UNICAR*agil*: Challenges in Thermal Management for Autonomous Vehicle Concepts

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Abstract

This paper gives an introduction into the collaboration project UNICAR*agil,* conducted by seven German universities and six industrial partners. In the project funded by the Federal Ministry of Education and Research of Germany (BMBF) four autonomous vehicle concepts are developed with the goal to build up corresponding prototypes for testing and demonstration purposes. The project aims to cope with changing demands introduced by new megatrends in individual mobility. A characteristic of the concept is the high demand for computational power needed to enable autonomous vehicle operation, resulting in high thermal loads. Challenges in thermal management arising from the pursued concept and possible solutions are highlighted in this paper. Finally an outlook into future work within the scope of the project is given.

1 Introduction

In 1978, four universities collaborated to develop and build the prototype of a future car for the year 2000 in scope of the project UNI-CAR. The project focused on exhaust and noise emissions, energy consumption as well as safety features. One of the measures to increase efficiency was a streamlined shape of the vehicle with a drag coefficient of 0.24 measured in the full-scale wind tunnel [1, 2]. The great interest shown by the automotive industry in both, the final report and the researchers involved, was indicative of the project’s success. Many of the developed technologies have found their way into production vehicles by today [3].

Since completion of the UNI-CAR project, the mobility behavior and therefore requirements for development of on road vehicles have changed. Megatrends such as autonomous driving, electrification, urbanization, big data and ridesharing pose new challenges for the automotive industry [4-6]. A survey among 619 persons conducted by RWTH Aachen has shown increasing demand for new mobility concepts as well as a high acceptance of autonomous vehicles [7]. Many large cities today face issues such as high local emissions caused by internal combustion engines and long traffic jams during rush hours, which in turn further increase emissions [8]. Electrification of the drivetrain as well as automation of traffic are only two efforts made to cope with these issues. To keep up with the aforementioned developments, a consortium of 7 universities with 15 different institutes as well as 6 industrial partners has initiated a new cooperation project named UNICAR*agil*. The goal is to develop four fully autonomous battery electric research vehicles, each for a different use case, sharing the same overall concept and similar structure, thus providing a great degree of modularity. Work packages assigned to the Chair in Automotive Engineering at IVK

University of Stuttgart include, amongst others, the thermal management of the vehicles and the thermal comfort in the cabin.

This paper presents the overall concept of the project and focuses on the challenges in thermal management of autonomous vehicles. Finally, it describes the thermal management concept for UNICAR*agil* to cope with these challenges and gives an outlook on future work planned for the project.

2 Concept Overview

The overall concept of UNICAR*agil* is based on a scalable driving platform, which can be equipped with an individual body for each use case. The driving platform is equipped with four so-called dynamic modules, one in every corner. The dynamic modules combine the drive unit in form of a 48 V wheel hub motor and a second electric motor for steering. This allows for a steering angle of up to 90 degrees for each wheel, which in turn enables the car to perform agile driving maneuvers in tight urban environments such as sideways parallel parking. A sketch of the overall concept of the project is shown in figure 1. The vehicles can communicate over a cloud service, which aggregates sensor data from the vehicles, the Info-Bees and other road users. The Info-Bees are unmanned aerial vehicles, which monitor the traffic situation where significant traffic incidents occur or sensor data is sparse. This allows for a better planning of driving routes and a more efficient traffic flow. Human operators in a control room oversee the vehicles and can take control remotely if necessary. Thus, safety is ensured should the vehicle be unable to maneuver with its autonomous driving functions or enters an unsafe driving state.

