ROBOTIC ELECTRIC VEHICLE WITH CAMERA-BASED AUTONOMY APPROACH

Autonomous driving is increasingly attracting public interest due to various research projects over the past years. Usually, conventional cars are converted with significant effort and many different sensors are placed on the roof. The advance of electromobility provides the chance for completely new vehicle concepts. By breaking away from classic approaches, it is possible to consider and integrate autonomous driving into the vehicle architecture with respect to IT- and sensor systems, energy management and design. The Center for Robotic and Mechatronic of DLR describes all relevant technologies, being on board for autonomous driving.

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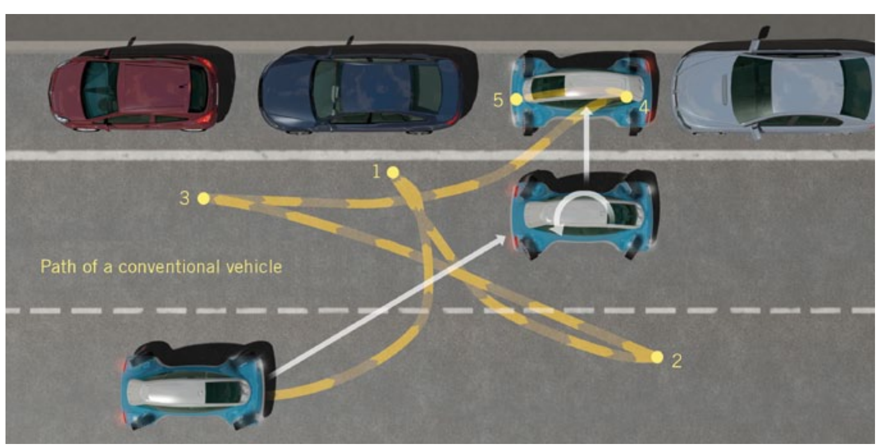
EXPERIMENTAL VEHICLE

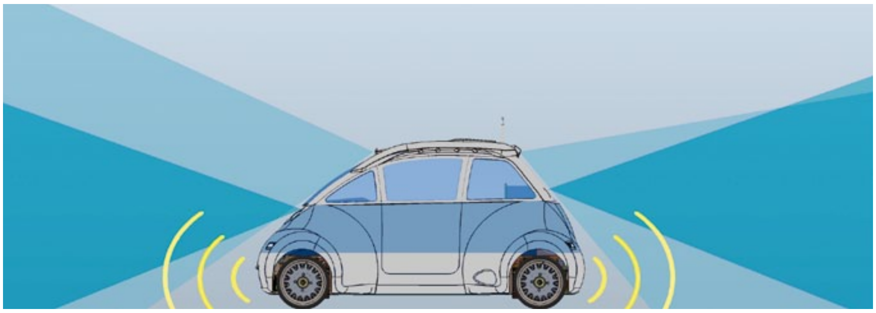
The Robomobil (Romo) is an innovative electromobility concept based on the intelligent central control of four-wheel robots, which integrate the drivetrain, brakes, steering mechanism and dampers. The electrically actuated drive-by-wire steering with components from robotics realizes steering angles of 95° to -25°. With this single wheel steering and drivetrain the Romo achieves an unmatched maneuverability. The Romo is able to rotate around its own vertical axis (centric and eccentric) or move sideward, ❶. Running the Romo with various degrees of autonomy, from shared to full autonomous driving, has been a main target from the beginning. It is irrelevant whether the vehicle is driven directly using a sidestick or from an external base station. The Romo's concept of four independent modules results in a high flexibility of the system. Hereby, the vehicle is composed of the front and rear chassis modules, the battery module and the body module with the central vehicle control unit. Each of them is easily changeable, as functionalities are locally grouped and interfaces, both mechanical and electrical, are provided. Besides autonomous driving, the Romo is used as a prototype for different research topics from vehicle dynamics control to energy management concepts. Similarly to modern robotics, the required control of the ten actuators is calculated in the chassis controller from a desired motion using a so called inverse dynamic model in real time. The Romo should demonstrate on different levels, how closely future electromobility will be connected to robotics.

