ELECTRIC VEHICLES DRIVE CONTROL – THEORY AND PRACTICE

Alexandros Soumelidis, PhD
leader of research group, MTA SZTAKI
research professor, SZE JKK

Ádám Bakos
researcher, MTA SZTAKI, JKK

Basic research for the development of hybrid and electric vehicles section

Hungarian Academy of Science
Budapest, 31 January 2014

Introduction

Electric Vehicles Drive Control

Mission

Electric Vehicle Drives – an inevitable component of **electric** and **hybrid** vehicles. Realizing a **controlled electric drive** system for a car is an extremely important task by the viewpoint of different requirements, e.g.

- Riding and transportation comfort, safety and reliability,
- High efficiency, economic power consumption ,
- Low or zero emission of polluting materials,
- Economic operation and maintenance, etc.

Control design for Electric Vehicle Drives is not a new concept, however

- enhancing the traditional control design methods by using the contemporary results of the **modern control theory**,
- applying the principles of mathematical **modelling**, system **identification**, and model-based control design

offer new perspectives in realizing these goals.

Collaboration of MTA SZTAKI with SZE JKK undertake this mission, an outline of these activities is given in this presentation.

Components of Electric Vehicle Drives

- Electric motor
  - DC, BLDC, stepper, PMS, etc.
- Electronic motor controller
  - High efficiency power
  - Embedded (microcontroller / microcomputer based) controller
  - Sensors, measurement devices
- Coupling and gear mechanism
  - Mechanical elements
- Power supply, power management
  - Batteries, capacitors, fuel cells
  - Charging / recharging mechanism

Electric Motor Types for Vehicle Drives (examples)

- DC motor (brushed DC motor)
- BLDC motor (brushless DC motor)
- AC motor (induction motor)
- PMS (Permanent Magnet Synchronous) motor
- Stepper motor
- Switched reluctance motor
- …

Principles Electronic Motor Controllers

- Switched mode operation in power drives that
  - ensures high efficiency in power utilization,
  - fits to digital control principles – embedded control realizations.

Requirements for Vehicle Drives Operation

General requirements

- Riding/transportation convenience

  e.g. smooth movement, avoiding sudden changes in speed, uniform power distribution in the whole region of operation from start to maximal speed.

- Ensuring safe operation in movement and braking

  Providing precise speed and torque distribution on the tires of the vehicle in any path by any speed and acceleration conditions.

- Small power consumption, high efficiency

  Small power loss in the mechanical and electric components, small heat dissipation, high level utilization of waste energy, e.g. during braking

Requirements for Vehicle Drives Operation

Specific requirements

- Controlling speed and torque in every region of operation

  4-quadrant control including both forward / backward movement and braking.

- Regenerative braking

  regenerating kinetic energy of the vehicle during braking into electric energy that can temporarily be stored (e.g. using batteries / capacitors)

Requirements for Vehicle Drives Operation

The requirements imply

application of sophisticated control methods

- realizing measurement based feed-back control mechanisms,
- applying sophisticated mathematical models in describing physical devices and operations,
- applying system identification techniques to obtain real-world models,
- using the results of the modern/postmodern control theory.