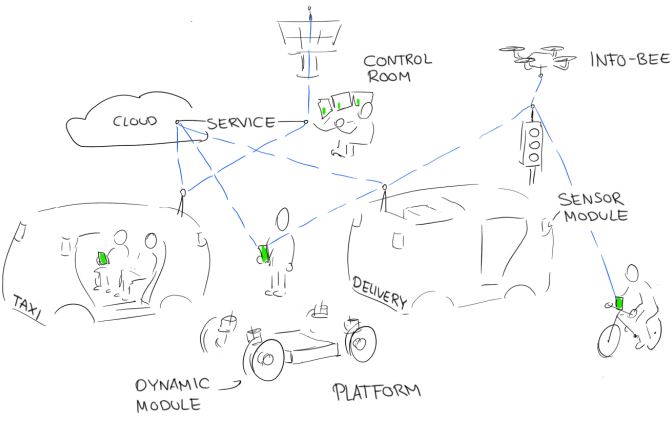

Figure 1: Overall concept of UNICAR*agil* [9].

Figure 2 shows a sketch of the planned E/E architecture. It resembles the structure of a biological nervous system. All sensors for the autonomous driving functions are clustered together with the hardware for sensor data processing in the so-called sensor modules. These modules rely on several different sensor types such as LiDAR, RADAR, mono and stereo cameras. The use of all these sensor principles provides a certain degree of redundancy within a single sensor module. Each corner of the vehicle is equipped with such a sensor module, in order to cover the complete surrounding. One module covers a horizontal field of view of 270°, which leads to overlapping areas and in turn further redundancy in the perception of the environment. Furthermore, the driving platform uses ultrasonic sensors for near field recognition. Each sensor module has its own data processing unit that analyzes the sensor data and generates an environment model. This model includes a dynamic list of objects the sensors recognize in the environment. Geometric dimension, positions and object class characterize every object in this list. An occupancy grid map, divided into quadric sections, represents the surrounding. The probability of being occupied by an object is calculated for every cell of the grid. Preprocessed sensor data of the sensor modules is fused in the cerebrum and a combined environment model is computed; the target driving trajectory is then calculated and passed on to the brainstem. The brainstem monitors the target driving trajectory and calculates the required accelerating and braking torques as well as steering angles needed to follow this trajectory. It is connected to the corner modules via the spinal cord, which controls the required voltage and current supplied to the dynamic modules for the driving task. The energy supply is also located in the driving platform and has a redundant design. This is achieved by use of four identical battery modules and a redundant electrical connection to the main system.

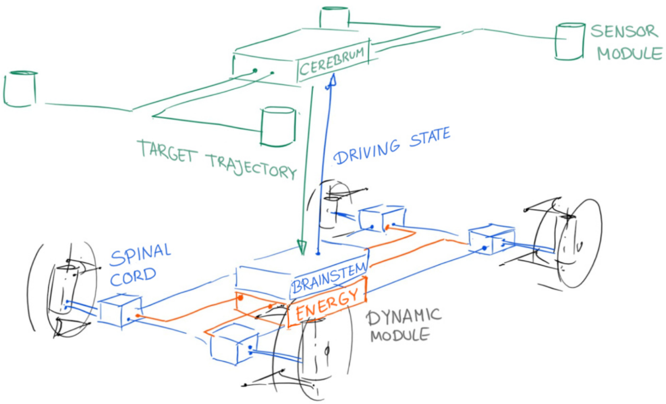

Figure 2: E/E architecture of the vehicle [9].

Two separate driving platforms are being developed, one with a short and one with a long wheelbase. These form the basis of the four vehicle prototypes for different use cases: a driver-less taxi that can be interacted with via smart devices, a family vehicle used for private transportation, a delivery vehicle for parcels and a shuttle used to supplement urban public transport. The taxi and private vehicle both use the short, delivery and shuttle vehicles the long wheelbase driving platform. Each vehicle has its own body with corresponding interior, which is mounted on the platform via eight points. All vehicles utilize a one-box design to maximize the interior space and allow for new interior concepts. Delivery and shuttle are not only longer, but also have a taller body with an overall height of around 2.6 meters, whereas taxi and private vehicle are around 1.9 meters high. Figure 3 shows the long wheelbase version of the driving platform. The four battery modules are housed in equal compartments in the floor and electric wiring runs along the I-beam in the center. The short platform is scaled down by subtracting the middle portion between the battery compartments, which shortens the platform by about 430 mm. This similarity between the platforms as well as the platform's front to back symmetry allow the use of common parts between the four vehicles.

