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UNICAR*agil* news

Building Four Driverless Vehicle Prototypes

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Editorial

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2021 was a remarkable year. With ups and downs, tops and flops and a lot of work to be done. In 2021 the UNICAR*agil* consortium has accomplished some incredible work in the progress of developing and building fully automated and driverless vehicles from scratch. An impressive team effort that pushed the limits of inter university research.

Four years ago, UNICAR*agil* started with an ambitious list of work packages and one clear objective. It has not taken much time, that the nationally spread consortium of eight universities and eight smaller industrial partners grew together to a focused group of researchers interdisciplinary working together like they have never done something else before.

Originally, the project should have come to an end in January 2022, but COVID has not skipped research for us either. This left us with a bunch of video conferences instead of meeting each other in person and faced us with major logistical challenges on the assembly and integration of our vehicle prototypes. However, we coped with it and were able to present the first rolling vehicle in April 2021. The rollout day marked a new chapter for UNICAR*agil.* Vehicles were driving for the first time, and all the functions previously only running in simulation will now be integrated to make the vehicles truly driverless.

We are pleased to announce, that the project has been extended until May 2023 in reaction to the COVID restrictions. Thanks a lot to the Federal Ministry of Education and Research for the opportunity to finish this project the way it meant to be finished. Stay tuned for some more insights and demonstration of the UNICAR*agil* vehicles in 2022. Maybe we meet at this year's IEEE IV Conference in Aachen or at IAA Transportation? Anyway, enjoy this newsletter on the assembly and integration of our vehicles.

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Reaching a milestone: The first vehicle leaving the workshops on its own power

27th of April 2021

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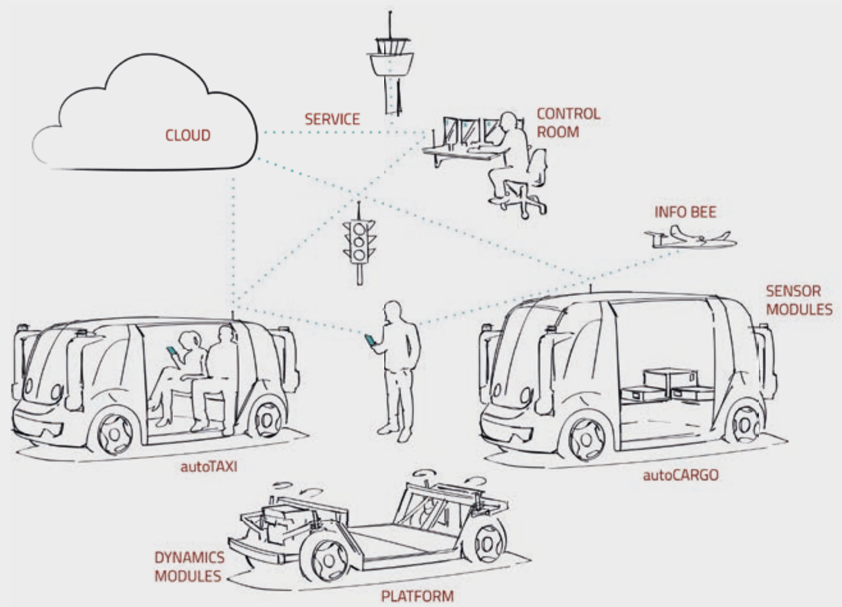
During four intense years – starting from February 2018, including a lot of workshops and discussions – the UNICAR*agil* consortium developed disruptive architectures for agile future mobility systems. The architecture comprises all domains – from geometry and mechatronics to safety and (automated driving) software – and leaves out of consideration what was previously taken for granted. The scientists started from scratch and with requirements in mind that a future mobility system around self-driving vehicles would pose.

The upper image visualizes some key aspects of the UNICAR*agil* mobility system architecture. A common platform uses dynamics modules for electric propulsion, steering and braking as well as the energy, thermal and information networks. It is scalable in its length and height to cover various use cases, e.g. a self-driving taxi or an autonomous delivery vehicle. Two more possible applications are prototyped in UNICAR*agil*. The *auto*SHUTTLE as flexible extension of public transport and the *auto*ELF as a privately owned family vehicle (cf. page 8 – 9).

Yet to be proven is that this architecture also delivers what it promises in reality. For this reason, four full-sized vehicles are being prototyped within the project to demonstrate that the architecture is not just innovative but also versatile and practicable. The vehicle prototype is the place where all domains come together. Now we will see whether the high demand for modularity has borne fruit and facilitates the combination of hardware and software components, which have been built up in a distributed consortium. Of course, everyone involved was eager to see if their ideas would work.