Case Study

Control of a Direct 4-wheel Vehicle

Vehicle Architecture

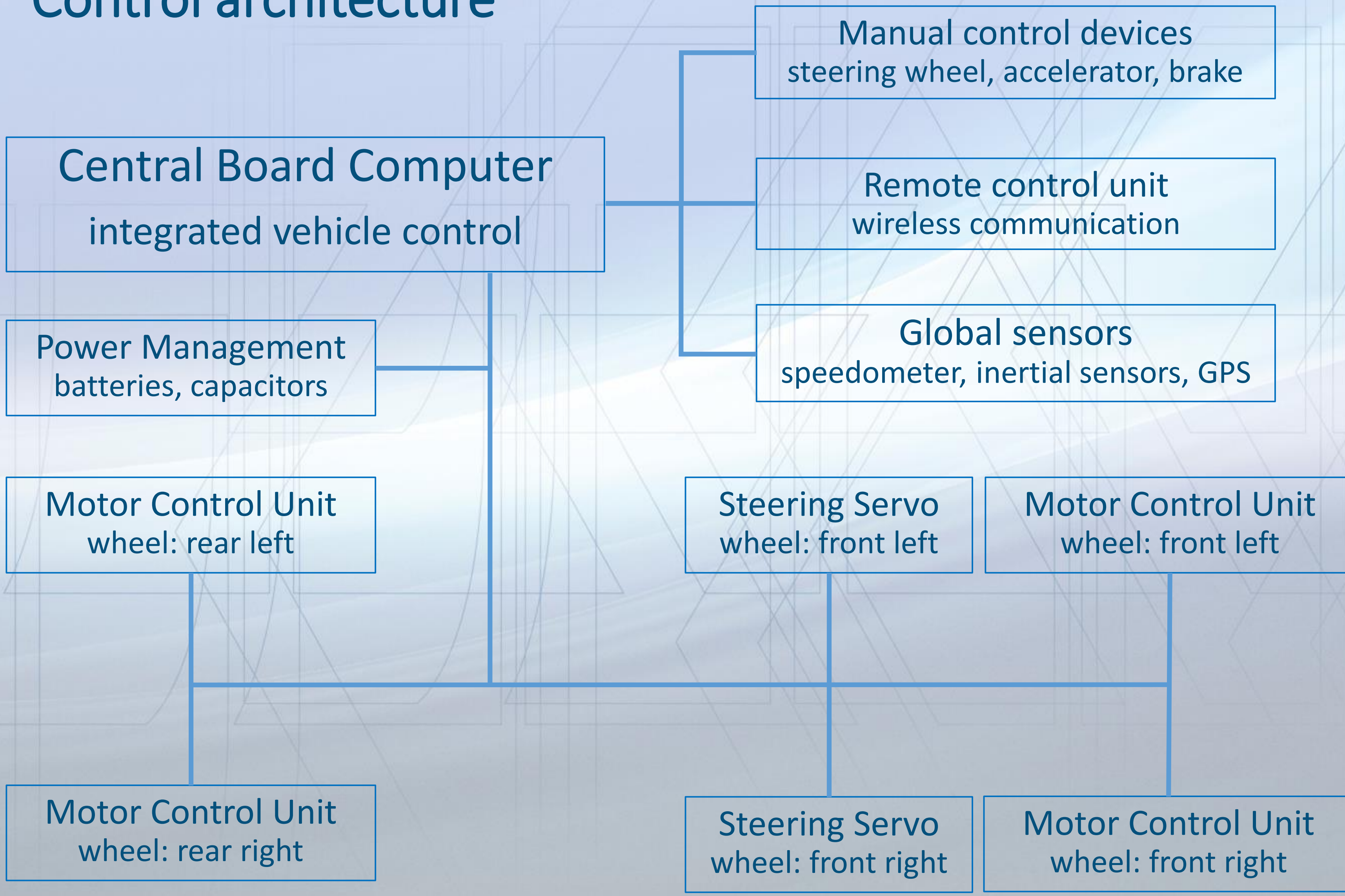
Main units

- 4 independent wheel motor drives with individual embedded motor controllers
  - Controlling of a particular drive can be realized by digital network communication – CAN
- Steering of the front wheels by electronic servo mechanism
  - Joint or individual steering on the front wheels by embedded DC motor servos.
  - Controlling the servo(s) can be performed by digital network communication – CAN
- Power supply control system – realized by an embedded microcontroller – to manage the charging/recharging processes
- High performance board computer for the higher hierarchical level of control

Control opportunities arising from the structure

- A synchronized speed (rpm) / torque distribution can be performed to ensure precise an safe movement of the vehicle by following any feasible track at any feasible speed and acceleration conditions including also braking.
  - Cooperating speed/torque control can be realized by distributed digital control strategies.
  - No complicated mechanical constructions (gear-boxes, couplers, differentiators) are necessary.
- Efficiency on power can be increased – and optimized – by utilizing regenerative braking, i.e. feeding back kinetic energy of the vehicle during braking to be temporarily stored.
  - Regenerative capabilities of the motor drives can be utilized in the charging/recharging processes controlled by the digital power management control.

