UNICARagil - Where We Are and Where We Are Going

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Summary

In 2018, the German research project UNICARagil started as a collaboration between eight universities and eight industrial partners. Within four years, the project will develop disruptive modular architectures for agile automated vehicle concepts and present four fully automated and driverless vehicle prototypes. This paper gives a general mid-term overview on the project status and the first results. It introduces the different research domains addressed within the project. This paper does not contain any unpublished research and only summarizes the current project status.

1 Introduction

UNICARagil [1] is funded by the German Federal Ministry of Education and Research. The project started in 2018 and has reached its halftime in the beginning of 2020. This paper gives an overview on the mid-term status of the project, which was firstly introduced in [2] on this Colloquium two years ago.

UNICARagil aims at the development of disruptive modular architectures for agile automated vehicle concepts. Within four years of project duration, four ready to drive prototypes are to be built by the consortium. These prototypes will be fully automated and driverless, striving towards SAE Level 4 of automation [3].

In contrast to many other research activities, UNICARagil focusses on the overall system of connected and automated driving. Many different research questions arise and are summarized in [2]. Fig. 1 encapsulates the overall concept of the project. Based on a modular driving platform equipped with dynamics, add-on and sensor modules novel architectures in mechatronics and software are to be developed. Additionally, the vehicles are connected to the UNICARagil Cloud and the control-center. Supplementary environment information may be gathered by the so-called info-bee and enhances the collective perception of a future vehicle fleet.

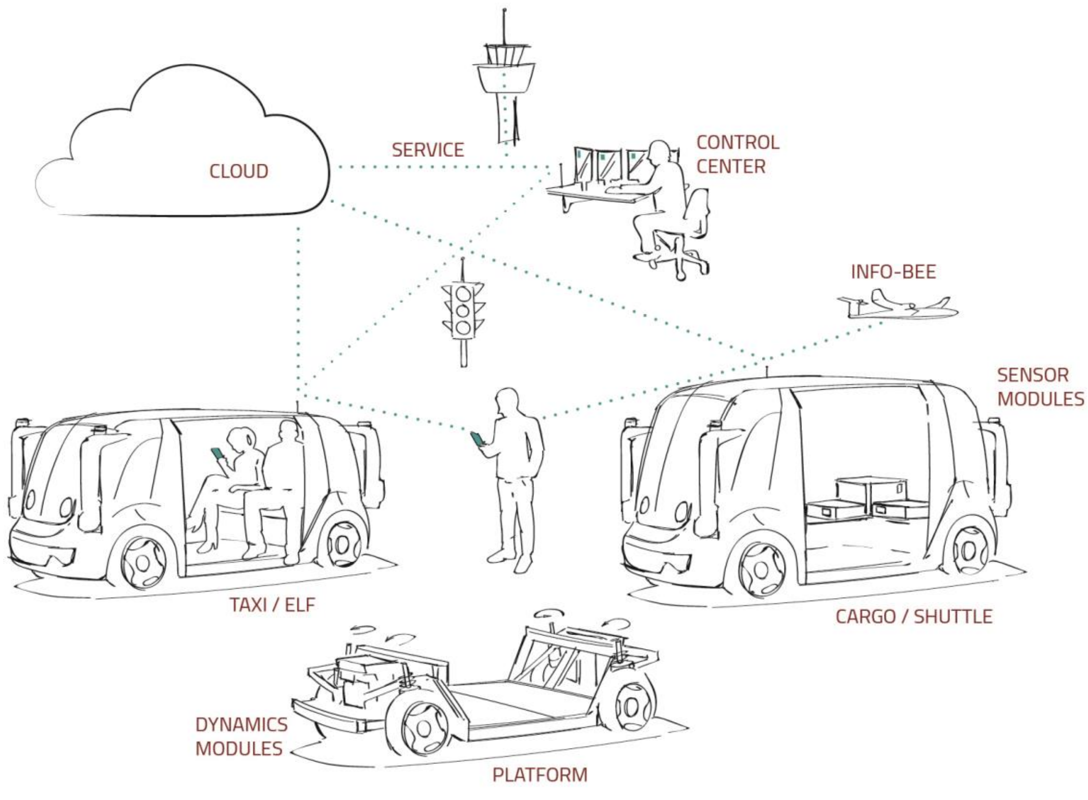

Fig. 1 Overall concept of UNICARagil

More than 100 researches from mechanical engineering, mechatronics, computer science and many other fields are collaborating to reach the aforementioned project goals and integrate the different architectures, modules and systems into the four realized prototypes. Therefore, the project structures into five different research domains, which coordinate the interfaces between the different workpackages in each domain.

The **Geometry** domain (cf. section 2) focuses on the development of the vehicle structure, its design and the human-machine-interaction, whereas the **Mechatronics** domain (cf. section 3) realizes the energy supply, the communication architecture and the thermal management. With more powerful computing units and new geometric concepts, these topics face some novel challenges.
Automated driving functions develop in quicker time cycles than conventional automobiles. The introduction of automated driving functions will require updatable and upgradable architectures to ensure latest and thus safest software to be rolled out. Therefore, a novel automotive service oriented software architecture is realized within the **Software** domain (cf. section 4).
The **Automated Driving** domain (cf. section 4) uses the aforementioned architectures to implement the services necessary for SAE Level 4 automated driving of the UNICA-Ragil vehicles.
Higher levels of automation will no longer require a human driver as a fallback level. Therefore, safety of the overall system is becoming more and more important. The **Safety** domain (cf. section 5) focuses on different research questions about how to enable safety in modular vehicle concepts.

This colloquium hosts further papers that are related to UNICARagil and give deeper insight into the different research domains introduced above:

- In [4] Torben Stolte et al. discuss the safety concepts for automated driving in UNICARagil.
- In [5] the dynamics modules are introduced in detail as part of the mechatronics and geometry domain by Martens et al.
- Mokhtarian et al. [6] give an overview on the dynamic automotive service-oriented software architecture
- And Buchholz et al. [7] summarize the automated driving domain in UNICA-Ragil.