BASICS OF AUTONOMOUS DRIVING

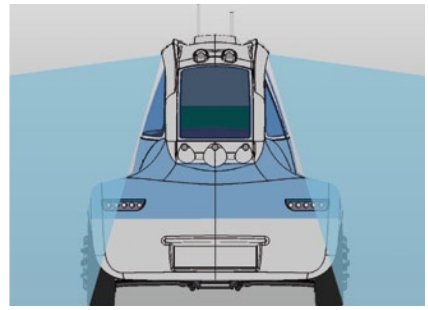
The basis of autonomous driving is perception. The extraordinary maneuverability of the vehicle results in increased requirements to sense the environment. In order to achieve 360° stereo camera coverage several cameras are integrated into the roof, front and rear, ❷ and ❸. The choice of passive optical systems as primary sensors will be discussed later in detail. Each camera is equipped with gigabit ethernet connectors and is linked to the vision PC in the trunk of the vehicle via network switches. Functional subsystems with separate physical data links to the vision pc are formed so that the huge amount of data of the uncompressed image stream can be handled. Each camera that is needed at a given time is activated by an intelligent scheme and all others are kept in standby. The Romo is mainly equipped with monochrome cameras, which are the best choice for image processing since they provide four times as many pixels compared to a color camera with the same chip size. Additional color cameras are installed in the front of the Romo to recognize, for example, the state of a traffic light. Despite an optimized camera positioning blind spots cannot be completely avoided, ②. A ring of conventional automotive ultrasound sensors is integrated to cover invisible areas close to the vehicle. The blind spots are only critical, if an object moves into the dead zone while the perception system is inactive and the Romo wants to move afterwards. For global orientation and determination of the six spatial degrees of freedom a dGPS-



❶ Romo maneuverability at parking



❷ Rear and front camera coverage and ultrasound



❸ Camera coverage left and right

aided inertial navigation system is used. A positioning accuracy of only a few centimeters is possible through the global positioning system with differential signal. Additionally, the system is equipped with a second GPS antenna in order to determine the orientation while stationary.

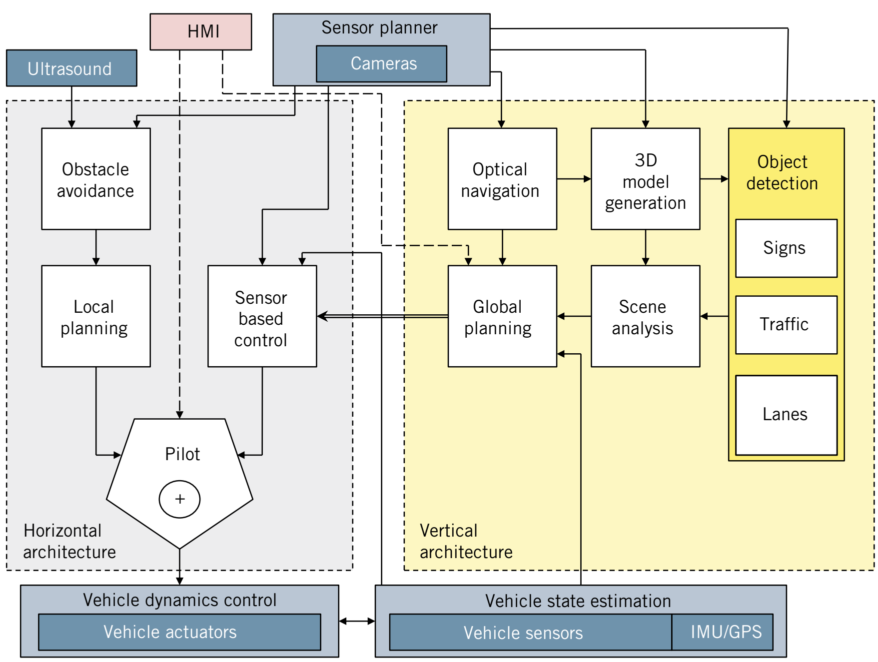
REASONS FOR CAMERA-BASED NAVIGATION

Nowadays intelligent mobile systems consist not only of sophisticated control systems, which make vehicle operation easier, but are taking over an increasingly active support function. The recognition of the environment by sensors becomes a central element that must provide a reliable perception regardless of adverse weather conditions. For choosing a sensor system, operational aspects like the necessary computing power for processing, reliability of data capturing at changing weather conditions, human safety, and possible mutual interference in the case of active measuring principles must be considered.