The 27th of April 2021 marked a highly anticipated milestone in the UNICAR*agil* project. It was the day when the first UNICAR*agil* vehicle has driven on its own wheels. Still by a test driver, of course, but it demonstrated that some fundamental components were successfully integrated and work in interaction with each other. In particular, the vehicle structure with dynamics modules, sensor modules and a test driver's workplace, as well as, on-board networks and control units. This is the necessary prerequisite for the integration and testing of automated driving software, which started right after the successful roll-out.

The consortium was honered that epresentatives of the Federal Ministry of Education and Research participated in this exciting event and motivated the team for the remaining project duration. A statement of the Parliamentary State Secretary as well as some words by Prof. Lutz Eckstein, overall project coordinator, and by Prof. Ulrich Rüdiger, rector of RWTH Aachen University, are available in a video on www.unicaragil.de/en/rollout.



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Prototyping - from vehicle frames to add-on modules

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After finishing the build of four platforms in 2019 the design of add-on module structures and the additional exterior panels were making huge progress. The build concept as well as the parts layout was finalized by December 2019 and in January 2020 the CAD data was released for manufacturing to Roding Automobile GmbH.

One platform of each length was used as a welding rig for the add-on modules of all four prototypes. After preassembly and welding, the carbon fiber sandwich panels for the shear fields were manufactured and fitted to the aluminum frame to complete the load bearing structure.

The first picture on the left depicts the finalized structure of the *auto*CARGO including the attachment points for the sensor modules. The overall structure is double-symmetric, so front and rear are identical and the left and right only differ slightly for the long derivatives. The door opening on the left side is not used in the bigger vehicles, therefore the side is reinforced with detachable profiles.

The CAD concepts of the exterior panels were transferred into layup tooling and manufactured out of prepreg CFRP material. The panels as well as the windows are fitted to the tubular frame and after adjusting the parts clearance permanently bonded. At the same time, colleagues from Munich integrated the door mechanisms and tested their basis functionalities.

The finalized assemblies were than primed, sanded and sent off to the final color coating. The idea was to give every vehicle a unique outer appearance while still emphasizing the modular nature of the design.

The painted vehicles were then shipped to Aachen and Stuttgart to fit the electric and electronics as well as the dynamics modules.

It is great to see that in less than three years' time our team was able to build up four running prototypes. Starting from an idea in 2018 we now see four vehicles making their first steps to automation.

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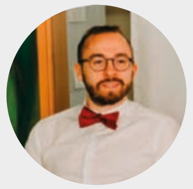
A reliable on-board energy supply



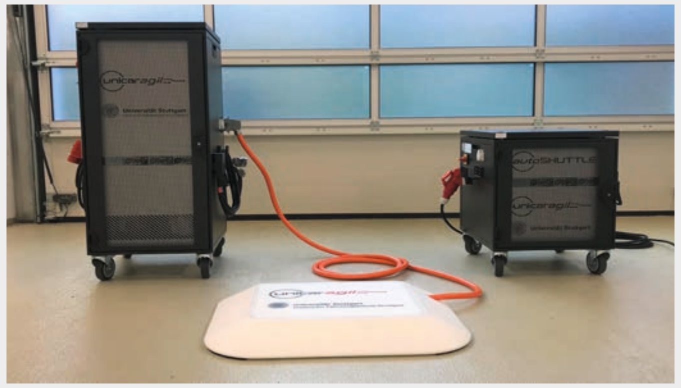
Jonas Maier
Institute of Automotive Engineering and Vehicle Engines Stuttgart
University of Stuttgart

The on-board energy supply system comprises the 48 V batteries, control units providing energy-related services within the Automotive Service-oriented Software Architecture (ASOA) and the energy distribution with 12 V and 48 V voltage levels in the vehicle.

The on-board energy network is required to supply the various components of the vehicle with energy, and in addition, in the event of an energy surplus (e.g. recuperation) the energy can be stored in the batteries. In the last 1.5 years, the integration of *auto*CARGO and *auto*TAXI has been completed. In *auto*SHUTTLE and *auto*ELF, the system was fully integrated and tested. The behavior at higher load will be investigated in the course of integration of further systems. The system differs from conventional electrically driven vehicles in that it is divided into four zones. If a fault occurs in one of the zones, it can be disconnected to isolate the fault. If, on the other hand, the connection of a zone to the overall system is interrupted, it can continue to supply the consumers of the same zone. This has advantages in terms of safety and reliability of the system. In addition, by separating the energy storage units, greater flexibility is achieved in the packaging. One challenge in the integration of the on-board energy network was to make the energy available at various points in the vehicle under the given packaging situation.