The following sections present the mid-term status and the first high-level results of the research domains described above

2 Geometric progress

The scalable modular structural kit builds the basis for all UNICARagil vehicles. Aiming at automated and driverless operation, the UNICARagil vehicles face the opportunity to rethink the vehicle structure under the new circumstances of a no longer applicable driver's workplace. Four prototypes with different use cases are build up in the project to demonstrate the capabilities and flexibility of the structural kit. It needs to be mentioned that these use-cases are just example applications and many more vehicle derivatives are conceivable. The scalability of the platform is demonstrated as two vehicles are realized based on a short platform, the autoTAXI and autoELF. Based on a slightly longer platform and scaled in their height as well, autoSHUTTLE and autoCARGO complete the UNICARagil vehicle family. More information on the different use-cases can be found at [1].

Fig. 3 describes the development process of the geometric structure. The project started with a detailed requirement analysis based on architectural requirements (e/e architecture, dynamics modules and automation), legislative requirements (vehicle categories and basic structural requirements) and user-centered requirements. Detailed information on the process can be found at [8].

With the basic structural requirements set, the first safety and package concepts for the platform can be developed iteratively. Thereby, requirements from the drivetrain and chassis as well as from other package components needed to be considered. As an example, Fig. 2 shows the dynamics module [5] of the UNICARagil vehicles. Each vehicle is equipped with four of these mechatronically independent and individually steerable modules. The mechanical linkage between dynamics modules and the platform mainly influences the geometric platform design and stated a key challenge to the platform construction.

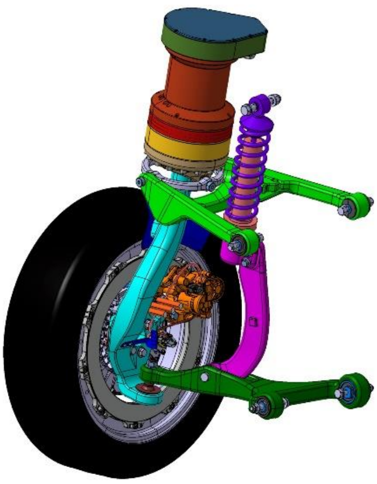

Fig. 2 Dynamics Module of the UNICARagil vehicles. [5] presents the module in detail.

Furthermore, crash safety needs to be assured for the prototype vehicles. Since there are no possibilities to realize prototypes for crash tests within the research project, all necessary considerations were executed simulatively.

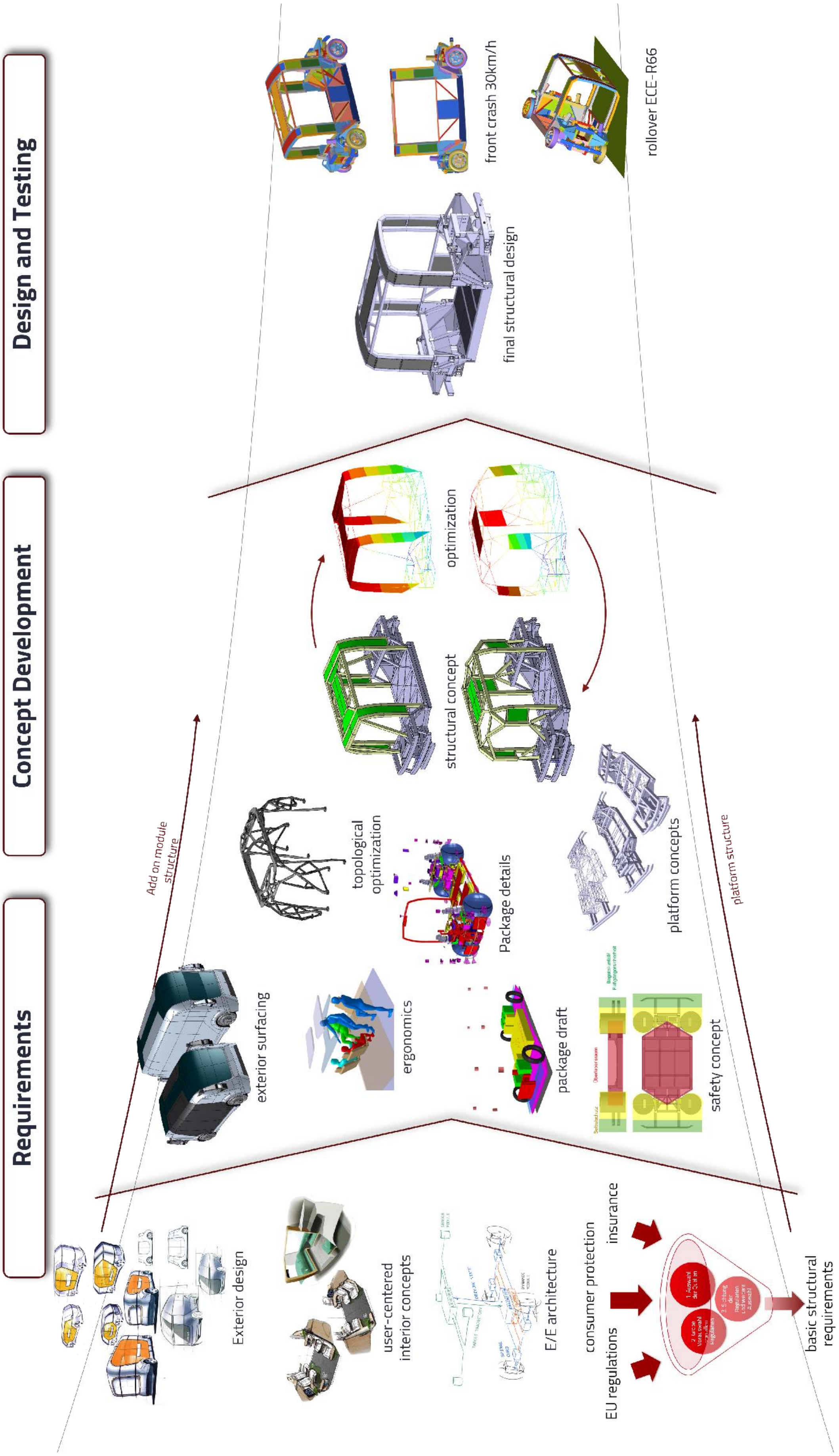

Fig. 3 Concept development of the modular geometric architecture [8]

Tire load, drive power and steering moment for 90° steering emerged as limiting points for the overall vehicle weight. Since many developments were running in parallel work streams, a transparent and agile weight management process needed to be carried out. This allowed the researches to iteratively set and adapt weight goals for each component and module based on the limiting factors of the overall system.

