Enhancing Mobility Using Innovative Technologies and Highly Flexible Autonomous Vehicles

Timo Birnschein, Christian Oekermann, Mehmed Yüksel, Benjamin Girault, Roman Szczuka, David Grünwald, Sven Kroffke, Mohammed Ahmed, Yong-Ho Yoo and Frank Kirchner

Abstract. The combination of automobiles and typical robotic technologies such as high computational power, advanced exteroceptive sensors, and complex control algorithms can lead to a new kind of mobility. Features like extended maneuverability, autonomous driving systems, and new safety features become imaginable. To create the best combination of both fields, a new design philosophy is required. At DFKI, we have developed two generations of innovative concept cars (EO smart connecting car 1 and 2) with the intention to build the bridge between robotics and cars. The development of key parts like suspension, drivetrain, electrical steering, and braking system is more interconnected than in conventional vehicles. In this paper, we describe the development process of EO smart connecting car 2 - a highly innovative and fully functional robotic electric vehicle with double Ackermann steering, the ability to turn on the spot, go sideways, drive diagonally, change ride height, and shrink by adjusting the position of its

---

T. Birnschein(✉) · C. Oekermann · M. Yüksel · B. Girault · R. Szczuka ·
D. Grünwald · S. Kroffke · M. Ahmed · Y.-H. Yoo · F. Kirchner
German Research Center for Artificial Intelligence,
DFKI GmbH - Robotics Innovation Center,
Robert-Hooke-Straße 5, 28359, Bremen, Germany
e-mail: {timo.birnschein,christian.oekermann,mehmed.yueksel,genjamin.girault,
roman.szczuka,david.gruenwald,mohammed.ahmed,Yong-Ho.Yoo}@dfki.de,
sven.kroffke@uni-bremen.de

F. Kirchner
DFKI GmbH - Robotics Innovation Center,
Department of Mathematics and Computer Science, University of Bremen
Robert-Hooke-Straße 1, 28359, Bremen, Germany
e-mail: frank.kirchner@dfki.de
http://www.dfki.de/robotik

J. Fischer-Wolfarth and G. Meyer (eds.), *Advanced Microsystems for Automotive Applications 2014*, Lecture Notes in Mobility,
DOI: 10.1007/978-3-319-08087-1_5, © Springer International Publishing Switzerland 2014

rear axle and tilting the cabin as well as docking at charging stations and extension modules. Detailed information of the utilization of Rapid Control Prototyping, and optimization strategies will be given as well as the design constraints for these technologies. Finally, the conclusion section will cover problems and challenges that had to be overcome and future work that will follow.

Keywords: Electric Vehicle, Autonomy, Artificial Intelligence, Drive by Wire, Hardware-in-the-loop, Software-in-the-loop, real-time control, path following, simulation, construction.

1 Introduction

Today's market of electric vehicles is still in a very early stage. For many car manufacturers it is a leap of faith when they actually start developing a completely new chassis around the electric power system - which is why most of them don't do it. Instead, most electric or partly electric (hybrid) vehicles are refits of their combustion engine driven models. This reduces financial risk and increases the chance of the models success - but not specifically the e-models success.

Truth is, cars don't evolve the way they could when designed completely around the fully flexible electric drive and battery system. Unlike e-cars that are based on a combustion driven model, a completely new design is not restricted by axels, gearbox position, differentials, main engine, and the gas tank. Instead, motors can be integrated into a wheel, motor controllers can be anywhere in the car and, for more stability, batteries help to get the center of gravity as close to the ground as possible. What can we do with this new category of flexibility in design? We can start from scratch and build a car that does not follow the rules everybody is used to for the last 125 years. Instead, we can build a car that is able to turn on the spot, go sideways and drive diagonally as well as change its ride height. We can even shrink the car because there is no need for lengthy solid parts running through the middle of the car because there is neither an exhaust system nor a center drive shaft.

Here at DFKI - Bremen we therefore decided to go the unknown and complex path of creating a completely new, fully electric vehicle with all of these features plus the ability to automatically dock at power outlets and autonomously drive in a virtual road train configuration: EO smart connecting car 1 and 2 (EOscc1 and 2).