The **conductive charging system** comprises a mobile charging station that converts the enegy from 400 V to 48 V and charges the batteries. For this purpose, the current is adjusted depending on the state of charge and the voltage change in the batteries. By means of the conductive charging stations, DC charging of up to 10 kW is possible, so that the batteries can be fully charged within 6 hours. The control unit of the charging pole communicates with the vehicle via Wi-Fi. The construction and testing of the charging columns is completed. This included the construction of a prototype, the testing of functions and communication with the vehicle as well as the investigation of safety aspects. An external service provider confirmed the safety of the charging columns and their legal conformity (DGUV) in the third quarter of 2021, so that they could be delivered to the consortium partners at the end of 2021.

The **inductive charging system** includes the inductive charging column with charging plate and the coil in the vehicle. Both subsystems have power electronics for converting the currents and voltages. The inductive charging system includes a positioning aid that enables automated positioning of the vehicle on the charging plate. The construction of the charging station and initial tests have been completed. In the further course of the project, the charging plate will be integrated into a chassis to test and demonstrate the charging and positioning function.



Combined thermal management (system) for passengers and components

Daniel Gehringer
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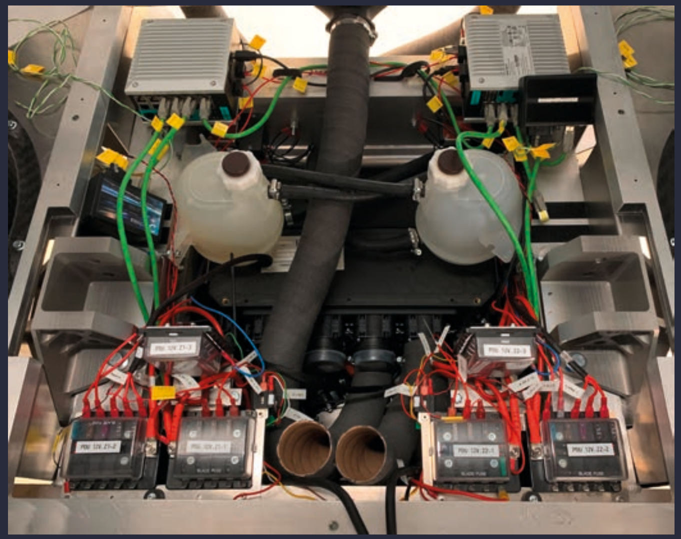
University of Stuttgart

After the concept phase and procurement of components for the thermal management system, the integration into the vehicle platforms was started in the first quarter of 2020 with fitting all components and tubing for the cooling circuits. Preliminary testing has shown that the data processing units require a much lower cooling inlet temperature then the dynamics modules.

The cooling circuit was therefore divided into a low- and mid-temperature circuit. By using liquid-cooled components in the data processing units their excess heat can be used to heat the cabin. This approach was chosen because the data processing units are always running in vehicle operation and the heat output is independent from the driving condition. The dynamics modules on the other hand may supply a very low amount of heat depending on vehicle speed, gradient or load. An additional electric heating element was integrated to further heat the cooling liquid on cold days before entering the interior heat exchanger. Underfloor heating will also be integrated into the vehicles once the cabin interiors are installed in a later stage of the project.

To cool down the cabin a refrigerant circuit with 48 V compressor and modular HVAC-Box was used. This modularity allows the system to adapt to each of the four different interior concepts. The HVAC box supports recirculating and fresh air mode as well as three individually controllable zones for air outlets. To save energy, recirculating mode is primarily used and the cabin air is constantly monitored using a CO_2 as well as a humidity sensor to efficiently control the fresh air mode.

The control unit for managing the HVAC system is developed in-house, which allows for support of the ASOA framework. This way the AC control unit can communicate with other services in the vehicle. The current interior and exterior temperature measured by the AC control unit for example are provided as a service and can be used by other control units in the vehicle if required. In addition, services such as the interior HMI can influence parameters of the interior climate control if needed. The integration of all thermal management hardware components has been completed and the cooling circuits are successfully operating in all four platforms. The next step is to implement the developed AC control unit and tune the controller to efficiently regulate the interior climate during vehicle operation.




autoSHUTTLE


autoCARGO


autoTAXI


autoELF

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Dynamics Modules: Wheel-individual acceleration, steering and braking

Timm Martens
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Regarding the dynamics modules, 2021 was a pivotal year. The first vehicle equipped with the traction battery arrived in Aachen so that the commissioning phase for the dynamics modules could begin. Not only were the chassis components, the wheel with the wheel hub motor and the electric steering actuator assembled as a system for the first time, in addition the spinal cord control units, the brake system including a by-wire brake pedal and the sidestick for manual control during testing were integrated.