The first vehicle platforms were delivered in late 2019, when the package integration started at the University of Stuttgart.

Fig. 4 First delivered small UNICARagil platform in Stuttgart, late 2019

For the development of automated vehicles, the placement of the environment sensors faces another challenge to the structural and exterior design. In order to have an optimized sensor field of view, allow sensor upgrades, and show the vehicles' capabilities, UNICARagil vehicles use externally mounted sensor modules (cf. [7]). In order to maximize the field of view and minimize the shading by vehicle body parts, a sensor positioning tool was implemented. Based on raytracing algorithms, the different UNICARagil sensors are simulated in a simplified way and their positioning was optimized based on the given sensor design scope. Fig. 5 shows how the sensor placement was evaluated.

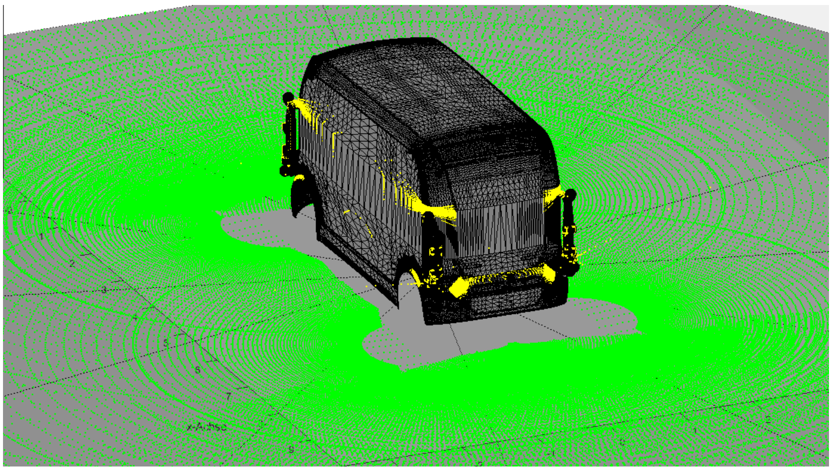

Fig. 5 Results of the sensor simulation tool for a large UNICARagil vehicle

With all given requirements, the construction of the UNICARagil vehicles' structure was finished in the beginning of 2020 and the building process of the prototypes in hardware began. The first built-up vehicle structure, consisting of platform, add-on module and doors, will be introduced in the presentation on the Aachen Colloquium in October 2020.

The potential of the scalable modular structure is directly visible by comparing the usable interior volume of the smaller to the larger vehicle derivatives. With the intended scalability in length and height, it was possible to nearly double the usable in-vehicle volume. Fig. 6 shows how the structure is scaled and carry-over parts in the exterior panels are used to realize the four aforementioned vehicle variants.