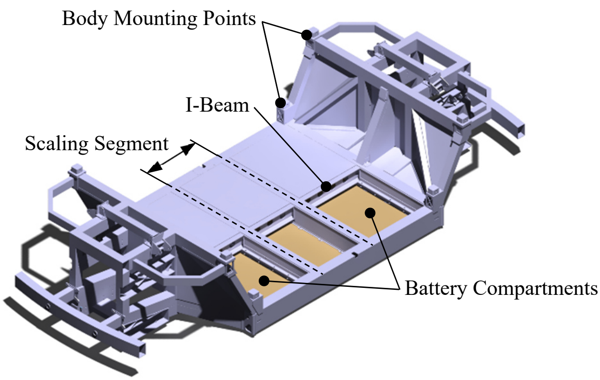

Figure 3: CAD model of long wheelbase driving platform.

Passengers enter and exit the vehicle through a bisected sliding door, which extends from top to bottom. In case of the shuttle, this allows entry and egress in a standing position without stooping. Loading of the preloaded parcel carrier in the delivery use case is also possible with this door concept. The taxi and private vehicle utilize the same sliding doors, but with a lower door height due to the lower overall vehicle height.

The software integration of the UNICAR*agil* concept uses an automotive service oriented architecture (ASOA). The approach of service oriented architectures is widely used in software development for IT-systems and is adapted to the automotive context here, where real time operation is an important requirement. Every vehicle functionality has its own service that runs on the corresponding electronic control unit (ECU). This enables the vehicle to be updated or extended with new modules, with services that can either be offered or requested. Services are integrated and coupled during runtime by the orchestrator. Communication between services takes place via a redundant Ethernet connection between the different ECUs. Redundancy is enabled by interconnection of several switches throughout the vehicle [10].

Another key part of software integration is the implemented self-perception. The software monitors its own status and functions, such as the performance of sensors, the environment modelling and trajectory planning for example. Therefore, failures in the system can be detected and the autonomous driving functions can react accordingly. Should the system detect severe safety hazards that make continued autonomous operation impossible, it can bring the vehicle to a safe halt and hand over operation to the control room. Further information about the overall concept of UNICAR*agil* and more specific descriptions about individual subsystems can be found in [9] and [10].

3 Challenges in Thermal Management of UNICAR*agil*

Requirements for the thermal management of autonomous battery electric vehicles (BEV) are profoundly different from the ones for conventional vehicles with combustion engines. The modular character of the UNICAR*agil* concept demands an inherently more complex cooling circuit operating at a relatively low temperature level. Challenges for the thermal management are divided into three groups: challenges due to geometrical topology, operation strategy and the autonomous vehicle concept. There are four sensor module data processing units in each vehicle, which provide the computational power needed for autonomous driving and consequently generate a large amount of heat. Computationally intensive algorithms are used to generate the environment models, which run even when the vehicle is stationary where cooling airflow is sparse. All vehicles will be used in an urban environment, therefore the expected average driving speed will be low. Thus, the cooling package has to be equipped with powerful fans to guarantee save operation of the vehicle in warm climates. The vehicle will spend a significant amount of time standing still with its large doors opened to allow entry and egress of passengers. This puts a high load on the implemented heating, ventilation and air conditioning (HVAC) system due to a high air exchange rate, when relying solely on direct air heating or cooling.

With the public transport and ride sharing character of the concept in mind, a one-box-design is used for the overall shape of the vehicle body. This leads to a large interior volume and glass surfaces, which demand a powerful HVAC system to keep the cabin climate in the desired range. A typical vehicle cabin has an interior volume of around 3 m³ [11], whereas the concept pursued in UNICAR*agil* yields an expected volume of approximately 5.5 m³ in the small and 10 m³ for the large vehicles. This large interior space and the low doorsills with a level floor throughout the vehicle also imply an unconventional package. Contrary to a conventional vehicle concept for example there is no transmission tunnel. A conventional driver workplace is not required, therefore the placement and orientation of the passengers is being reconsidered. Each of the three passenger vehicle designs will therefore have an individual interior seating concept, which in turn affects the placement and design of air vents, for instance. Figure 4 shows the planned seating positions in private and shuttle vehicle with 95th percentile male anthropometric dummies. Taxi will have a similar passenger position to the private vehicle and is therefore not shown here.