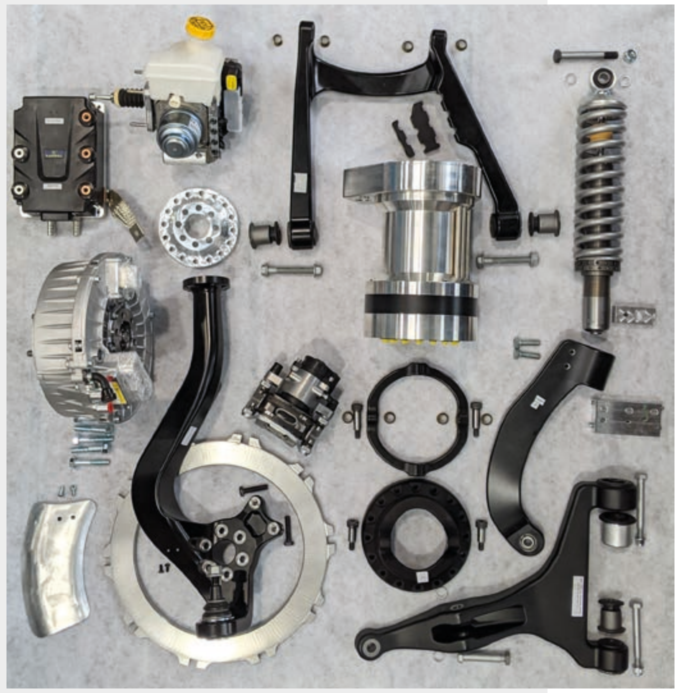
A special challenge was the cable and wire routing in the wheel arches. Unlike conventional vehicles, where usually only a couple are routed to the wheel, our vehicles have more than 10 lines and cables running through the wheel arch. For the wheel hub motor three phases and one ground line, one sensor cable and two cooling lines. A hydraulic line and one control cable are connected to the brake caliper. And finally, a cable with three phases for the steering actuator and the control line for the steering angle brake and another one for connecting the torque, position and temperature sensors.

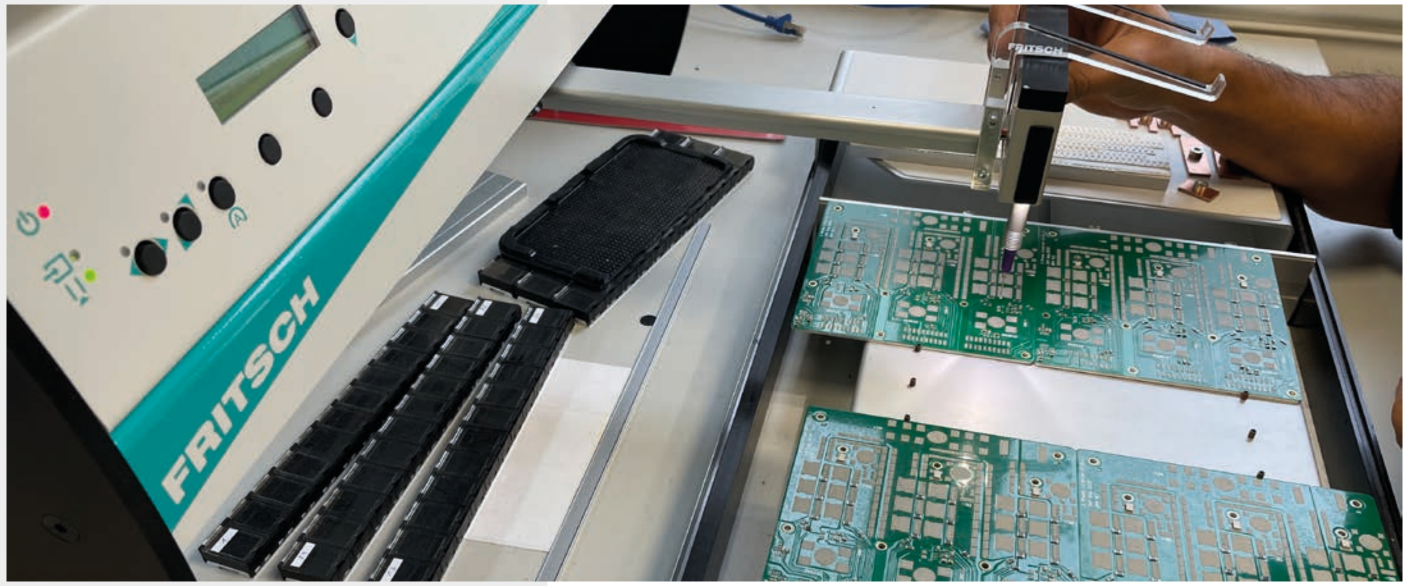
The chassis components were designed at ika and manufactured externally whereas the wheels were provided by the associated partner Maxion and the wheel hub motors by project partner Schaeffler.