This concept, realized in an actual fully functional and well-made concept car, is the basis for a new mobility concept of cars parking themselves at power outlets of regular parking spaces, automatically picking up passengers at their front door or drive in large platoons of road train driving cars on the highway or inside of big cities. This helps releasing the tension of heavy traffic today, reduces rush-hour traffic and enhances energy efficiency by having a smoother ride and the slipstream of other drivers without compromising safety.

The project started in October 2011 following the initial design of “EOscc1” (see [1] for a comprehensive state of art). The goal of optimizing this car and building a successor was a tricky and hard task considering the projects runtime of just 30 months.

Fig. 1 Folding EOscc2 for reduced parking space and higher maneuverability

After thoroughly reviewing the cars features as well as construction and its pros and cons we decided to remove some features and change major design decisions. The core decisions that were made in the process, are:

- Solid but light weight construction
- Wheel hub motors with integrated brakes
- Secure CAN-bus communication for all control units
- Simplified construction of major chassis and body parts
- Multiple sensors for autonomous parking and driving as well as comprehensive telemetry
- Docking interface for autonomous charging

After building the technology prototype EOscc1 in just twelve month with additional six month of software development and debugging the schedule for the development of EOscc2 was tight. Thanks to the deployed RCP system for hardware as well as software in the loop development, development of control algorithms, CAN-protocols and graphical user interfaces could be started immediately, even without the target hardware.

2 Designing a Robotic Car

Nowadays, most modern cars can be interfaced with a computer to control the car replacing the driver, but only for development or science purposes. A car for individual transportation usually is a front, rear, or all wheel drive vehicle with an electro-mechanical or hydraulic-mechanical steering and a direct link between the steering wheel and the tires.

EOscc2 is designed with the opposite approach. It is a car with all-wheel drive electric wheel hub motors, electrical servo motors directly controlling each of the four wheels individually and no mechanical link to any of the controlling systems, except for the hydraulic brake - for safety reasons. Every system is exclusively controlled by a computer and the driver may override the computer while driving manually. In normal manual drive mode, the car almost behaves like a regular car, except that four wheel steering is slowly activated at lower cornering speeds. It is also possible to turn on the spot, drive sideways into a parking space, and shrink the cars' length by 80 cm to safe even more parking space. In automatic drive mode it can move diagonally to change lanes, it can drive around corners sideways and park autonomously using sensors that are positioned all around the cars body. The car can also dock at charging stations. Basically, it is a wheeled mobile robot with two comfortable seats and a steering wheel as well as a gas and brake pedal.

When designing a car that has independent four wheel steering with a maximum steering angle of 92° as well as folding capabilities to shrink its size, designing an attractive body is a very challenging task. Big industrial manufacturers have many people working on different body parts, design, prototypes, clay models and final CAD construction using specialized software. The same is true for electronics, software, chassis construction, docking interface and wheel suspension. At DFKI the team working on the car contained between seven and 13 motivated scientists. A designer, two constructing engineers, two software engineers, an electronics engineer, a simulation engineer, and the project manager/software engineer as well as two students. A small team like this has to concentrate on all topics at the same time. In consequence, parallel and interconnected development was key and unavoidable as well as using as many readily available components as possible. Unfortunately, the latter didn't work out as planned as can be seen in the electronics chapter, later.

In the following chapters different design areas are described in more detail giving insights into the development as well as problems and challenges that the team dealt with during the last 27 month.

3 X by Wire Suspension

Technically, for an electric vehicle with wheel hub motors, the suspension system including the motors is the most important part.

Since EOscc2 uses four wheel drive as well as four wheel steering new motors with built-in brakes had to be designed to be used with standard rims. It was important that the motor mount and the kingpin lies inside of (or very close to) the motor and therefore close to the middle of the tires' contact area. This minimizes the scrub radius and therefore the necessary steering forces during turn, acceleration and braking. A 90° steering angle also requires the kingpin to be straight up vertical - otherwise the tire would tilt when going sideways. It also requires a solution for the steering mechanism so that the steering knuckle cannot lock-up with the steering gear in a force singularity when steering into the extreme positions. The steering knuckle is equipped with a complex innovative link mechanism (see fig. 2) to provide an almost linear force distribution throughout the unusually wide steering range of 122 degrees. Position and length of these links was determined using genetic algorithms within a precise computer simulation [2].