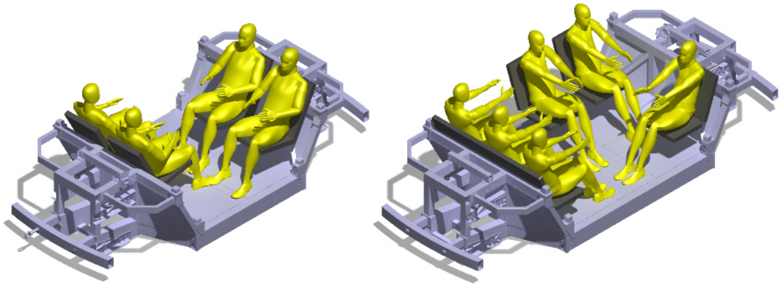

Figure 4: Seating concept of private (left) and shuttle (right) vehicle.

4 Thermal Management Concept of UNICAR*agil*

One benefit of the proposed vehicle concept is the amount of data available from different sensors as well as from cloud services. For example the planned route including the elevation profile and traffic congestion is known before departure. Thus, the thermal management functions can be controlled according to the projected cooling demand along the route. Control of the thermal management system will be implemented as two separate services running on one ECU, a general thermal management and an interior climate service. The ECU is connected to the vehicle´s main system via Ethernet and can obtain data from other services or the cloud. Each service is capable of self-perception. Therefore, the remaining cooling capacity can be communicated between thermal management and driving service to control the vehicle speed or acceleration accordingly.

The cloud integration present in the vehicle concept can be used to control the HVAC system more efficiently. In case of a cool summer morning, for example, excessive heating of the cabin can be avoided, knowing that higher temperatures will occur later in the day. With knowledge of the expected temperatures and the planned departure time, the cabin can not only be preconditioned but also over conditioned while idle and charging. This provides a thermal buffer during off-grid operation of the vehicle. If the consignor provides information on the thermal requirements of his parcel, the delivery vehicle can regulate its interior temperature accordingly or even avoid air conditioning of the interior completely. Through the use of decentralized heating devices such as resistive heating films or infrared heating panels in the proximity of the passengers, the interior air temperature can be reduced in heating cases. Because more heat is transferred to the passengers via radiation, convection can be reduced to maintain the same comfort level. The use of such close to body heating elements therefore attenuates the effect a frequent opening of doors has on the required heating power. They can also be combined with seat occupancy sensors to allow for efficient and automatic control of the elements by only enabling them where needed.

To control the amount of heat introduced into the cabin by solar radiation, glass surfaces with alterable radiation properties are used. In the summer the heat up effect can be reduced when the vehicle is parked and in the winter all available radiation power can be used to support the HVAC system.

An average human emits a heat flow rate of about 120 to 160 W without physical activity and clothing appropriate for the ambient temperature [11, 12]. In a typical use case the passengers call the vehicle via a smart device. Therefore, knowing the number of passengers, the required power for heating and cooling of the cabin can be adjusted accordingly in advance. In a public transport scenario, it can be expected that passengers are wearing appropriate clothing for the prevailing climate. Thus, the cabin air temperature can be controlled to meet the specifications of the VDV Eco curve [13]. This curve is designed to allow battery electric vehicles in public transport to meet the required driving range.