Laser and radar based systems are entering the new vehicle models, but they are based on active measurement principles, which could result in a harmful level of radiation for humans in the case of a malfunction. At the same time, active systems are more susceptible for mutual interference in situations where several sensors operate in the same environment, which will occur more often with steadily increasing traffic intensities. Another considerable aspect is the fact that such a system must, due to its operating principle, send out active signals to its environment, which definitely limits its maximum range.

An important aspect favoring the choice of cameras in a vehicle concept is the fact that current traffic routing systems are designed for a human driver and, therefore, for a visual perception and processing. Traffic signs and road markings should serve as an example, as they are optimized for the visual recognition of a driver and an interpretation of them via laser or radar is hard or even impossible. The reflectivity of road markings is distinguished at night according to an ISO standard, which favors the navigation in this difficult illumination for a camera system. Besides, new and more sensitive camera technologies blur the borders to night vision devices. The passive camera systems do not contain any moving parts, and this leads to a particular robustness against vibrations. They can be integrated in a space efficient manner in many parts of the vehicle and consume only sparse energy for operation. The passive character permits an extensively free determination of range, as no active signal has to lighten the scene.

Novel developments in the field of optical systems have led to an excellent comprehension of picture generation processes. Sensors that can yield information over a wide angular range concurrently are used. This is essential in the case of a vehicle moving at a high velocity in a scene with many independently moving objects in order to capture the temporal context properly. The high integration levels of cameras allow a very exact sampling of the environment even in large distances from the vehicle. The resolution is only determined by the spatial offset of the camera during the measurement, which



❹ Autonomy architecture Romo

can be chosen independently of the vehicle motion to a large extent. The only limiting factor is the available computing power. This is a question of efficient algorithms to achieve the required reliability and quality of perception with a constricted computing power. The developed sensor concept demonstrates the performance, which can be achieved with current processing algorithms.

SYSTEMS ARCHITECTURE

Autonomous driving should be realized by a scheme based on the combination of two fundamental different architectures, ❹. Rodney A. Brooks from the MIT introduced already in the 1980s the distinction into a vertically and a horizontally arranged architecture for calculating actuator commands from sensor values [1], ❺. In a vertically oriented architecture several modules have to be sequentially passed through to execute an action. In a horizontal arrangement several modules, functionally subdivided, are executed parallel. The main feature of the vertically arranged part of the Romo autonomy scheme is the accumulation of sensor data. Data is collected and processed over multiple time-steps and an environment map is generated. Thus, it is tried to provide a long-term planning of autonomous actions. Only data from the last few time-steps is analyzed in the horizontal part of the scheme in order to ensure a fast short-term planning and a reactive behavior. Normally, autonomous vehicles are based on conventional cars that are rebuilt. Hence, a vertical hierarchical configuration must be chosen, as the direct reach-through from sensors to actuators is not possible. This architecture is equivalent to the yellow part of the scheme in ④, which can be realized on an arbitrary vehicle. The sequence of tasks in the vertical part of the scheme is explained at first in detail.

The cameras, designated for autonomous driving, are activated adaptively to the current situation by a sensor planner. A 3D model of the environment is reconstructed from the active pair of stereo cameras. It is important to know the motion in the three dimensional space, for 3D modelling and for other purposes. The optical navigation module obtains information about the six degrees of freedom purely based on camera data.

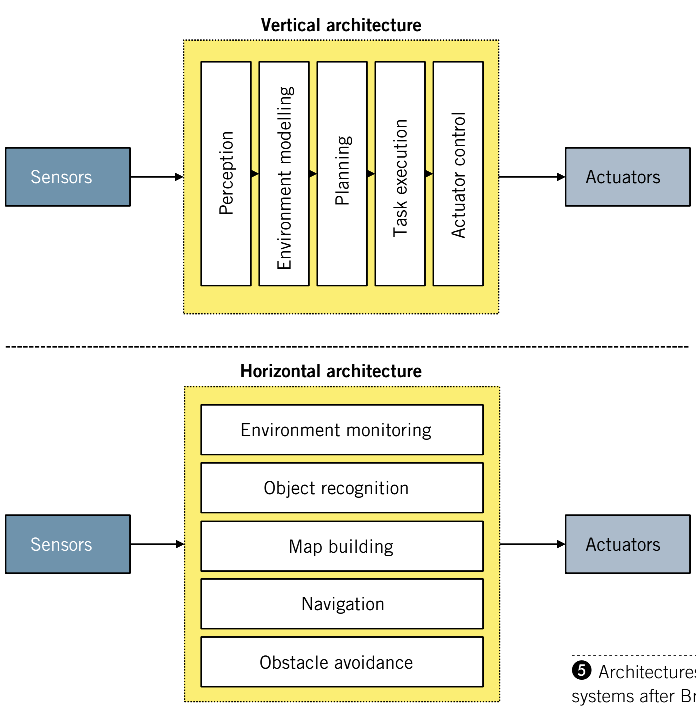
Thereupon, relevant objects must be detected in the reconstructed 3D data and the two dimensional camera data. In order to do so, individual algorithms are needed for the detection of traffic, lanes, and road signs, as the single components vary significantly in their properties. After those are correctly identified, they have to be interpreted accurately in the context of the scene, in order to provide a rule-compliant behavior in the given traffic situation.