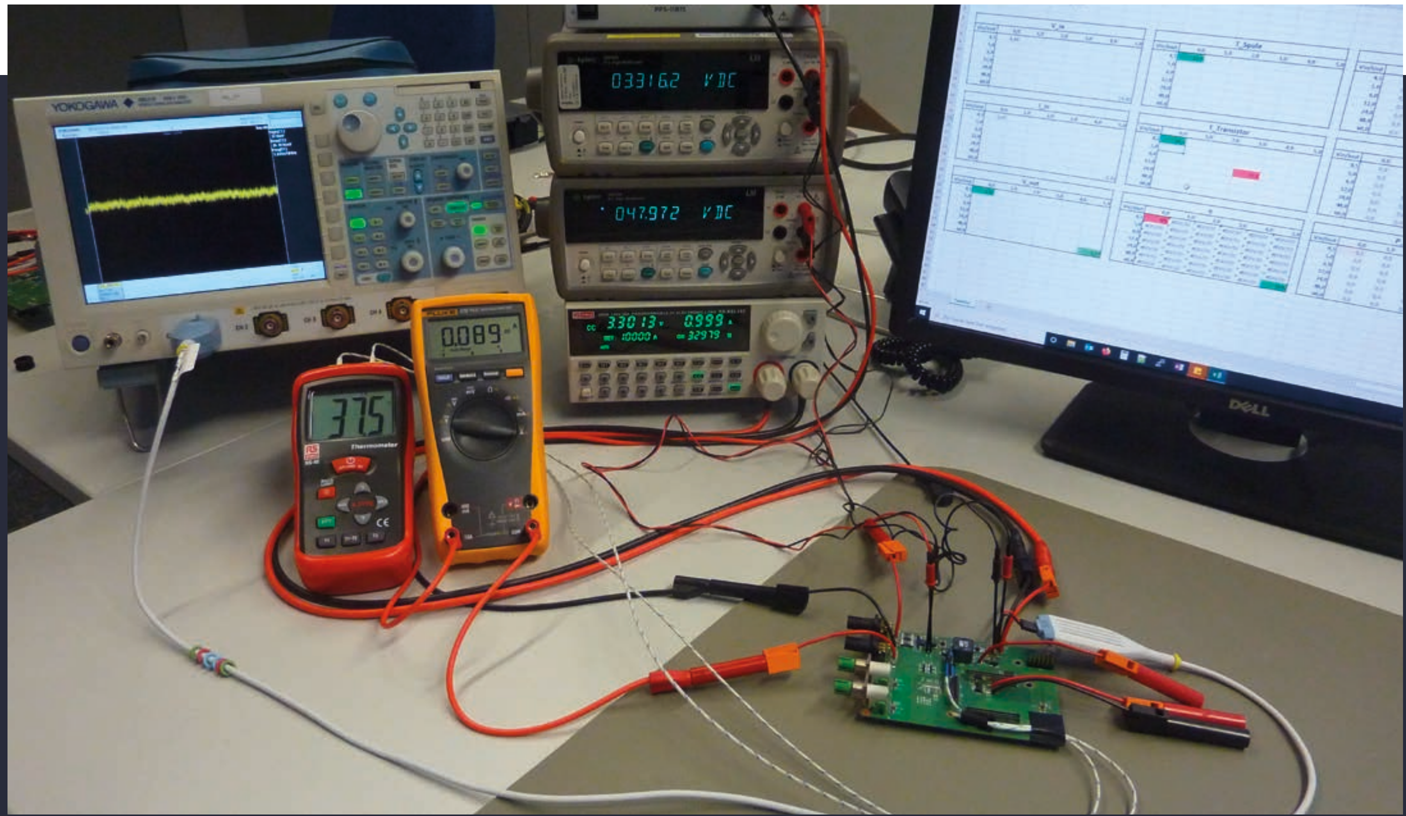
The steering actuator and the braking system as well as the sidestick were developed externally according to ika-specifications, with the brake pedal being provided by Curtiss-Wright. The spinal cord control units, which enable the dynamics modules to communicate with each other and the rest of the vehicle, were developed, assembled and tested at our institute.

