# The Innotruck Case Study on A Holistic Approach to Electric Mobility

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**Abstract** We present an interdisciplinary approach to electric mobility based on three main research areas: Energy Management, System Architecture and Human–Machine Interface. A flexible energy management model is developed to suit the needs of arbitrary aggregated configurations in different hybrid vehicles. Our modular and data-centric vehicle ICT architecture reduces communication overhead, while addressing component plug-and-play and automotive safety. The classical human–machine interface is extended with a highly integrated HMI module which analyzes the interaction context. A drive-by-wire hybrid vehicle prototype has been constructed, the Innotruck, which serves as both testing ground for the developed concepts and a presentation area for communicating the results to public. Emphasis is placed on the societal importance of our work, impact and dissemination of results. More than 20 industry and research partners contribute directly to the project and the further development of the prototype vehicle.

## 1 Introduction

The presented work is the summarized result of the project Diesel Reloaded, organized by the Institute for Advanced Study (IAS) and the International Graduate School of Science and Engineering (IGSSE) of the Technische Universität München,

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together with the industry partner Siemens AG. The project started in 2011 and is led by Prof. Dr.-Ing. Gernot Spiegelberg, a Rudolf Diesel Senior Industry Fellow at the IAS and the head of concept development for electric mobility at Siemens Corporate Technology. The principal investigators are Prof. Dr.-Ing. habil. Alois Knoll from the Chair for Robotics and Embedded Systems and Prof. Dr.-Ing. Markus Lienkamp, from the Chair for Automotive Engineering. Three doctoral candidates are active in three research areas. Dipl.-Ing. Claudia Buitkamp is responsible for the vehicle's energy management. Ljubo Mercep, M.Sc. is working in the field of human–machine interfaces. Dipl.-Ing. Hauke Stähle is developing the system architecture. The interdisciplinary approach is focused on three different aspects of electric mobility: business models, enabling technologies and communication of science to public.

## 2 The Innotruck

The Innotruck is our scientific prototype and the project demonstrator at the same time. It is a hybrid diesel-electric drive-by-wire truck with a bionic design from Prof. Luigi Colani. Observing it from the outside, three basic segments can be identified: The self-contained drivetrain, the large semitrailer and the trailer. The semitrailer is internally composed out of three functional segments: Driver's workplace, business lounge and presentation area. The driver's workplace features a highly integrated human–machine interface consisting of a driver's seat with two spherical sidesticks and a central console with the virtual dashboard. The business lounge is outfitted with ambient lighting control and presentation displays. The presentation area is equipped with four large interactive presentation displays (Fig. 1).

**Fig. 1** The innotruck at the Hannover Messe 2012

# 3 Energy Management

Within the Innotruck there are many different electric sinks and sources. Sinks are defined as components that use electrical energy to fulfill their functionality, whereas sources are components which convert power of another form into electrical power. Every component has an energy interface to the electrical intermediate circuit. Furthermore there are components, like the battery, which can be both, a sink and a source. The following table gives an overview of the main sources, sinks, and source/sinks.

| Sources | Sinks | Source/sinks |
|---|---|---|
| Range extender | Compressor | Li-Ione battery |
| Solar panels | Steering pump | Electric motor |
| Wind power | Air conditioning | Eight electrical cars |
| | Lights, navigation… | External power net |

## *3.1 Necessity of an Energy Management*

Depending on the driver wish, the electrical motor is a sink, while driving, and a source while braking and recuperating. Because of the series hybrid configuration, the electrical motor can use the electrical power of two different possible sources, the battery and the range extender with a diesel engine and a generator. Therefore the state of the battery (charging or discharging) and the range extender do not depend on the driver wish and have to be defined by the electrical energy management. Additionally solar panels on the roof provide electrical power and sinks like the air compressor, the steering pump and the air conditioning have to be supplied.

While standing still, the Innotruck can be considered as a smart grid. In this mode, wind power can also be harnessed. Furthermore, up to eight electric cars can be charged by the truck or they can charge the truck's battery and supply its auxiliaries. The truck is also connected to the external power net, to gain power of it or to feed in power.

As shown, depending on the mode of the truck (driving/standing still) different sources provide power and different sinks have to gain it. The electrical energy management is therefore needed to determine the state of each component, i.e. determine the amount of energy each source has to provide and each sink will gain. It has to assure that safety critical sinks are supplied with sufficient power at all times and all sources can be activated by a start-up process. For instance, if the engine-generator unit was turned off in a series hybrid vehicle, the battery should always be sufficiently charged to restart it. Furthermore operating limits of the components should never be exceeded.