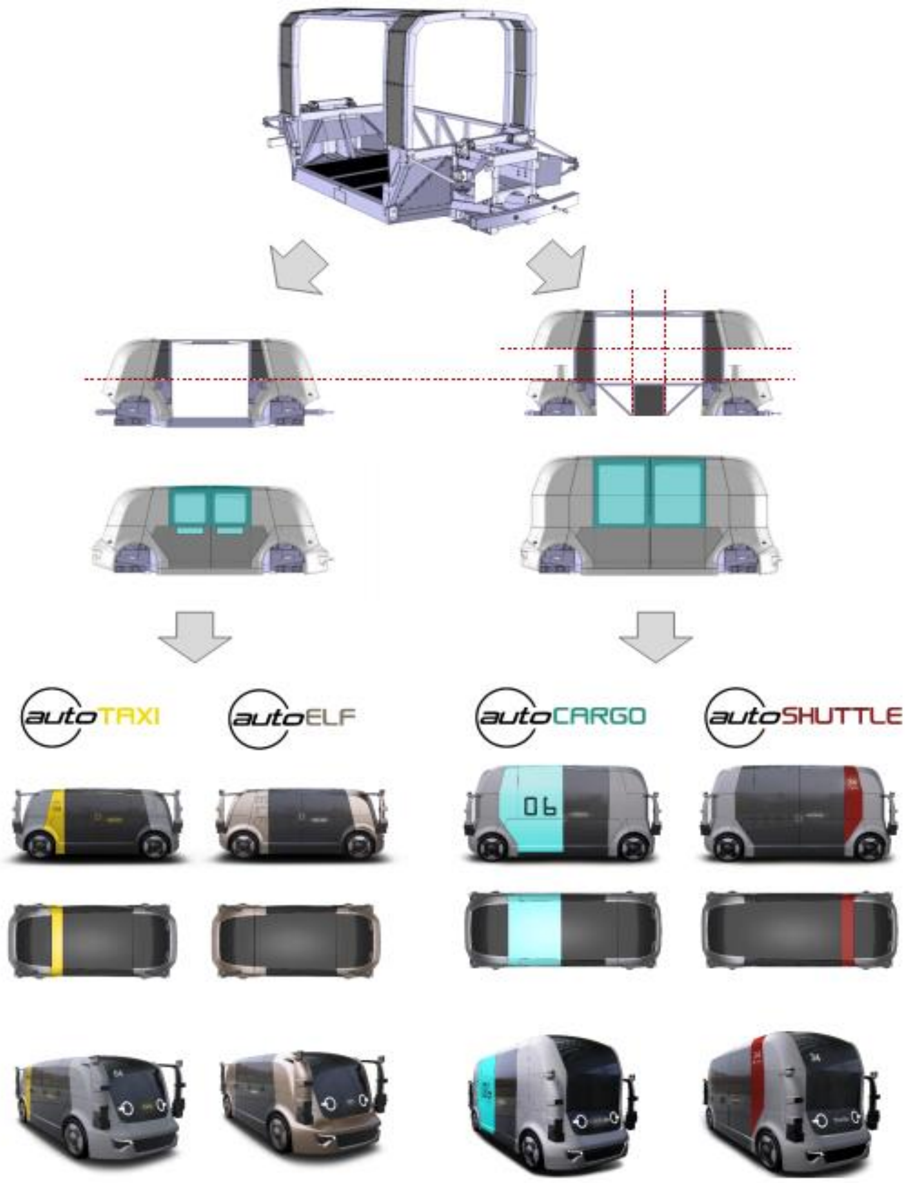

Fig. 6 Scalable modular structure with scalability in length and height derives into four different vehicle derivatives.

Each individual UNICARagil vehicle addresses another use case and its interior is designed to match the requirements of the specific vehicle use. The following pictures show the status of the interior development. Detailed Information on the different use cases can be found at [9][10][11] and [12].

Fig. 7 Interior renderings of the autoELF (top) [12], autoSHUTTLE (middle) [9] and autoTAXI (bottom) [10]

Since the autoCARGO does not transport any persons, there is no classical interior design process, but the development of the handling technology to automatically deliver and pick up parcels.

Fig. 8 CARGOlab, as development laboratory for the autoCARGO [11]

3 Mechatronics

The domain mechatronics comprises the on-board thermal system and the power supply system as well as the communication network of the UNICARagil vehicles.

Fig. 9 visualizes the structure of the communication network. The architecture as presented in [33] and [28] provides four zones representing the four corners of the vehicles. The network communication is based on Automotive Ethernet (BroadR-Reach). Each corner of the vehicle comprises a sensor module [15], a dynamics module [5] and an exterior HMI module [29]. The other devices such as communication modules, the additional platform sensors [36] and the control units, which are called spinal cord, brainstem and cerebrum, are distributed to the four zones. A network switch is located in each zone, which connects the control units and further network devices of each zone to the others. The four switches are connected to each other in ring topology and safety-critical control units such as the brainstem are linked to two switches hence providing redundancy in case of a network error. As the sensor modules have a high demand on the network bandwidth, they are additionally connected directly to their control unit, the cerebrum, via 10 Gigabit Ethernet while the other devices are connected via Gigabit Ethernet or CAN for some conventional automotive hardware.

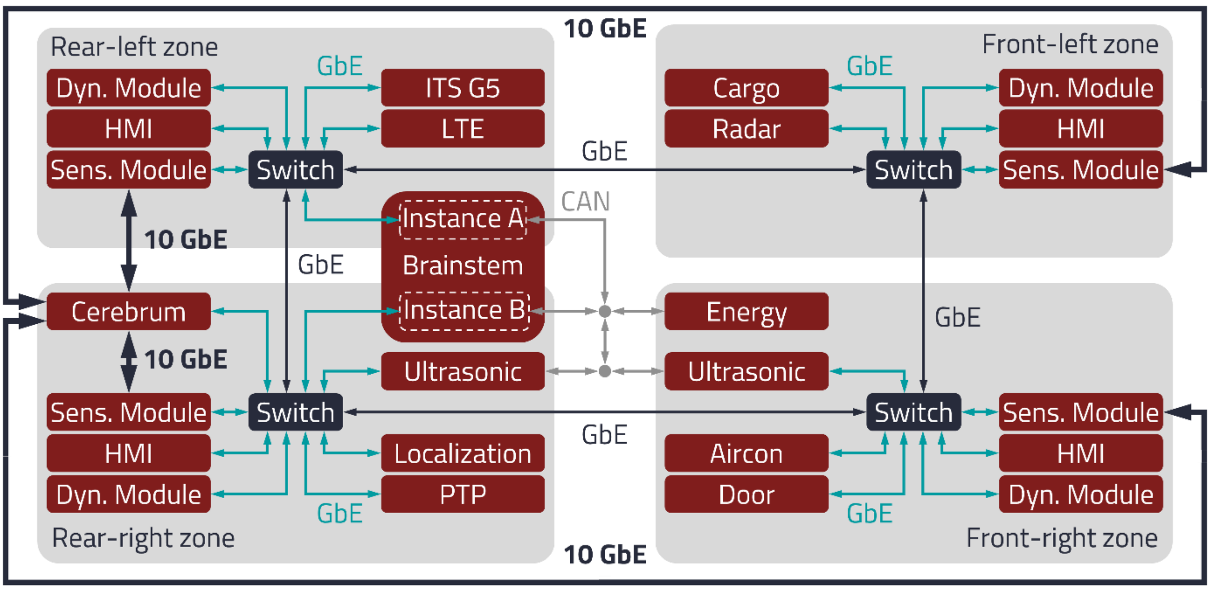

Fig. 9 Scheme of the communication network in the UNICARagil vehicles. Adapted from [28].

The naming of the control units results from an analogy between the developed communication architecture and the human nervous system [2]. The spinal cord is integrated into the dynamics modules and offers the services Driving, Braking and Steering as part of the Automotive Service-oriented Software Architecture (cf. section 4.1). During regular operation, it receives its control commands from the brainstem, where the trajectory control module is located. In case of a breakdown of the brainstem, the spinal cord provides its own motion control function to realize an emergency stop. More information regarding the dynamics modules is presented in the accompanying paper [5].