Control architecture



Control Tasks Emerging

- Precise 4-quadrant speed(rpm)/torque control in the individual motor controllers.
- Integrated supply/recharge control between the motor by involving the motor controllers and the power management system.
- Integrated vehicle control by involving the steering, drive and braking actions.

Precise realization of these tasks – today – involves application of methods offered by

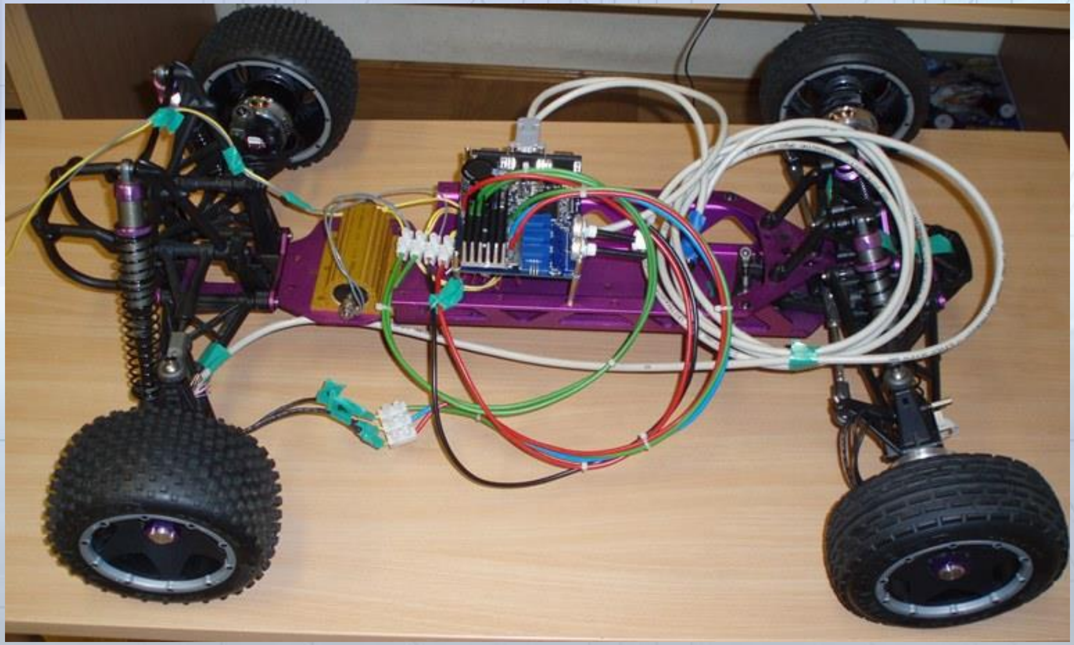
modern/postmodern control theory.

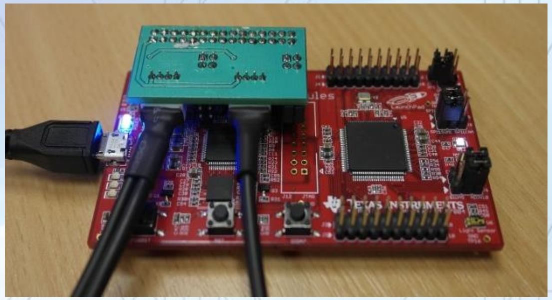
Reasons (as examples):

- Complicated, nonlinear, time varying component models occur.
- Analog and switching techniques are combined.
- Uncertainties, nonmodeled effects should be considered.