## 3.2 *Flexible Energy Management*

During the project a flexible energy management, which allows adding and removing different numbers and characteristics of sources and sinks, has been developed (Buitkamp 2013). It is built on a market based approach, where sources and sinks trade electrical energy within the energy management unit. Every energy component tells the energy management, via a cost-power function, its operating costs for electrical power in case of a source, or its priority to be supplied in case of a sink. Components, which can be source and sink, provide two cost-power functions. Every cost-power function takes the operating limits into account. These functions are used by the energy management to calculate the market price and determine the amount of energy each component has to supply or to gain. Thereby the electrical energy management ensures the energy balance, i.e. the same amount of electrical power is provided as it is consumed.

### 3.2.1 Advantages for the Vehicle Manufacturer

By using autonomous cost-power functions (the function of each component does only depend on its own characteristic and state data), the energy management does not have to be redeveloped and tested for every series hybrid or electric vehicle variant. This allows vehicle manufacturers to reduce development, application, and commissioning costs.

### 3.2.2 Advantages for the Vehicle Operator

Additionally, every component has to assure the economical operating point for every amount of electric power. For example, the range extender can control the torque and speed of the diesel engine in the most fuel efficient mode for every possible power provided. As the energy management only determines the sources to provide electrical power, which have the lowest operating costs in total, the vehicle operator benefits from minimal operating costs. These do not only include minimal fuel costs, but a minimum of all operating costs in total, including battery aging costs or maintenance costs.

# 4 System Architecture

A modern vehicle is built with multiple electronic control units (ECU's) from different vendors, which are connected with heterogeneous networks. Each ECU is dedicated to a limited number of tasks and comes as a black box, meaning that only the communication protocols and the functionality are known.

The task of the cars' original equipment manufacturer (OEM) includes the specification and integration of the ECU's while the development and production is outsourced. During this process, the different signals of the ECU's are matched and a solution for the interconnection, timing and safety requirements has to be found.

As the demand for functionality increases the interconnection complexity and whole system complexity increases as well. It is said, that the functional amount increments with linear magnitude, while the interconnection demand increases quadratic, and the integration effort grows with cubic magnitude.

Consequently, this leads to significantly increasing costs if the classic architecture is kept while extending a vehicle's functionality. High-end functions like autonomous driving or driver assistance systems are likely to have even higher requirements for data throughput and quality (Fortiss Technical Report 2011).

## *4.1 Centralized Architecture*

One possible solution to the increasing integration efforts is the implementation of a centralized architecture, which pushes the functionality into the software level based on a run-time environment that offers various system services. The development process should be data-flow based instead of component based.

### 4.1.1 Principle of Smart Sensors and Actuators

The system architecture for the centralized approach is divided into the centralized processing units and smart sensors and actuators that are interconnected via a homogeneous network.

The sensors and actuators should preprocess the data in order to reduce the data throughput demand. Furthermore, the actuators can run local feedback loops to reduce the response time of control tasks.

All smart actuators and sensors have in common that they propagate their information to the centralized unit and are controlled by abstract commands.

### 4.1.2 The 5-Module Concept

The 5-module concept was developed by Prof. Spiegelberg to reduce the communication demand between the individual domains in a car by using a data-flow oriented functional distribution. This does not only reduce the costs of wire harness but also the development costs. Less physical communication between the components also means that the resource-intensive developing of interface definitions is reduced to a minimum.

The 5-module concept is divided into a strategy and an execution level. The strategy level consists of the human–machine interface and an optional virtual co-driver. An arbitration unit is in charge to determine if the information of the human–machine interface or the virtual co-driver should be forwarded to the execution level. The virtual co-driver is a software component that interprets environmental information gathered by various sensors in order to calculate a safe vector for the vehicle to move. In contrast, the execution level consists of the drive-train unit and comfort systems units. The drive-train unit controls the individual actuators and stabilizes the vehicle. A communication and management module completes the setup.

### 4.1.3 Run-Time Environment

As the software components should be able to deterministically interact with each other, a sophisticated run-time environment is necessary to abstract the hardware and communication complexity as well as to ensure the semi or full-automatic enforcement of non-functional requirements. Non-functional requirements include end-to-end latencies, security considerations and safety demands. Further, the run-time system should offer system management, plug and play abilities, component encapsulation, mixed criticality and a set of automotive standard services like sensor-fusion (Buckl 2012).