Preliminary testing with a prototype of the data processing unit has shown that air-cooling of the central as well as graphical processing unit (CPU and GPU) is not sufficient. In the test a state of the art active air cooler with heat pipes and two fans was used on the CPU. The data processing unit was placed in a climate test chamber to simulate different ambient temperatures and was then subjected to a stress test, which put the CPU and GPU under 100 % load. Figure 5 shows the air inlet temperature at the enclosure of the data processing unit, the CPU die temperature as well as the CPU clock speed relative to the base clock speed. The CPU can raise its clock speed up to a factor of 1.4 under certain conditions. The temperature of the CPU die reaches the thermal limit of 68 °C shortly after starting the stress test; the CPU then regulates its clock speed to stay under this thermal limit. When the inlet air temperature at the enclosure increases, the clock speed is therefore reduced accordingly. Above 25 °C inlet air temperature the clock speed begins to fall and at around 35 °C the clock speed falls as low as 63 percent. Other tests have shown that above 40 °C the clock speed is reduced to a mere 18 percent and a further increase in temperature would lead to a shutdown of the system. This is unacceptable, because the processing power is needed for sensor data evaluation and a reduction in clock speed poses a safety hazard for vehicle operation. Autonomous driving functions rely heavily on the computing power of the data processing units, so it is imperative that the clock speeds stay in the optimal range. If temperatures inside the enclosure get to high, the power management of the processing units will lower their clock speeds until they shut off completely. Air temperatures in the range of 35 to 40 °C can be reached during vehicle operation in the summer under high solar flux, so a different cooling approach for the data processing units is required. Liquid cooling offers a much higher cooling capacity and is therefore chosen here.

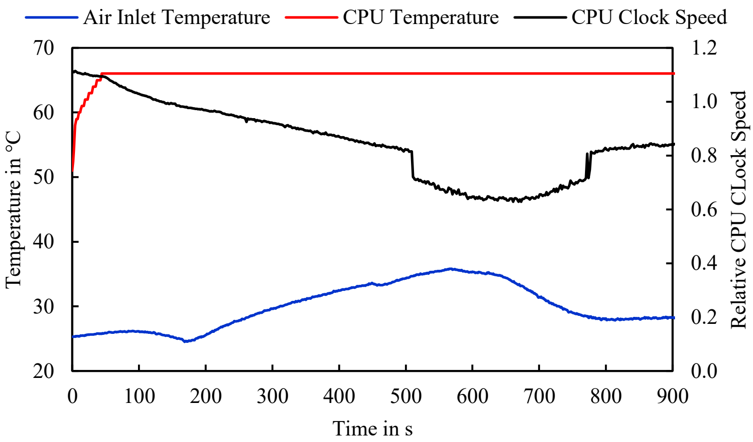

Figure 5: Thermal behavior of the data processing unit.

To use the heat of the sensor modules data processing unit as well as the cerebrum effectively during winter conditions, the control units' liquid cooling system is integrated into the main cooling circuit. This allows all generated heat to be combined in one cooling circuit, where it can be used for cabin heating. There are four sensor modules in every vehicle, each with a heat output of 1.2 kW under full load. The cerebrum generates about 0.8 kW of heat under load. Combined, this heat output could already be enough to heat up the cabin in the winter. Though the cooling circuit temperature level is not sufficient for direct use in the interior heater core, so to obtain the appropriate coolant temperature a heat pump is used. Due to the autonomous battery electric nature of the vehicle, the thermoelectric effect will be used within the heat pump. This avoids moving parts or additional refrigerant circuits. A three stage thermoelectric heat pump transfers heat between two main cooling circuits and the interior heating circuit. It uses peltier elements to transfer heat between liquid cooling plates and therefore is able to pump heat in both directions by inverting the current flow. The 48 V voltage level of the vehicle is used to supply the thermoelectric heat pump.

The planned cooling circuit topology of UNICAR*agil*'s thermal management concept is shown in figure 6. There are two main cooling circuits, one for the dynamic modules (DM) and one for the data processing units of the sensor modules (DPU) as well as cerebrum. Each dynamic module consists of the wheel hub motor and converter of the motor as well as the steering actuator converter, which are connected in series. Cooling fluid first enters the steering actuator converter, then the motor converter and finally the motor. This order is used due to the motor having the highest tolerable operating temperature and the steering actuator converter having the least heat output of the three components.