Subsequently, the behavior of the Romo is planned for multiple steps in advance in the global planning module based on the data from the scene analyzer, the vehicle state estimation, and the optical navigation. For this a certain task, e.g. searching for a parking lot with subsequent parking, is decomposed into multiple subtasks. The whole process is based on the internal map that is generated and consistently updated according to current and past sensor data. Thus, a certain time elapses before a reaction to a sudden change in the environment can happen.

The Romo concept provides the realization of a fast reactive behavior according to a horizontal architecture. In contrast to the previously described transferable part, the reactive part that will be described now is vehicle specific and depends on a fast communication within in the vehicle system. The sensor based control module in the reactive part of the scheme, which is colored grey in ④, receives certain sub goals which it must achieve. However, the control does not depend on a generated 3D map, but is rather based solely on camera data and vehicle states, which are obtained in the vehicle state estimation module by the fusion of different sensors. The sub goals are merely given by the global planning module in the form of required positions of features in the picture and the controller tries to move the vehicle so that the features are located on their desired positions in the camera picture.

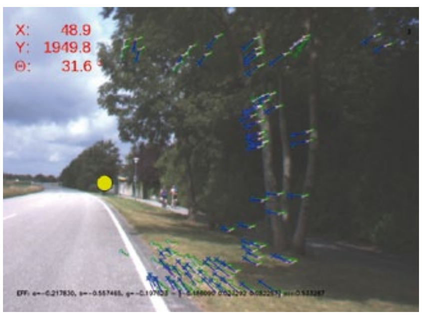
The respective obstacle avoidance module is fed on the one hand by pictures from the currently relevant camera and on the other hand by the ultrasound sensors, as a virtual bumper, in order to detect quickly undesired objects lying on Romo's route. After that a local planning module calculates the required action for the next few time-steps to avoid the obstacle without using the detailed and slow map of the vertical oriented part, in order to ensure a fast reactive behavior.

The pilot module combines the trajectory requests from the sensor based control and the local planning module to ensure that the global goal will be reached concurrently with obstacle avoidance. The motion demands from the autonomous control are passed by the pilot module to the vehicle



❺ Architectures of autonomous systems after Brooks

❻ Depths-reconstruction from binocular stereo (Figure: Daimler AG)



❼ Optical navigation

dynamics control. This part controls the ten individual braking, steering, and drivetrain actuators to keep the desired path. A close information exchange with the vehicle state estimation supports the vehicle dynamics control at this task.

The designated Human-Machine-Interface (HMI) module provides different possibilities for human interventions to the autonomy scheme. In the fully autonomous driving mode the HMI can set the mission goals of the global planner. The coupling of the HMI with the autonomy scheme is particularly close in the shared-autonomy mode, which will be described in detail later.

EXPERIENCES WITH THE IMAGE DATA PROCESSING MODULES

The introduced autonomy modules of the Romo use proven methods of sensor data preprocessing, which are already applied in several DLR projects. The system can rely on robust depth-reconstruction, optical navigation and detection of movable objects, from which a safe behavior can be derived.

A safe navigation, especially in city traffic and parking lot scenarios, is ensured by the binocular system of the Romo. All objects not lying on street level are color-coded depending on their distance, ❻. This information can be used for trajectory planning. The method used for stereo processing is called "Semi-Global Matching" (SGM), which was developed at the Robotics and Mechatronics Center of the DLR [2] and will also be used in future cars from Daimler. The vehicle has the choice of two different distances between the cameras in order to obtain sufficient sensor accuracy in different fields of range (parking lot/city or highway).