The brainstem is a safety-critical control unit with high requirements regarding real-time capability, computing power and fault tolerance. Due to its specific needs, a dedicated control unit as described in [30] is developed in the UNICARagil project. A duo-duplex architecture makes the control unit fail-operational. It uses two instances of the Zynq Ultrascale+ platform running in parallel. Each instance has a redundant computing unit itself thus providing double redundancy. Various central services are executed on the brainstem such as the self-perception service (cf. section 5), the safe halt and the trajectory control module. The control module receives driving trajectories from the cerebrum and computes control commands for the dynamics modules accordingly. This places high demands on the computing power, which is satisfied by four ARM Cortex-A53 and two ARM Cortex-R5 processors.

Redundancy is also an important aspect of the vehicle's power system. The wheel hub drives in the dynamics modules require a 48 V power supply while conventional devices are fed by an additional 12 V energy network. The energy system of the UNICARagil vehicles as described in [24] and [31] provides fourfold redundancy. Following the previously described four-zone architecture, four batteries are connected in ring topology. This decentral power supply allows the isolation of failures in each zone such that only the sensor module and the dynamics module at the corresponding corner of the vehicle are deactivated and the vehicle is still able to perform an emergency stop. AC and DC charging stations can charge the batteries and the automated delivery vehicle autoCARGO [11] can additionally be charged inductively.

The development of the on-board thermal system faces special challenges due to the vehicle architecture as presented in [34]. The wheel hub drives in the dynamics modules as well as the high performance computers running the automated driving functions generate a considerable amount of heat, which makes their cooling a safety-critical function. To achieve an excellent degree of effectiveness in this special constellation, a multi-stage thermoelectrical heat pump is developed within the project as described in [32]. Three cooling circuits are realized. The first circuit is used to cool the computing units while the second one is cooling the wheel hub drives. The third circuit is used for air-conditioning in the cabin. The heat pump allows for using the waste heat of the computers and wheel hub drives for heating the cabin by lifting it to a higher temperature level. A connection of the thermal system to the ASOA allows for innovative use cases such as using weather data from the cloud and conditioning the cabin considering the vehicle's mission.

4 Software and Automation

Two domains which are strictly coupled within the project are the software architecture and the automation of the UNICARagil vehicles. Both domains are represented with their own contributions at the Aachen Colloquium 2020 such that only a short overview of the progress in the covered research topics will be given at this point. For further details the reader is referred to [6] and [7].

The Automotive Service-oriented Software Architecture forms the framework for the on-board software modules of the UNICARagil vehicles. Additional off-board modules that are executed in the UNICARagil Cloud support them. A combination of on-board and off-board software functions is used to realize the automated driving of the vehicles.

4.1 Automotive Service-oriented Software Architecture (ASOA)

The Automotive Service-oriented Software Architecture (ASOA) as presented in [13] is one of the key concepts in the UNICARagil project. The accompanying paper [6] describes it in further detail such that in the following, only a short introduction describing the motivation and the concept will be given.

While current automotive software architectures, such as AUTOSAR, already provide standardized software interfaces and runtime environments for ECUs, their major drawback is the static integration of software components at design time. This makes it difficult to exchange software modules, especially after a vehicle has been sold. For an efficient development of automated vehicles, updateability and reusability of software components are essential requirements. The software architecture developed in UNICARagil addresses this problem [2].

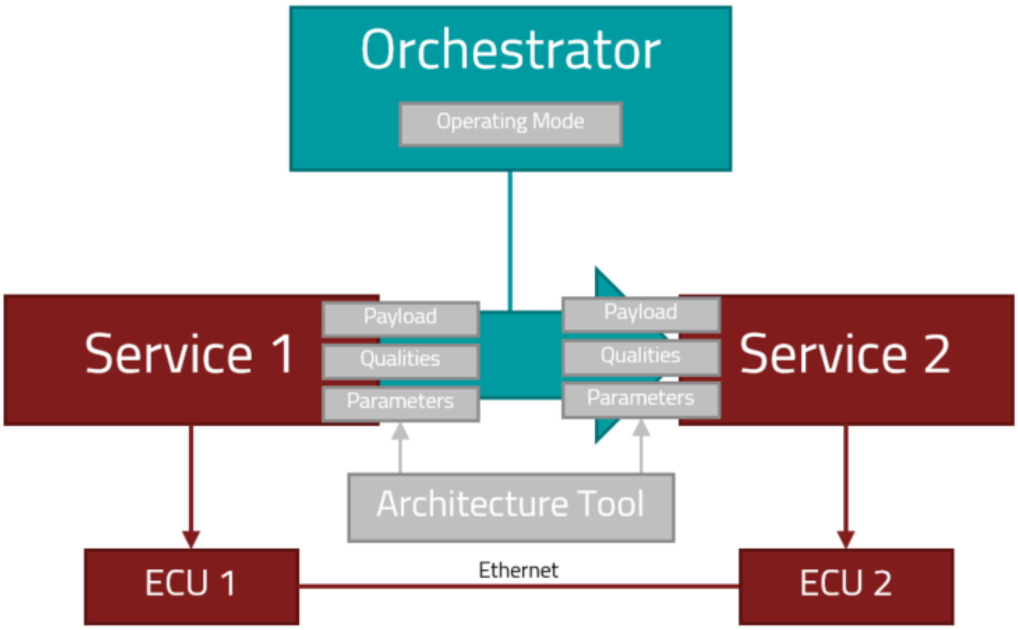

Fig. 10 Simplified concept of the Automotive Service-oriented Software Architecture

Fig. 10 visualizes the basic components of the ASOA. Each software module is realized as a service. Needs and capabilities describe the interfaces of the services and are represented by the three components payload, quality and parameters. The payload contains the actual transferred data while the information about the available quality and parameters of the service is considered for a dynamic combination of services. The quality of a service is also an important input for the self-awareness [38] of the vehicles and is separated from the payload to reduce the amount of transmitted data for that service. The so-called orchestrator performs a runtime integration based upon the requirements that result from the current operating mode. Possible operating modes are "Autonomous", "Remote Operation" and "Safe Halt" [6].