In contrast to existing systems, the environment should be aware of the requirements of the individual components to be able to offer a reconfiguration service.

### 4.1.4 Communication Paradigm

For the communication between the software components, we propose the usage of the data-centric paradigm. In the data-centric paradigm, the sender and receiver of data are de-coupled from a developer's point of view. Instead, the requirements for the data transfers are defined for each data receiver and the supported properties are specified for each sender. The runtime environment and the tooling are responsible to match the different requirements.

## *4.2 Impact of a Centralized System Architecture*

The implementation of a centralized system architecture is a challenging task but manufacturers as well as vehicle owners will benefit from it on the long run.

### 4.2.1 Advantages for Manufacturers

A centralized architecture enables the optimized addition of further functions. This eventually leads to reduced development costs and a shorter development cycle. A standardized and modular system will also open the market for small and medium manufactures.

### 4.2.2 Advantages for the Vehicle Owner

The safety of a car can be increased by the usage of pre-certified components. Due to the dynamic platform management, the end-user will experience a higher flexibility in system configuration with the possibility of functional extensions. As software implementations from different vendors will compete, it is expected to have a wide variety of different implementations available with free market pricing.

## 5 Human–Machine Interface

This section can be broken down into answering two main questions:

- How can the intelligent vehicle augment the driver's capabilities?
- How can the HMI affect the business models regarding electric mobility?

### *5.1 Augmenting the Driver*

The Human–Machine Interface (HMI) is currently understood as the part of the technical system which interacts with the user. During such interaction, two intermediate translation steps can be observed.

The first one happens at the user's side, while he translates his ideas to the movements of body parts and interprets the machine's feedback.

The other happens at the machine's side, while it is interpreting the physical input being received through what is currently called a HMI and preparing the feedback through various HMI modalities.

Throughout these steps, a man–machine interaction has been performed and an understanding has been reached.

The interaction was executed with a certain level of mental and physical effort on the user's side and processing and power effort on the machine's side and the interaction had a specific quality in regards to the overall human performance in the task. In the ideal case, the machine would possess artificial intelligence which processes the entire interaction context and it would interact with the user using complete situation awareness. The translation of the original driver wish would be faster and less physically intensive. The feedback would only add to the existing user perceptive abilities and not overlap or overload the user.

The development of such future HMI can be further optimized by leveraging solutions from adjacent domains and defining intermediate steps from the current automotive HMI to the long-term vision (Mercep 2013a).

### 5.1.1 Context Processing

The first building block is therefore well-designed and well-performing context processing, which enables situation awareness. The user-vehicle-world construct, together with its inherent uncertainties, can be represented with Bayesian networks. Their exact description, through the rules of conditional probability and associated probability distributions, provides predictability and enables formal testing. We focused on exact inference for the same reasons. Four specific areas for improvement in the HMI domain were identified:

- Inference complexity on embedded hardware.
- Separation of conditional dependencies between sensor modalities.
- Dynamic addition and removal of data sources.
- Time constraints for safety relevant functionality.

The extension of the Junction Tree algorithm, called the Probabilistic Application Layer (PAL), has been developed to improve all the four areas (Mercep 2013c). It has been implemented on an Intel Atom-based embedded computer as a part of a combined HMI—Driver Assistance module inside the 5-Module architecture.

### 5.1.2 Integrated Interfaces

The second building block is composed of physical HMI solutions which minimize the physical effort during the interaction and provide a consistent feedback. Two aspects were considered: Control of the vehicle dynamics and the control of all other vehicle functions. For the primary vehicle control, a spherical sidestick solution from a project partner was integrated as-is. For the control of all other vehicle functions, a centralized touchscreen-based dashboard was constructed (Mercep 2013d). Furthermore, two HTML-based apps for the dashboard were developed: An energy management and a parking and maneuver assistance application (Stoeck 2012). In addition to the HTML apps, a control panel for the electric vehicles' charging stations is provided in the native dashboard software platform.

### 5.1.3 New Interface Modalities

While new interface types, such as side sticks and brain-computer interfaces, can already be used for vehicle control, we focused on the additional data which they capture by design and which is not related to the primary driving task. We refer to this additional data as "added value" of a specific interface and we attempt to mine it in order to determine the driver state. We focused on the electroencephalography-based brain-computer interfaces and have developed a method for robust detection of driver vigilance, which classifies the drivers into two states based on the spectral analysis of the significant independent signal components (Mercep 2013b, 2013e).