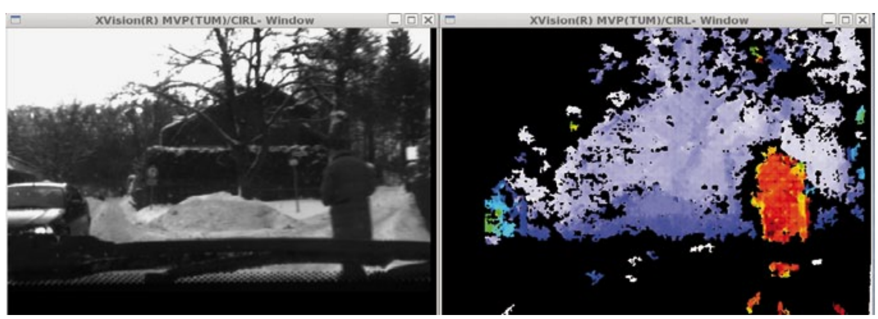
The optical navigation unit is a picture-based tracking system (Zinf) [3], which determines firstly the rotational information between two pictures in a temporal picture series to detect subsequently the direction and absolute value of the motion together with an additional tolerance for the current navigation result. The direction of motion is depicted as a yellow circle in picture, ❼, which is the intersection of the resulting flow vectors. The information can be used on the one hand for the integration of path information and on the other hand for the determination of the reference flow of the optical flow vectors, which are utilized for the detection of moving objects in the vehicle's surroundings, as described below.

The depth-information from the stereo system can be supplemented by a temporal picture series, which provides a robust detection of objects, ❽, that are in a critical distance to the vehicle and are themselves in motion. Their motions are determined by the deviation from the reference vector field, which was already calculated by the optical navigation unit.

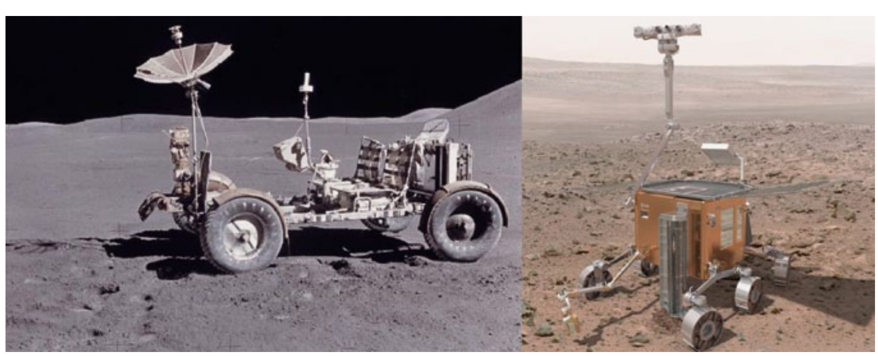
OUTLOOK

Partial autonomy ("shared autonomy"), which is propagated in space robotics since a long time and has been demonstrated by the DLR several times, means that the human operator expresses a raw demand that is refined subsequently by the subordinate autonomous system on its own. In contrast to assisting systems the user cannot reach the system directly. Therefore, the Romo is capable of refusing to cause an accident.

