to automotive applications and becomes the automotive service orientated architecture (ASOA).

Furthermore, the mechanic structure of the four vehicles AUTOtaxi, AUTOelfe, AUTOliefer and AUTOshuttle is described.

1 Introduction

Automated driving, electrification, shared mobility, and connected vehicles are the megatrends of today [1]. Many projects address the different research questions arising. With todays' shorter innovation cycles, the automotive industry with its evolutionary development methods faces new challenges to keep track of the emerging technological trends.

The UNICARagil project introduces new concepts in order to develop modular architectures for agile, fully automated, and driverless vehicle concepts. The development avoids inherited liabilities in order to provide solutions for challenges imposed by emerging mobility trends and to set impulses for the future. Figure 1 shows the overall concept in a schematic overview.

The vehicle concepts are realized based on a modular and scalable vehicle platform. Four individually steerable dynamics modules drive the platform. These modules combine the tasks of steering, propulsion, and braking in one geometric module. To address the growing demand for agility in growing urban areas, each dynamics module is capable of steering angles up to 90 degrees and driven by 48 volt in-wheel motors.

The add-on transport module is combined with the platform and overall scalable in its length and height. With its modular design, a consequent strategy of equal parts is pursued. To ensure a sufficient environment perception for fully automated and driverless operation, the concept of sensor modules is introduced in UNICARagil. These modules combine different sensor technologies to guarantee high precision perception and ensure detection safety by implementing necessary redundancies.

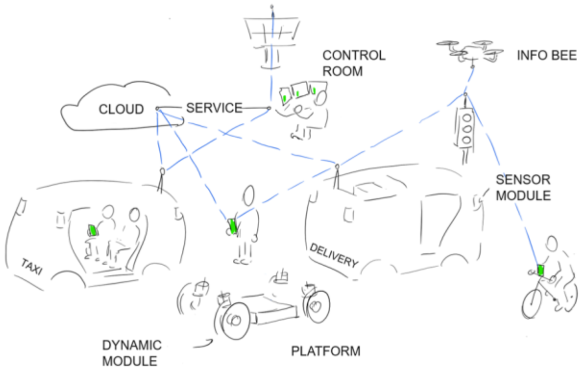

Figure 1: Sketch of the overall System [2]

In addition to its own perception, cloud functionalities and intelligent infrastructure sensors support the vehicles developed in UNICARagil. To reduce cost intensive stationary infrastructure sensors, the Info Bee concept is introduced. Drones act as flying sensor clusters and generate additional information for the automated vehicles. The UNICARagil fleet is managed and surveilled by the control room. The control room can remotely take over the vehicles from standstill if necessary.

Finally, four working prototypes will be realized and exemplarily demonstrate the potential of the developed modular vehicle concept. The AUTOtaxi and AUTOshuttle aim at public transport use cases with a capacity of up to 4 and 10 passengers, respectively. The AUTOliefer displays the delivery service of the future: fast, autonomous, and efficient. The last vehicle concept, the AUTOelfe, focuses on individual mobility. It represents the family car of the future, still in private hand and individualized to the family's needs.

In order to realize the aforementioned vehicle concepts with full functionalities, new architectures in software as well as in hardware become necessary. Therefore, UNICARagil focuses on the development of these new architectures in different levels of abstraction. This paper focuses on the mechatronic, the software, and the mechanic architecture.

2 The Mechatronic Architecture

To control an automated vehicle requires three well-known tasks. First of all, the environment needs to be sensed. Based on this information, the next steps like the target trajectory are calculated. And, finally, the existing actuators must be controlled. Since the UNICARagil project follows a modular approach, these three tasks are not only separated in terms of calculations, but also in terms of the hardware. Figure 2 shows a sketch of the ECU concept. In the style of the human body, the different ECUs are called cerebrum, brainstem, and spinal cord.