## *5.2 HMI-Based Business Models*

This section deals with the HMI as an enabling technology for different business concepts in the scope of electric mobility. The first step was developing presentational versions of every technical interface, in order to communicate the benefits of specific technology solutions to public (Mercep 2013f). For the second step, an assumption was made that combined traffic solutions and car sharing will be one method of introducing electric vehicles on the larger scale.

### 5.2.1 Interface Personalization

The concept of personal mobility provided as a service can be a starting platform for customer binding over the HMI. The customer retains his own styles and preferences, together with the infotainment content, from the previous vehicle type or instance. One requirement is a standardized description of such user profiles and standardized software interfaces. Our prototype uses a generic markup language profile description for dashboard elements visualized by vector graphics, which can be extended to describe arbitrary user preferences.

### 5.2.2 Assistive Applications

Stored user profiles can also contain the description of the driver's skill level, in order to consistently deliver the preferred level of assistance. This level can stay unchanged throughout different vehicle types. In this way, new users or elder population can be gradually integrated into semiautonomous or autonomous vehicles. It is advisable to continuously present the next system step or system state, to attain user's trust. Our maneuver and parking assistant, which comes with an offline training mode, is one of such assistive systems.

## 6 Summary and Future Work

We have shown how research and engineering in three complementary disciplines can shape and affect the concepts of electric mobility and mobility in general, while addressing the relevant megatrends. For our studies, we have used the Innotruck, a driving simulator with a full chassis mockup and an ENUBA[1] transport truck. The future work includes refinement of current prototypical components into automotive grade systems, which can be integrated into different types of electric vehicles. In the area of HMI, a more complete framework for HMI and driver assistance applications will be developed, in order to strongly separate the developers from the context processing models.[2]

## References

Buckl C, Camek A, Kainz G, Simon C, Mercep Lj, Staehle H, Knoll A (2012) The software car: building ICT architectures for future electric vehicles. In: Electric vehicle conference (IEVC), IEEE international, Greenville, 2012

Buitkamp C, Spiegelberg G, Lienkamp M (2013) Reducing costs during development and operation of hybrid commercial vehicles through a market-based electrical energy management. In: Electric & electronic systems in hybrid and electric vehicles and electrical energy management conference (EEHE), Bamberg, 2013

Fortiss GmbH (2011) The software car: information and communication technology (ict) as an engine for the electromobility of the future. Technical Report, Munich

Mercep Lj, Spiegelberg G, Knoll A (2013a) A case study on implementing future human-machine interfaces. In: The 2013 IEEE intelligent vehicles symposium, Gold Coast, 2013

Mercep Lj, Spiegelberg G, Knoll A (2013b) Reducing the impact of vibration artifacts in a brain-computer interface using gyroscope data. In: IEEE Eurocon 2013, Zagreb, 2013

Mercep Lj, Spiegelberg G, Knoll A (2013c) Context processing for human-machine interface. In: Science and information conference 2013, London. In Review, 2013

Mercep Lj, Spiegelberg G, Knoll A (2013d) Die Entwicklung einer zentralisierten MMS im Rahmen des Projekts Innotruck. In: Automotive meets Electronics, VDE/VDI/GMM, Dortmund, 2013

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[1] Project ENUBA (ger. *Elektromobilität bei schweren Nutzfahrzeugen zur Umweltentlastung von Ballungsräumen)* attempts to reduce the $CO_2$ footprint of transport trucks through hybrid drive trains and catenary lines.

[2] This is work in progress together with fortiss Institut der Technischen Universität München.

Mercep Lj, Spiegelberg G, Knoll A (2013e) A robust driver assessment method for the brain-computer interface. In: IADIS interfaces and human computer interaction 2013, Prague. In Review, 2013

Mercep Lj, Spiegelberg G, Knoll A, Stoeck J (2013f) Interface concepts for communicating green cyber-physical systems to public. In: Smartgreens 2nd international conference on smart grids and green IT systems, Aachen, 2013

Stoeck J, Mercep Lj, Spiegelberg G, Knoll A (2012) Platform-independent interface for the management of sensor-generated power and data flows in an automotive data-centric architecture. In: 6. VDI/VDE Fachtagung USEWARE 2012 – Mensch-Maschine-Interaktion, Deutsches Forschungszentrum für Künstliche Intelligenz DFKI Kaiserslautern, pp 33–36