The communication is based upon Ethernet connections between the different control units and uses the Real-time Publish-Subscribe Protocol [25]. A major challenge arose from the diversity of the control units used in the UNICARagil vehicles, from embedded systems to fully-grown Linux systems. To make the ASOA also usable on embedded systems, e.g. the units controlling the dynamics modules, an embedded implementation of RTPS [27] was created and contributes to the open-source software framework ROS 2 [26].

The agile collaboration of multiple universities and industry partners developing different services made a simplification of the definition and linkage of services necessary. The Architecture Tool [6] tackles this challenge as a web-based tool that allows the definition of services and their interfaces. It ensures the prevention of inconsistencies in the interfaces and shows unfulfilled needs of services. The tool supports code generation to assure the consistency and to speed up the implementation of services.

Latency is a critical factor especially for software modules regarding automated driving. Therefore, a test bend was built up that consists of all the control units that are installed in the UNICARagil vehicles. It is connected to a continuous integration pipeline and allows the offline analysis of latencies in the communication between the services [39].

4.2 UNICARagil Cloud

The on-board software functions of the UNICARagil vehicles are supported by cloud-based functions that communicate with the vehicles using mobile network as described in [22] and [21].

Two types of services are meant to be running in the UNICARagil Cloud. At first, comfort functions allow for fleet management and offer interfaces to external services such as route planning or weather data. A use case survey in the consortium served to collect the need for such functions in the four vehicle types. A user management service is connected to a mobile application, which is meant for ride planning by the passengers. Based upon a common layout individual apps for the vehicles are created with respect to their requirements. Functions such as authentication and access control are common for several vehicle types while there are dedicated functions for single vehicle types, e.g. for the communication between the autoCARGO [11] and parcel boxes.

Additionally, the cloud connects the vehicles to the Control Center as described in [35] and [20], which consists of a service and a teleoperation workplace. The personnel at the service workplace monitors the vehicles and can be contacted in case of an emergency. The teleoperator is able to overtake the control of a vehicle in which the automation reached its system limits. Depending on the degradation of the vehicle which requested teleoperation they can support with the detection of unclassified objects on the road, control the driving trajectory or manually control the vehicle using pedals and a steering wheel.

The second type of services extends the on-board vehicle automation with collective information that is computed in the UNICARagil Cloud based upon the collected knowledge of connected vehicles and the Info Bee [40]. This is an unmanned aerial vehicle which is equipped with sensors and can extend the perception in interesting areas. The next section describes the collective driving functions in further detail.

Collective Driving - Extending the Vehicle Automation

Three cloud-based software components that are capable of directly and indirectly supporting the automated driving of vehicles are developed in UNICARagil. Fig. 11 shows the main modules Collective Environment Model (CEM), Collective Memory (CM) and Collective Behavior (CB) and their interaction.

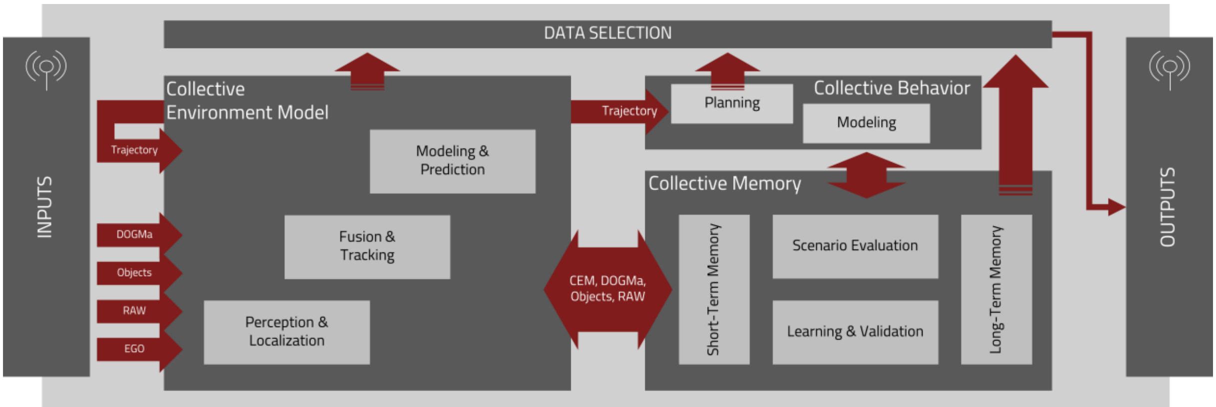

Fig. 11 Simplified architecture containing the cloud components Collective Environment Model, Collective Memory and Collective Behavior [21].

The on-board vehicle automation relies on the vehicle's perception which may be restricted by occlusions or sensor limits. The CEM collects perception data from multiple traffic participants as well as from the Info Bee. The perception data is processed and fused to create a combined environment representation [23]. Automated vehicles may use this to extend their perception range.

The CM addresses another challenge for automated vehicles. While human drivers constantly improve their driving skills with increasing experience this is not yet the case for algorithms overtaking the driving task. The CM receives driving trajectories from the vehicle fleet and stores them in a database. The data is analyzed and used to create a prediction model. Thus, vehicles can request trajectories from the CM as a cloud-based service. These can be used to validate and evaluate the trajectories calculated by the in-vehicle automation.

Since the interaction of vehicles via cloud services needs to be tested extensively before deployment to and testing with real vehicles, the development of a suitable simulation environment is a central aspect in developing the CEM, the CM and the CB.

Fig. 12 visualizes a selection of data provided by the developed simulation environment. Multi-vehicle simulations that cover all aspects from raw sensor-based perception to actuator control are important parts in the development and testing process.