A double wishbone setup with two electric servo motors to control the steering angle and ride height was constructed as a module for each wheel in a symmetrical setup. Both servos utilize a worm-gear in combination with a spindle drive to create fast and powerful linear movement and are controlled using a CAN-bus. The lower mounting point of the shocks is connected to the wishbone; the upper one is connected to a movable support link and the spindle. This way, force from the cars' weight and bumps is only coaxially applied to spindle (see fig. 2 for details). These modules are then attached to a lightweight central axle housing in the front and at the back which protects electromechanical parts and also connects the axles to the chassis. Additionally, the center housing provides space and mounting points for the foldable docking interface.

Fig. 2 Shock absorber connected to ride height changing spindle and the new motor housing

At the same time, CAD design began on the construction of the BLDC motors. As a starting point, E-Max scooter wheel hub motors from Proud Eagle International ltd were disassembled and equipped with a new housing. The required internal mechanical brake as well as the constraint to be able to mount standard rims lead to a complete redesign of the motor housing (fig. 2), while the motor windings, hall sensors, and magnets remained untouched. The resulting motor is a compact direct drive 4 kW out-runner motor with internal brakes that fits into a 15" rim with its attachment flange inside of the rim.

4 Docking Interface

As advised from the requirements the car has to be able to dock at power outlets and drive with extension modules in a road train. Designing an invisible docking interface for an electric car is difficult because of its requirements:

- Foldable and invisible within the body
- Damping mechanism to absorb shocks
- Play free and stiff connection
- Strong enough to pull a car
- Provides communication and high current lines for charging.

Since the front tires of the car are further in front of the car than the front bumper, the docking interface has to be even longer when it is unfolded so that an extension module or another car can be docked while the car is making turns, similar to a regular drawbar of a trailer. Due to the very confined space, simply folding the docking mechanism was not enough. Hence, we designed an interface that can be elongated while unfolding. The designed mechanism also includes a shock absorber which is integrated into the elongation mechanism (fig 3).

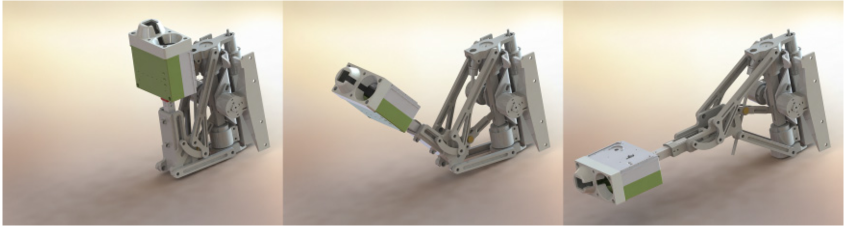

Fig. 3 EOscc2 Docking Interface in different folding positions

5 Morphological Chassis

Designing a chassis for a car with the ability to go sideways and change its size is a complex challenge - the same is true for the body design, as explained later. The cars' size was supposed to be roughly the size of EOscc1 which in turn is roughly the size of an older MC01 Smart ForTwo with a wheelbase of ~1800 mm when unfolded. When folded, EOscc2 shall reduce its size by 80 cm without compromising usability, except for the maximum allowed speed. A completely new tube frame chassis was designed with attachment points at the front for the axle. The rear was equipped with a rail system to provide the axle with a mechanical guide when sliding to the front while folding the car. During folding neither the front nor the rear axle changes its rotation relative to the road surface, therefore, except for the wheelbase, none of the steering parameters change (fig. 1). The rotation of the front axle is realized using a servo actuator.

The frame itself is built using welded 25CrMo4 steel tubes that were CNC cut and CNC bent with high accuracy. All joints were strengthened using welded triangles, more statically loaded parts are made out of thicker material with larger diameter. The chassis offers many mounting points for lights, body panels, electronics, seatbelts, seats, sensors, and so on.