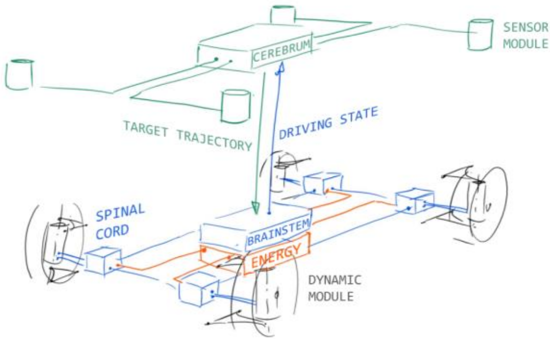

Figure 2: Sketch of the brain concept [2]

The sensor modules are – together with the cerebrum – responsible for the environment perception. The cerebrum then plans the target trajectory as well as a fallback trajectory and provides the brainstem with this information. The task of the brainstem is to calculate the main control signals like torque and steering angles for the dynamics modules. These four modules control the electric motors to ensure that the required values are met. For this reason, they are called spinal cord.

The concept of the three brain levels – cerebrum with sensor modules, brainstem, spinal cord – follows the idea of a modular concept within the UNICARagil project. Each task as well as each hardware component can be improved without affecting other components as long as the interface information does not change. As a consequence, simultaneous development and future updates and upgrades can be implemented.

2.1 The Sensor Modules and the Cerebrum

Each of the UNICARagil vehicles will sense its environment by four sensor modules placed on the corners of the chassis/cabin. Each module will comprise of LiDAR, RADAR, as well as monocular and binocular camera sensors together with a sensor data processing unit and will cover a range of up to 270° around the respective vehicle's corner. Due to the overlapping fields of view of neighboring sensor modules, this concept provides sufficient redundancy for safe operation even in the case of a single failure of one sensor or one sensor module.

The data processing unit of a sensor module performs all required preprocessing of the collected raw data, e.g. disparity calculations of binocular camera images, scene labeling, object detection and classification, etc. Additionally, each sensor module already calculates an internal perception model by fusing the information from its different sensors and tracking the detected objects. The module's environment model is the interface to the cerebrum, which performs further tasks of automation. However, if needed for other tasks, data from earlier stages of data processing is available from the respective preprocessing steps (e.g. objects from a single sensor for assistance of teleoperation) thanks to the service-oriented software architecture.

The cerebrum is the central processing node for information fusion and behavior planning. It receives the preprocessed environment models of every single sensor module over a direct 10GBit/s Ethernet link. The cerebrum fuses the incoming environmental models into a consistent representation that overcomes the limited fields of view of each individual sensor module and that uses cross-checks to detect erroneous and inconsistent data in the overlapping fields of view. This results in a full and complete depiction of the vehicle’s surrounding for the further automation steps. Based on the environment model and the digital map of the road infrastructure, the cerebrum decides upon the next maneuvers of the vehicle by analyzing the present traffic situation and deriving geometric and dynamic constraints for the future movement of the vehicle. It predicts the behavior of other traffic participants and considers worst-case scenarios in order to generate safe behavior. It provides a trajectory for normal target-oriented driving and a safe-stop trajectory. The latter one becomes relevant in cases of unexpected failures of the vehicle, which prevents the vehicle to continue driving safely. Those trajectories serve as input for the trajectory following controller in the brainstem.

2.2 The Brainstem and the Platform Sensors

At the architectural layer of the brainstem, a fallback level for the dynamic driving task is provided. It is required because fully automated and driverless vehicles are developed for the UNICARagil project and no human driver serves as a fallback at this level of automation. The purpose of this fallback level is a safe transition of the vehicle into a risk-minimal state in the event of a failure of an essential vehicle component. Since the vehicle operates in a dynamic environment, this fallback level called "Safe Halt" utilizes environment sensors that are completely independent of the environment sensors on the cerebrum level. This ensures a collision-free stop of the vehicle even if the cerebral environmental sensors have failed. As the brainstem is assigned to the vehicle platform, those independent environment sensors are called "platform sensors".

2.3 The Dynamics Modules and the Spinal Cord

Each dynamics module consists of the actuators for the movement of the vehicle and the corresponding control unit. The wheel, the suspension, the integrated hub motor, the friction brake, and the steering motor make up the mechanical part. Both electric motors have their own power electronics mounted on the vehicle platform. In addition to that, each dynamics module has its own ECU, the so-called spinal cord (see Figure 3). All the control algorithms are running on this ECU. From the software-architecture perspective (ASOA) it offers the services of driving, braking and steering.