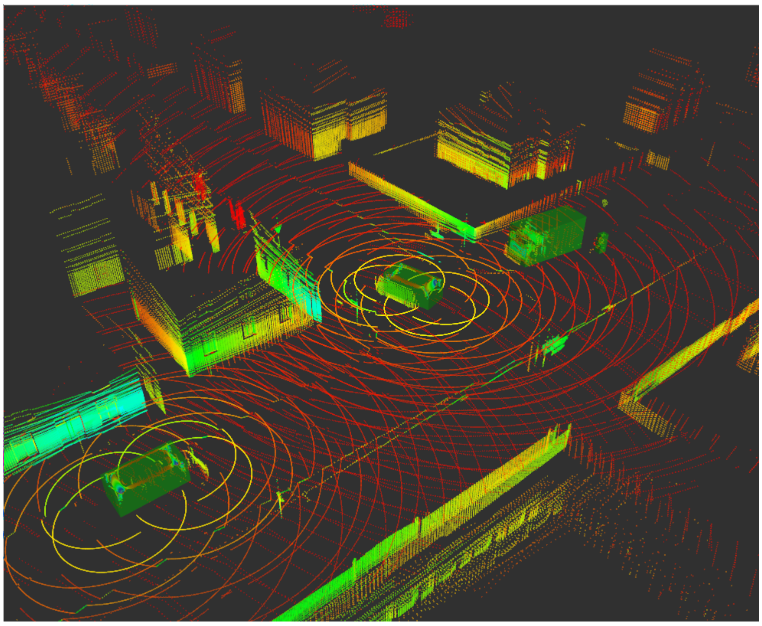

Fig. 12 Visualization of synthetic data generated in the developed simulation environment. Among others, sensor data such as the depicted lidar point clouds and object data (green boxes) can be generated for multiple vehicles. An interface to the services developed in UNICARagil allows testing these before deployment to real vehicles.

4.3 Vehicle Automation

In the driverless UNICARagil vehicles, the vehicle automation is overtaking the tasks which are performed by the driver in non-automated vehicles. Its main tasks are to perceive the environment using sensors, to plan the behavior and driving trajectories with respect to the perception and eventually to control the vehicle movement using its actuators. Fig. 13 visualizes this simplified data processing.

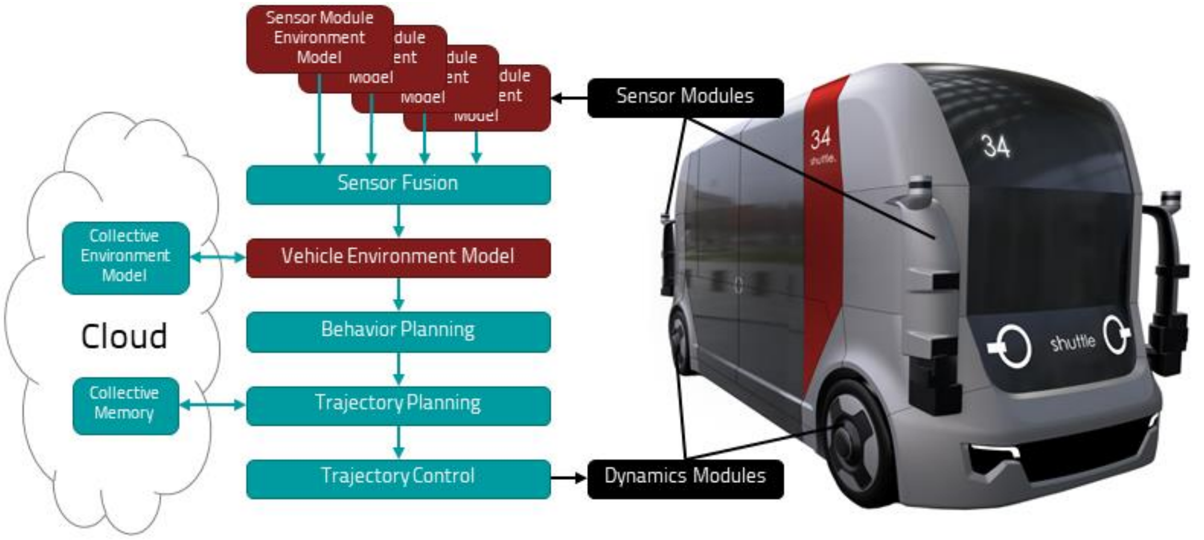

Fig. 13 Simplified data processing in the automation of the UNICARagil vehicles

The UNICARagil vehicles are equipped with four sensor modules at the four corners of the vehicle (cf. Fig. 13). Each of them is equipped with a lidar sensor, two radar sensors, two color cameras and a pair of stereo cameras generating depth information [15]. Additionally, each module contains a data processing unit which computes the sensor module environment model consisting of object lists and occupancy grids [16].

The modular approach of the vehicles is strictly considered by using four equivalent sensor modules two of which are each mirrored. Thus, the hardware and software components are replaceable and reusable. The environment models of all four sensor modules are fused into a single vehicle environment model [17].

This vehicle environment model is shared with the cloud-based Collective Environment Model, which is capable of enriching the environment representation using collective information (cf. chapter 0). Based on this, the behavior and trajectory planning is done. Two particular aspects result from the overall concept of the UNICARagil vehicles. First, the dynamics modules with individual steering angles of up to 90° introduce an additional degree of freedom compared to conventional vehicles (cf. section 2). This results in new motion possibilities such as driving sideways or driving around obstacles without yawing. Second, the safety concept provides that at any time an emergency trajectory is computed in addition to the normal trajectory (cf. section 5). In case of a system degradation, it switches to the emergency trajectory guiding the vehicle to the next possible safe halt. To make this independent of the sensors used for automated driving, the driving platforms contains additional simpler sensors that allow driving the emergency trajectory [36].

As two different partners realize the behavior and the trajectory planning, both modules are independent of each other [18]. This again underlines the modular approach of UNICARagil. The trajectory planning, as well, can benefit from collective information from the cloud-based Collective Memory that proposes driving trajectories learned by experience of the vehicle fleet.