6 Body Design

Similar to the chassis design, the body has to fulfill the same requirements and is therefore very restricted in terms of length as well as front and rear design caused by the 92° steering and the docking interface. From very early on, it was decided that the tires shall not be covered up by the body and have individual fenders instead. While in the car, the driver must have the best possible overview over the surroundings to be able to safely navigate through dense traffic which led to a massive windscreen going from the headlights right onto the roof. This also helps when driving in the folded pose. To enter and to leave the car without using additional space, the car is equipped with scissor style doors that rotate around the front wheel center which works perfectly in both poses. In order to maintain an ergonomic seat position at any cabin inclination angle the seats are mounted on a mechanism that varies the seats pitch and position. In both positions, all controls need to be reachable without a stretch, especially the steering wheel, both gas and brake pedal, as well as the drive mode selector and the manual hand brake. The seat mounting plate therefore utilizes an additional actuator with a spindle drive to move.

Since the rechargeable batteries are swappable a hatch was needed near the door sill under the car to be able to slide them in and out.

Figure 1 showcases the final design of the body shell which was fabricated using CNC milled molds for each panel and glass fiber. Finally, the finished part will be laminated to the chassis where necessary using specially shaped frames.

7 Electronics and Sensors

Within the project, a set of electronic control units has been developed to support and control all the necessary actuators, motors, sensors, and batteries in the car. Namely, these are:

- Vehicle Control Unit (VCU)
- Peripheral Control Unit PCU)
- Power Supply Unit (PSU)
- Analog Sensor Array (ASA)
- High Current Battery Management System (BMS)
- High Current Solid State Relay (SSR)
- High Current Ultra Cap Charger (UCC).

The VCU acts as the main controller. In the final stage, there will be three VCUs comparing results of calculations to rule out any possible error and improving safety for the drive by wire system. It is equipped with five CAN bus drivers, three of which are realized using additional CAN controllers, the two main busses are driven directly using two internal CAN controllers of the STM32F4 microcontroller. The VCU, as well as the PCU and PSU, also provides an extension interface to connect several analog and digital signals directly to the board.

To control all peripheral units such as the ASA boards, lights, and SSRs, the PCU is connected to the VCU via low speed CAN bus. It also communicates with the ASA board via RS485 and collects all its sensor information from front and rear axle. Two ASA boards are integrated into the axles housing themselves to be as close as possible to the analog sensors of the suspension system. Shielded wires needed to be used on these sensors because EM radiation from high current switching of the motor controllers became visible on the sensor feedback data. Each axle module contains two of each sensor: linear potentiometer for wishbone angle, rotatory sensor for lift actuator position, rotatory sensor for steering angle.

In the front part of the main chassis, covered by the dashboard, an electronics rack contains power electronics and control systems. Two motor controllers, two SSRs, a VCU, PCU, and PSU, a high power DC/DC converter and a high as well as a low current fuse box are bolted into place. The SSR is an additional safety device which works in series with a mechanical high current Schuetz-relay.

Each of the four battery packs contains four $LiFePo_4$ rechargeable batteries and a complex battery management system. The BMS is able to balance the packs under load with a maximum current of five amps. It was developed with the need for CAN-communication and active high current balancing with the additional option to switch itself off completely. This way, the battery cannot discharge itself by just balancing. In addition to the master-slave communication and safety features it also supports active balancing from cell to cell to further enhance efficiency.

When braking with an electric vehicle, like with a conventional vehicle, energy is wasted by heating up the brakes. Some electric cars support recuperative braking where a small part of the kinetic energy of the car is fed back into the batteries. However, this technique is limited in several ways, like the maximum C-rating for charging a battery and the maximum capacity of the system as well as the number of available recharge cycles. For example, our battery system can be charged with 100 A current. While normal braking from 75kp/h (~ 47mph) the car produces almost 790 A. This process can lead to the destruction of the batteries molecular structure and is dangerous for the battery module and its ability to store energy. A stronger system with the ability to store energy with a much higher current was needed, so we decided to design an UltraCapCharger. Four of these modules where integrated and tested. Connecting these in parallel results in 650 A brake current available for four seconds. This energy almost completely bypasses the vehicles batteries and is stored into high current capacitors instead and can be used for acceleration.