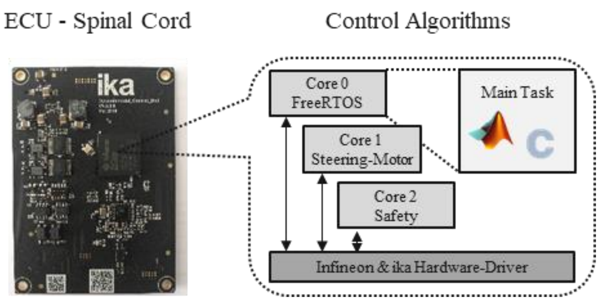

Figure 3: Spinal Cord – Control Board

The spinal cord resembles the bottom layer in the mechatronic architecture presented before. During nominal operation, it will receive its inputs from the brainstem, check if they are in range of the current capabilities, and control the different actuators, respectively. Additionally, the spinal cord is constantly offering information on the vehicles abilities (max. acceleration, max. steering angles, max. regenerative braking…) for other instances of the vehicle. In case of a brainstem failure, the spinal cord is able the receive inputs directly from the cerebrum and navigate the vehicle by its own motion-strategy to follow a trajectory demand. During the application and commissioning process, a human driver, controlling pedals and a sidestick, will often navigate the vehicle. The driver's inputs are directly connected to the spinal cord, so the vehicle can be operated even without brainstem and cerebrum.

All the control algorithms will be running on an Aurix Microcontroller with FreeRTOS, a real time operating system. The toolchain allows programming in Simulink and in C-code. Additionally, an interface board is developed, handling the connection to the rest of the vehicle, mainly by the use of Automotive Ethernet. The spinal cord is also able to communicate via FlexRay and CAN, since not all of the prototype components in the vehicles are ready for the use of Ethernet.

3 The Brainstem Hardware

In modern driver assistant systems traditional quality management measures reach their limits to guarantee the required Automotive Safety Integrity Level (ASIL), because not enough components are available that are certified for safety critical automotive applications [3]. Here, the integrity of control data can be guaranteed by monitoring their plausibility, e.g. by duplication of hardware with parity check. If a mismatch is detected, the ECU is deactivated or restarted. This concept is called fail-safe or fail-silent. Fail-silent automotive control systems, e.g. steering assist systems, rely on a human and mechanic fallback system [4].

A transition technology on the way to fully automated driving is drive-by-wire (steer-by-wire, brake-by-wire) without mechanical backup. Like in a fly-by-wire system, a safe state cannot be realized by deactivation of the erroneous control system or a hard stop, for example on a highway. The x-by-wire system needs an explicit backup in itself. Such a system is called fail-operational. Examples for current steer-by-wire systems are the Servolectric® Fail-operational System from Bosch [5] or the Q50 Infinity from Nissan [6].

In highly and fully automated driving, much more complex functions in the whole cycle of sense, plan, and act need to be fail-operational. This results in a need for high performant, flexible, and fail-tolerant control systems that were research object in projects like RACE [7] and SafeAdapt [8].

The UNICARagil project follows a concept of multiple fallback layers. The most important fallback layer is the so-called brainstem, which takes over the control of the whole vehicle in case of a failure in the main control system (cerebrum, sensor modules). Therefore, it is a highly safety critical, fail-operational ECU (ASIL-D) that still needs to be performant enough for sensor data analysis and data fusion as well as trajectory planning and control, at least in a degraded form.

To guarantee the required level of integrity and reliability, the brainstem has a duo-duplex architecture with two separate boards and one multi core main processor each.

The dual-core processor is running in lockstep mode, which implements the fail-silent behavior of each board and guarantees its integrity. The two fail-silent boards together form the fail-operational control system. Figure 4 shows the hardware structure of the brainstem.