Eventually, the trajectory is converted to commands for the dynamics modules by the trajectory control module. This module requires precise information about the motion state of the vehicle. Therefore, two fusion filters, which are developed by different groups to avoid mistakes, use two inertial measurement units, satellite navigation and odometry to provide a motion state estimation. Additionally, they provide quality information such that a voter can choose which estimation to use [19]. As the motion planning in contrast to the motion control is done using video-based localization an offset between both estimated poses may occur. To solve that problem, an algorithm for the correction of this inconsistent localization information was developed and proposed in [37].

In [7] Buchholz et al. introduce the automation concept of UNICARagil and give an overview of the different functional components. Mokhtarian et al. present the ASOA in [6].

5 Safety

With the introduction of SAE automation levels 3+, the driver is no longer available as a fallback level at all times. The absence of a human driver requires an extensive proof of sufficient safety. This proof of safety is often called safety assurance and addresses the questions how to verify and validate automated driving functions. Many different research projects address these topics, but do not often have the vehicle and function development as a project goal as well.

In UNICARagil, the vehicle itself, but also the automated driving functions are developed from scratch. During the development, safety and security aspects are handled as key factors for project success. Thus, an integrated safety framework was developed along with the vehicle and functional architectures. This sections gives a brief overview of the considered safety aspects. The accompanying paper [4] describes the process of deriving safety requirements and presents the developed safety and security mechanisms in detail.

In general, the project addresses five different safety perspectives:

- Behavioral Safety
- Functional Safety
- Crash Safety
- IT Security
- Operational Safety

These perspectives are monitored within the safety domain, but have large effects on the development in the accompanying domains, e.g. Crash and Operational Safety are part of the structural and geometrical design. Functional Safety needs to be addressed in the mechatronics domain, as well as in the software and automation domains.

Since automated vehicles, especially in the context of UNICARagil, make use of connected functions, for example the cloud or control room (cf. section 4), their connections need to be secure. Attacks from the inside or the outside need to be prevented. Therefore, UNICARagil develops concepts to protect future automated vehicles against digital attacks [41].

The concepts developed to approve the behavioral safety build up on an overall item definition, that describe the use cases as well as the functional boundaries. It specifies the operational design domain (ODD) and introduces important and highly relevant usage scenarios for the safety analysis. A technology independent hazard analysis and risk assessment additionally helps to formulate overall safety goals. The following functional safety concept combines this information to provide mitigation strategies and safety requirements.

With the introduction of the ASOA (cf. section 4.1), all in vehicle services provide their qualities and thus allow the overall system to monitor its overall health status. This mechanism is called self-perception [38] and is one of the key safety mechanisms in UNICARagil. The self-perception combines different monitoring aspects to combine all available information into a holistic state of the vehicles capabilities. With these mechanisms, the self-perception is able to detect degradations within the system and to trigger safety reactions accordingly. [4]

With previously analyzed and categorized routes, the requirements of a planned route and the capabilities of the vehicle can be matched [4][42]. This way, a vehicle may safely reach its destination even in degradation mode. In case the vehicle cannot longer fulfill its driving task safely, an automated fallback level needs to be provided. [36] introduces the concept of the Safe Halt in the context of UNICARagil, whereas [4] gives an overview on the function and its integration into the overall safety framework. Safe Halt is able to transfer the vehicle into a risk-minimized state at all times. Therefore, it has to be implemented independently and uses platform sensors, which provide the necessary redundancy to the sensor modules.

Furthermore, UNICARagil aims at a modular verification and validation process. With the strict modularization in hardware and software, it would be economically unviable to validate the whole system from scratch if one module is changed or updated. Therefore, tests on system level need to be broken down onto module level without losing the influences between modules and test these modules against safety goals on modular levels. [42] describes methods to breakdown safety goals to this modular level.

In [4], Stolte et al. breakdown the UNICARagil safety framework and the modular verification and validation approach based on examples.

6 Outlook

This paper presented selected parts of the mid-term status of the UNICARagil research project. More information on the project and a full list of publications can be found at [1].

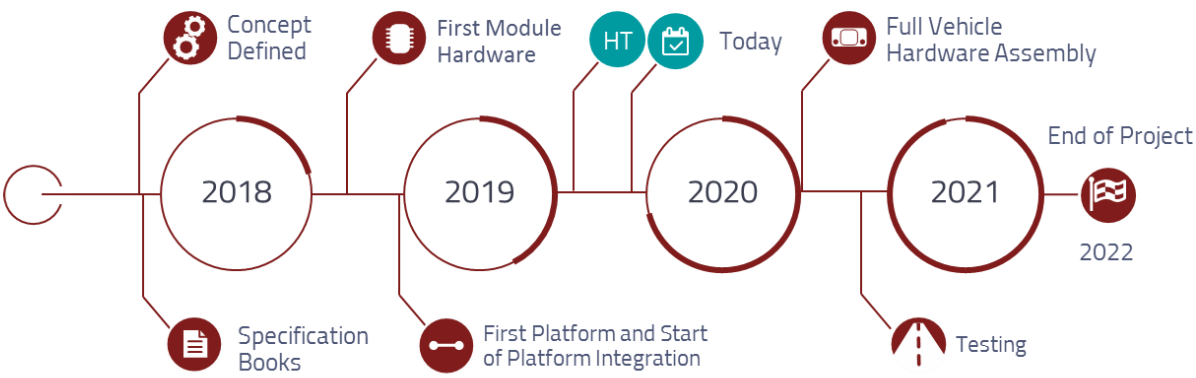

Fig. 14 Project Timeline

Fig. 14 shows the project timeline. In the end of 2020, we expect to reach a major milestone in having integrated all prototypes with dynamics modules, e/e-architecture,

communication architecture, platforms, add-on modules and sensor modules. The vehicles will then be put into manual operation first, before the software integration starts as a second major milestone to be reached towards the end of the project.
All testing activities will be performed before the interiors are manufactured and integrated at the end of the project.

7 Acknowledgment

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