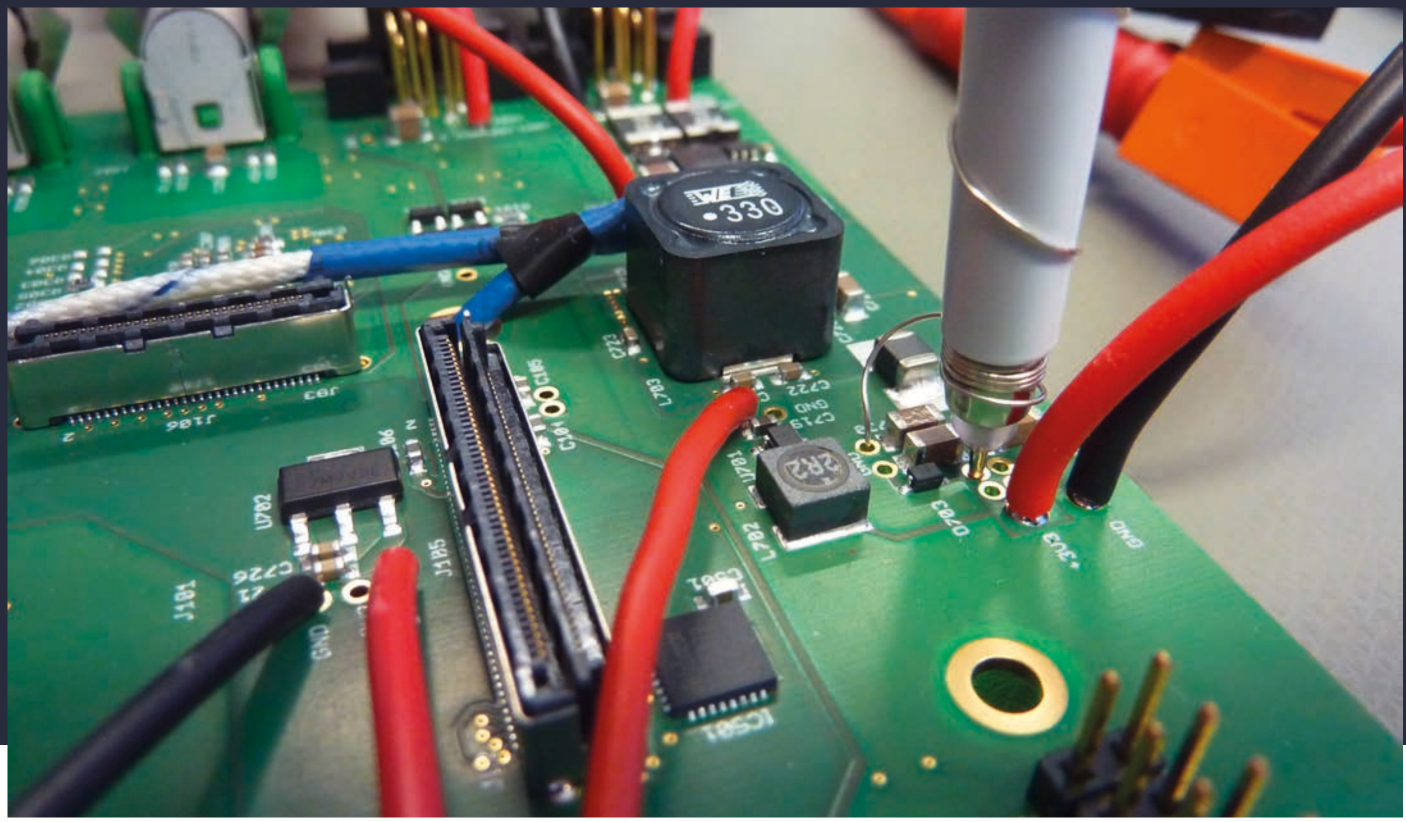
Shortly after that, another milestone was reached: the first ride! Even at low speed at first, it was nevertheless impressive proof of what is possible within three years of a project and after three months of commissioning.

With a new "drive" the fine-tuning and further software implementation started. The chassis was measured to verify the design and to define the "zero position" for the wheels. With regard to the software, the "slow manoeuvring" was first implemented to send the *auto*CARGO on its journey south to Ulm. After that, the commissioning continued with the *auto*TAXI and then the *auto*SHUTTLE. With the shuttle, the ASOA-interface was also put into operation for the first time for the dynamics modules. Since then it is possible to control each wheel individually via Ethernet. In November 2021 the *auto*ELF was the first vehicle tested at ika with more than 10 km/h before being transported to Darmstadt.