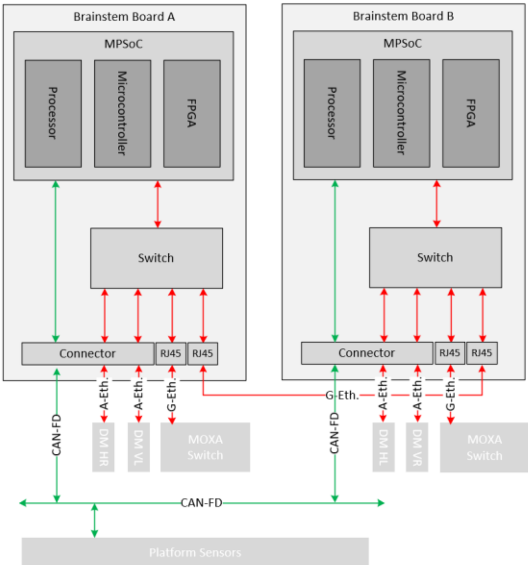

Figure 4: Hardware structure of the UNICARagil Brainstem

The main processor is a high performant multi-processor system-on-chip (MPSoC) and contains multiple processor cores, microcontrollers, and programmable logic (FPGA). It is capable to support performance intensive processes as sensor fusion for radar and ultrasonic sensors as well as hard real time processes as vehicle dynamics management. The three hardware paradigms processor, microcontroller, and programmable logic allow diverse implementations to avoid systematic errors in future projects.

The brainstem offers three interfaces: A Gigabit Ethernet (1000BASE-T) interface connects the brainstem with the main vehicle network, the dynamics modules are connected with automotive Ethernet (100BASE-T1), and several peripheral components are controlled over CAN-FD. This system also keeps the device compatible with automotive as non-automotive hardware components, which is important in academic research projects.

With this approach, several technologies with a non-automotive origin like the ARM architecture, Ethernet, and even Linux and FreeRTOS are brought into a highly safety critical automotive context with hard real time requirements. The applicability of those technologies are research object as well as the new TSN protocol and fail-operational behavior. The aim is to build a platform that unifies computing power, connectivity, and safety in a completely new way.

4 Automotive Software Orientated Architecture (ASOA)

The AUTOSAR platform and other development standards provide standardized software interfaces and runtime environments for ECUs to handle the arising integration and system complexity in today's vehicles [8]. The majority of the resulting architectures are function-oriented. Each functionality of the vehicle is implemented as a separate software component, which in turn runs on its own dedicated ECU. In the system integration phase, the software components are rigidly coupled, resulting in statically integrated system. System-integration decisions become a hard-coded part of software components and subsequently of the ECU software image. Such statically integrated systems pose challenges for quickly integrating new components and for adapting new system configurations. These steps become a painstaking process past the system-integration.

Future disruptive automotive trends such as connected and highly automated vehicles have short development and technology lifetime cycles. The flexibility required to keep up with the aforementioned agility poses a challenge to statically integrated architectures. A software architecture lacking proper update mechanisms will hinder vehicles on the road to always operate on the latest and best software, which in turn has severe consequences for the safety of automated vehicles.

For the UNICARagil vehicles, a service-oriented software architecture is proposed, which will allow for dynamic system reconfiguration and which provides mechanisms for seamless integration of new components. Applications of service-oriented software architectures for automotive applications have been an ongoing research subject. Such architectures have been partially implemented in various efforts [9,10,11], but to the best of our knowledge, none of them go to extend and implement the complete on-board vehicle software following a service-oriented approach.

Software components in service-oriented architectures, in contrast to systems with an inflexible runtime-integration, are implemented as loosely coupled services, which are integrated and connected at runtime [12]. A consequence of this paradigm is that services will only be connected at runtime to one another, thereby dynamically establishing the software architecture. As system-integration decisions are decoupled from the individual software components, interchangeability and reusability of software components is ensured. The integration and coupling of services at runtime is guided by an orchestrator, a designated and privileged software component that establishes situation-depended connections between services. The established connections between services instantiation induces a connection graph, to which is referred to as a service composition. This idea is illustrated in Figure 5, where the same services are connected in varying constellations at runtime, based on the mode of operation or the intended vehicle behavior.