8 Software and Hardware in the Loop

A drive by wire car of this complexity needs a safe and free of bugs software (ISO 26262 - *Functional Safety*). In addition, debugging should be easy and comfortable. To accomplish this, we implemented a development environment that includes several hardware and software components based on RCP and backed with precise and detailed simulation tools. Every component of the control process could therefore be designed and implemented within this environment (for further details check M.Yüksel et al. [3]). We built a functional test platform for EOscc2 named SujeeCar. Basically, it is made of a chassis equipped with most of the final electronics and actuators to make it fully drivable, hence, all available hardware and software in the loop. Graphical user interfaces were designed and used for data logging and online display of telemetry data. To enhance productivity, RCP tools offer several ways to visualize available data like graphs, gauges, sliders and numbers, all of which can be added and removed during runtime making it easy to perform online experiments. Next in the process, all of the developed control models were implemented into the VCU. With its five CAN busses and a faster main loop frequency, especially with operating system out of the way, all required drive modes, kinematic calculations and user interface functions could be implemented efficiently and fast.

9 Simulation

Our simulation environment (e.g. Adams/View, Matlab Simulink, and Mars Simulation) is used to simulate, optimize and build extremely complex robots and cars as well as combinations of the two in a relatively short time. Within this project, simulation was used to evaluate the dynamic properties of the design, implement and test path and motion planning algorithms based on 3D-maps scanned from the test environment. Also, it was used to optimize the links for the steering mechanics. To accomplish the required wide steering range (-32° up to 92°), an innovative steering mechanism was constructed. This mechanism is designed to minimize the steering forces and to attain almost linear forces. Evolutionary algorithms where used to optimize the link length and mounting. Additionally, all forces for spring rates, steering, ride height, and folding could be estimated to define the necessary gears and servo motors (further details can be found in Ahmed et al. [2]).

10 Conclusion

In this paper, we presented a comprehensive overview of the development of EOscc2, the second generation EOscc, with the ability to turn on the spot, drive sideways, diagonally, normal, to shrink in size to save parking, space and a foldable docking interface.

Later, the car will be able to drive autonomously, search for parking spaces and will be able to dock to charging stations. During development, several problems had to be overcome. Most of these problems were solved with interdependent and modular design. While conventional car design starts with the design first and build the chassis afterwards – or vice versa – our modules were built simultaneously to reach the functionality and the looks on time. During specification phase it was advised to include as many of-the-shelf components as possible to minimize development effort and get faster results. Unfortunately, this turned out to be a naive approach because not even wheel hub motors with integrated brakes to be used with standard car rims were available on the market, not to mention force feedback steering wheels with a CAN interface or simple low force - high current connectors for a possible docking interface. For this reason, most of the EOscc2 components were designed and implemented from scratch.

At present, the final assembly of the car takes place and will be finished within the next three months. After several experiments with a test platform and the two fully functional axles we are confident that no major problems will occur and we can finalize the project on budget and on time.

Acknowledgement. The authors would like to thank the whole EO smart connecting car team for their incredible work, motivation, imagination and willpower. In addition, Janosch Machowinski, Pierre Willenbrock, Sujeef Shanmugalingam, and Robert Thiel supported and enriched the project to bring the vision to life. This project is funded by the German Federal Ministry of Transport, Building and Urban Development. The program coordination is carried out by the NOW GmbH National Organization Hydrogen and Fuel Cell Technology (Grant Nr. 03ME0400G).

References

[1] Birnschein, T., Kirchner, F., Girault, B., Yueksel, M., Machowinski, J.: An innovative, comprehensive concept for energy efficient electric mobility - eo smart connecting car. In: IEEE International Energy Conference and Exhibition (EnergyCon-2012), Towards User-Centric Smart Systems, Florence, Italy, pp. 1028–1033 (September 9, 2012)

[2] Ahmed, M., Oekermann, C., Kirchner, F.: Simulation environment for mechanical design optimization with evolutionary algorithms. In: World Symposium on Computer Applications & Research WSCAR 2014, International Conference on Artificial Intelligence (ICAI 2014), Sousse, Tunisia, January 18-20. IEEE (2014)

[3] Yüksel, M., Ahmed, M., Girault, G., Birnschein, T., Kirchner, F.: A Framework for Design, Test and Validation of Electric Car Modules. In: Fischer-Wolfarth, J., Meyer, G. (eds.) Advanced Microsystems for Automotive Applications 2014 – Smart Systems for Safe, Clean and Automated Vehicles (AMAA 2014). Lecture Notes in Mobility. Springer (2014)