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The Brainstem - a control unit designed to meet the highest reliability requirements

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University of Stuttgart

For the brainstem, we could accomplish great achievements in both hardware and software since the last newsletter. On the hardware side, we first enhanced version 3 of the brainstem to a vehicle assembly ready prototype. We mounted this device on all four vehicles where it now enables the integration and test phase of the vehicles.

As a next step, we are now working on version 5, which is based on version 4 of the brainstem. It comes with numerous improvements like much more robust, vehicle suitable M12 connectors, a space-saving and splash-water protected housing, improved mountability and cooling, robust and more performant power supply with wide 4.5 V to 60 V input voltage range, native CAN supply and more. We achieved improvements in all aspects of the ECU like mechanics, part selection, schematic development and layout. Unfortunately we were, like the whole industry, affected by the worldwide delivery problems in the chip industry, which caused a delay in our work package but stayed without consequences for the rest of the project.

On the software side the last 18 months were very productive. Together with a highly motivated student team, we implemented numerous features related to the basis software and operating system (OS). First, we commissioned the second Ethernet interface of the brainstem, which required a deep insight into the hardware definition (HDF) and Linux configuration (device tree, interfaces initialization). In parallel, we implemented a CAN-to-Ethernet gateway functionality that will help to simplify the E/E-architecture of UNICAR*agil* in the future. The dual boot of the main processor (ARM Cortex-A53) and coprocessor (ARM Cortex-R5) was a great challenge, which we finally met. We implemented PTP slaves on both processor cores, so we can now synchronize the clock of the brainstem with all other members of the E/E-architecture. A newly developed Update-over-the-Air (OTA) functionality helps us to keep the devices in the field up to date, independently from their location. The new ASOA based boot and shutdown service enables a clean power up and down process of the UNICAR*agil* vehicles. Additionally we implemented an *auto*mated build-process, which ensures a reproducible generation of boot images with predefined properties. The new redundancy management, which we developed, will in future demonstrate the functional safety potential of the brainstem. Currently we are working on clean coding and an automated self-test as a first step to a closed CI/CD pipeline.

The test driver's workplace

Tobias Schräder
Institute of Control Engineering
TU Braunschweig

After the first year of the project, it became clear that safe, manual vehicle guidance was not possible with the novel interiors planned in the project. It was therefore decided to develop additional test driver workstations that could be installed in the interiors while the vehicles' automated driving functions are developed. In this way, the extensive design freedom afforded by the elimination of requirements for a conventional driver workplace was preserved.

The design shown below features two seats, restraint systems, field-of-view extensions and ergonomically arranged controls for manual vehicle guidance. A particular challenge was the development of a construction that could be installed in all four vehicles with little effort and that does not require any time-consuming deinstallation of the interior components. At the same time, test driver workstations had to be robust enough for everyday testing.

TU Munich coordinated the development and ergonomic design of the test driver workstations, KIT implemented the field-of-view extensions, RWTH Aachen performed the simulative validation, and TU Braunschweig was responsible for the mechanical design. In 2021, the development activities were completed and the test driver workstations could be manufactured in the workshops of various project partners. A test driver workstation was used for the first time during the rollout of *auto*CARGO in April 2021. During the implementation of the automated driving functions in the coming project months, the test driver workstations will make an important contribution to the active safety of the four vehicles during testing phase. When the vehicles are finally presented, the test driver workstations will be uninstalled again and the vehicle interiors will be fully utilized for the respective use cases.

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Sensor Integration

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After the vehicles were built, it was time to integrate the sensor modules. Ulm University coordinated the integration of the sensors and computers, and KIT was responsible for the trigger boxes that synchronize the large number of sensors. But before we could drive to Stuttgart, Munich, and Darmstadt to integrate all sensors and computers, we first had to prepare everything. In total, 16 computers were built from scratch with custom housings manufactured in Ulm. Further, we pre-mounted the lenses for 64 cameras, checked all sensors, and assembled in total more than 250 cables. Meanwhile, the trigger boxes were manufactured, built and calibrated in Karlsruhe. At lot of work to do, but at the end, it was worth the effort!