The Romo concept is strongly influenced by the DLR center's work on space



❽ Motion-estimation based on optical flow



❾ Apollo moon car und European Mars rover

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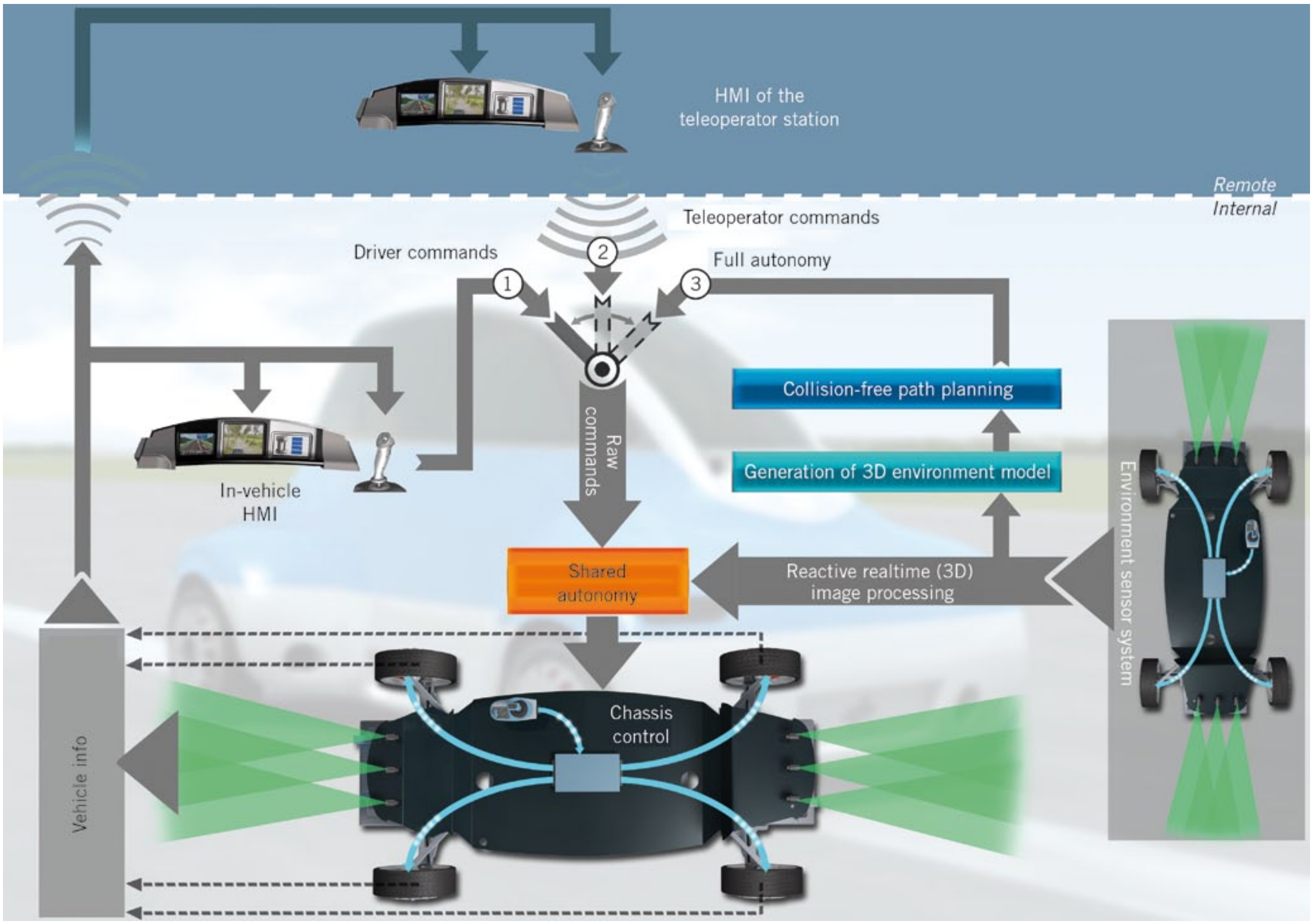

❿ The three main operation modes of Romo

robotics and planetary rovers like the contribution to the development of the first European Mars rover ExoMars, which should land on Mars 2018. This rover features single wheel drive and steering, so that it presents in a way an advancement of the Apollo moon car that was already equipped with wheel hub motors, thus single wheel drive, and sidestick control, ❾. The three main operation modes also emphasize the link to space technology, ❿:

- fully autonomous driving
- remote control with shared autonomy
- direct control by a driver with shared autonomy.

The technologies that are to be optimized with high priority, like the chassis control concept with vehicle dynamics control based on inverse dynamic models and the collision-free motion control by a FPGA implementation of the new SGM stereo algorithms, should be used in future developments of moon rovers. The optimizations of the HMI and of the energy management, which may be achieved through the highly accurate 3D landscape models from the institute, are further focuses in the near future. Moreover, we will focus on extensive road tests in three aimed fields of application:

- civil protection and emergency management
- logistics (factory buildings)
- megacities with flexible car sharing.

As mentioned before, the integration of sensors into a vehicle concept requires a connection not only on the abstract hierarchy level of mission planning, which can often be seen in projects with conventional vehicles. An interaction with the sensor must also take place on lower levels of the vehicle control. The proposed sensor concept of the Romo system shows how sensor data can be integrated in the vehicle system on different abstraction levels.

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