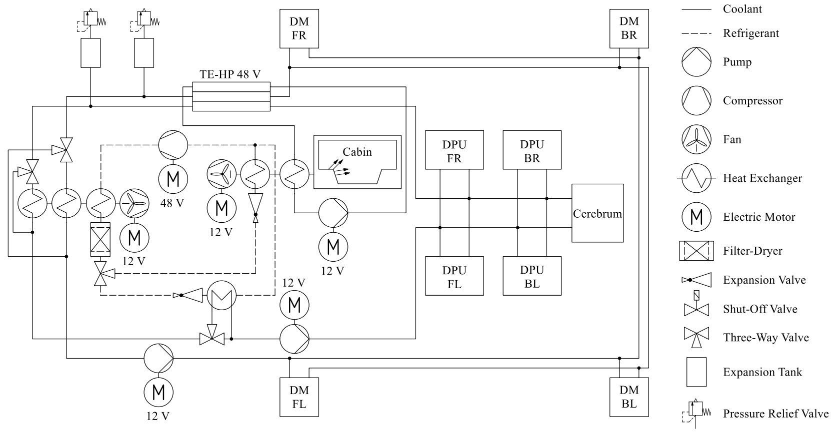

Figure 6: Cooling circuit topology of the thermal management concept.

Each cooling circuit has its own heat exchanger in the frontend of the vehicle. The cooling package can be bypassed using a three-way valve, which allows the heat to be kept in the loop for use within the interior heater core during winter conditions. For cooling and air conditioning of the vehicle cabin a refrigerant circuit with an electrical 48 V compressor is used. It has a second evaporator to condition the coolant in the sensor module data processing unit circuit. This chiller is used in case of high ambient temperatures and low driving speeds when the cooling capacity of the main cooling package is not sufficient to ensure safe vehicle operation. The thermoelectric heat pump (TE-HP) can also be used to transfer heat from the data processing unit circuit into the cooling circuit of the dynamic modules, which operates at a higher temperature level.

A 1D-simulation model of the shown cooling circuit, including the thermoelectric heat pump, is being developed in the multi-physics simulation software GT-SUITE. It is used to evaluate component requirements and to optimize the final topology considering different ambient conditions. All fluid circuits including the refrigerant circuit as well as HVAC module, air distribution system, cabin and thermoelectric heat pump are modeled. This holistic approach will later enable the model to be used for development of an efficient thermal management strategy by controlling of components. The resulting strategy will then be implemented in the vehicles using the two aforementioned services for thermal management and interior air conditioning running on the thermal management ECU. After integration into the vehicle prototypes, validation of results during vehicle operation will be possible.

5 Future Work

In the further course of the project, computational fluid dynamics (CFD) simulations of the interior will be carried out to determine the optimal position and design of air vents. Subsequently the final positioning of the air vents can be defined in collaboration with interior designers and the associated air ducts integrated into the CAD model. In addition, an efficient control strategy for the HVAC system with consideration of heating films integrated into interior panels can be developed. Thermal passenger comfort will be a key part of these simulations, which later will be validated using a thermal comfort manikin developed in the course of the project. The thermoelectric heat pump will be designed and manufactured for integration into the vehicles. Finally, four prototypes with the planned cooling concept will be assembled for testing of autonomous driving and demonstration purposes.

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Abbreviations

ASOA	Automotive Service-Oriented Architecture
BEV	Battery Electric Vehicle
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
DM	Dynamic Module
DPU	Data Processing Unit
ECU	Electronic Control Unit
FKFS	Research Institute of Automotive Engineering and Vehicle Engines Stuttgart
GPU	Graphics Processing Unit
HVAC	Heating, ventilation and air conditioning
IVK	Institute for Internal Combustion Engines and Automotive Engineering
LiDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
TE-HP	Thermoelectric Heat Pump

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