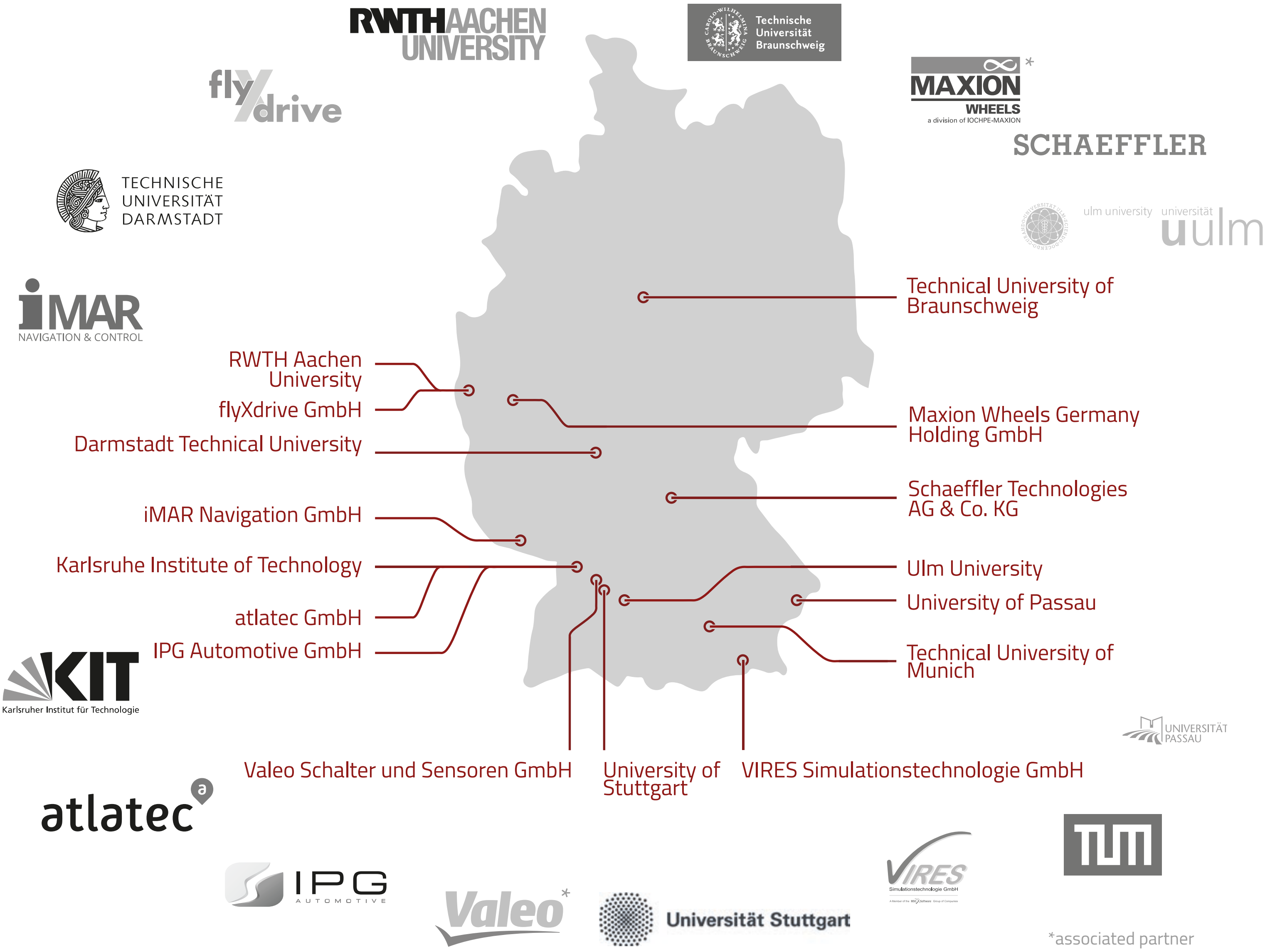
Due to the extensive preparation, we managed to integrate all sensor modules in only a few days per vehicle. We are really grateful for the help of all colleagues at the locations in Stuttgart, Munich, and Darmstadt. Further, we were working closely together with the colleagues from Stuttgart for connecting the sensor module computers to the liquid cooling cycle of the vehicles at every location.

The first vehicle that was able to drive manually and power the sensor modules from its batteries was the *auto*CARGO, which was delivered from Aachen to Ulm in July 2021. After integrating all parts in Ulm, we could finally start up all sensor modules and have a first look at the data of all four sensor modules on the monitors of the test driver workplace (cf. page 17). This was a really exciting milestone for us, as we had only seen simulations or data from single sensor modules until then.

Our next step was the calibration of the sensors. First, the distortion of the cameras caused by the lenses had to be compensated, since undistorted images are required for all further processing steps. Next, all sensors of the vehicles had to be extrinsically calibrated to a common coordinate system. Only this makes it possible to fuse the data of all sensors within a single sensor module and between different sensor modules. For this, we used a checkerboard for the cameras and a sphere with a radar corner reflector inside for the lidar and radar sensors. This combination enables a precise calibration of all different sensor modalities.

Meanwhile, the sensor modules could be integrated into all four vehicles and are providing data that is used to further optimize the environment perception algorithms.

The Project Consortium



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