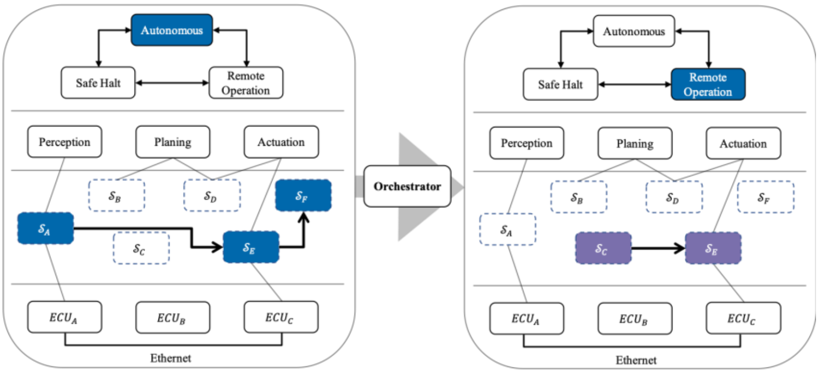

Figure 5: Service-oriented software architecture allows for flexible system integration.

In the example above, the set of services are composed in a different way for the autonomous driving mode than for the remote operation mode. Note that the connection is being guided by the orchestrator and not by the services themselves; this ensures the predictability of the resulting instantiation. Through the common Ethernet connection between the various ECUs in UNICARagil, services will be able to transparently interact with each other across compute platform boundaries. Among other things, the graphs will serve as a basis for a formal analysis of the software system. Please note that the displayed modes of operation are merely an example. The flexibility introduced by this approach is especially suitable for implementing the four vehicle variants pursued in UNICARagil, as services can be easily reused and intended vehicle behavior modeled through different service compositions.

5 Mechanic Architecture

For the four different vehicle versions of the UNICARagil project, two different platform variants are required. Both variants are based on a common basic concept. The platforms are designed as a space frame architecture and form the module carrier for all other vehicle domains. The aluminum space frame structure consists out of profiles, node elements, and sandwich panels.

The platform development begins with the specification phase. In this phase, rough structural requirements are taken as a basis. These can be defined from the individual properties or requirements of the four vehicle versions which are to be developed. The requirements of AUTOtaxi and AUTOelfe for the platform are the same, therefore the same platform can be used for both versions. Although the requirements of the AUTOliefer and AUTOshuttle are principally different, the geometrical dimensions of the platform are identical. For AUTOliefer and AUTOshuttle, a larger interior space must be provided than for the other two versions. The legislative requirements for the European area that are relevant for the vehicle classes are adapted for the crash safety design of the platforms regarding the project boundary conditions. Due to the classification into the M1, M2 and N1 vehicle classes, different crash requirements are relevant for the large and small platforms. As a result, the overhangs at the front and rear are also different. For the dimensioning of the platforms, conceptually similar vehicles are examined as geometric references. The uniform basic concept of the platforms' results in a development methodology based on scalability and modularization.

At start, a first rough measurement concept of the two platforms is developed. In the concept phase, various structural designs are constructed as CAD models and compared with each other. These structural concepts are thus simulative analyzed with Catia V5 with regard to their stiffness concerning the load cases bending and torsion. Resulting stiffnesses and the structural mass are converted into a lightweight design quality criterion. In this way, the effectiveness of the structural concepts can be evaluated in relation to the used mass. In addition, a qualitative evaluation of the concepts is carried out regarding manufacturability, usability of package space, and load path routing. Afterwards, the structural model is completed by the package components, which represent the chassis, drivetrain, thermal management, and the energy storage. The rough measurement concept is adapted to the package's space requirements. For an early estimation of the overhang lengths without simulative design, the crash relevant deformation zones are first designed based on an analytically estimation. The structural concept is shown in Figure 6.

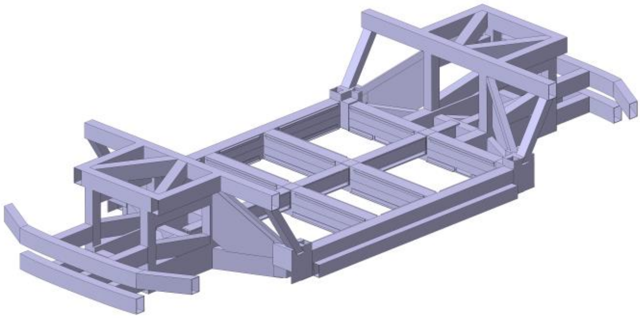

Figure 6: Structural concept of the platform in the long version

In the following design and finite element simulation phase, the structural concept will be further developed into a manufacturable platform model that meets the requirements. The final step will be the prototypical assembly of all platforms.

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