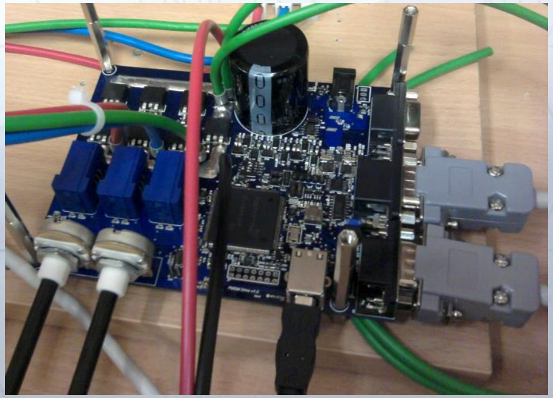
An experimental platform under development:

1:5 chassis





Board computer



Motor control

Applying Control Theory

in Electric Vehicles Drives

The Control Design Process

Main tasks

- Mathematical modelling
  - Applying physical rules
  - System identification
- Exploring constrains and uncertainties
- Selection of control strategy and criteria
- Control design
- Verification by simulation – repetition of previous steps if needed
- Controller realization
- Verification in the real platform – repetition of previous steps if necessary

Modelling of the Electric Drives

Modelling tasks

- Modelling of the electric motor
- Modelling of the components of the electronic control
- Modelling of the mechanical drive chain
- Modelling of the supply/recharge processes

Modelling for control purposes

- Lumped parameter models rather than distributed parameter ones
- Input / Output type models
- Uses limited number of parameters for simple controller design
- Dynamic models : uses ordinary differential equations of time variable

Modelling Practice of Electric Drives

- Modelling of geometry and mechanics
- Modelling the magnetic field and induction
- Modelling the heat transfer processes

These type of modelling

- Uses distributed parameter models
- Finite element methods
- Partial differential equations
- Result in high-fidelity, nevertheless rather complicated models

Simplified physical modelling

- Applying simplified physical models based on ordinary differential equations by using
  - Newton axioms or Lagrangian method for mechanical parts,
  - Kirchoff, Ohm, Faraday, etc. Laws in electric and magnetic parts, etc.

Control Oriented Modelling

Advisable method

- Using simplified physical modelling to set up the structure of a feasible system model
- Using the results of high-fidelity modelling
  - to determine accurately the model parameters, and
  - to refine the model structure for higher fidelity.

Consequence: a bridge should be built between the high-fidelity modelling (using distributed models, PDEs, FEM) and the ordinary modelling techniques.

Using identification methods

- Fitting the models to real world: measurement based identification methods
  - Parameter estimation
  - Structure identification – a new approach has been worked out based on nonparametric system pole identification.

Control Paradigms

Control oriented models used are

- usually nonlinear,
- in many cases time-dependent (time-variant, parameter-varying),
- in many cases hybrid (analog and switching type components mixed),
- inaccurate and uncertain (parameter and model uncertainties).

Consequence: classical linear control theory can be insufficient, methods of modern / postmodern control theory should be applied.

Control Design for Vehicle Drive Systems

Classical methods

- PI, PID control
- LQ optimal control

Advanced methods advised

- Robust control design methods
- Linear Parameter Varying (LPV)
- Nonlinear control
- Switching and hybrid control

Realization

- Design phase: using high level, high efficiency design tools, e.g. MATLAB®/Simulink®
- Execution phase: using high performance embedded platforms (microcontrollers, microcomputers).

} Automatic code generation from design to realization

Applying advanced controllers usually require higher computational capabilities – today advanced embedded controller realizations (based on 32-64-bit, multicore, etc. microcomputers) give this opportunity.

Distributed Control for Vehicle Drive Systems

- Dividing the control problem to be solved in smaller – individually realizable parts.
- Connection among parts are realized by applying digital networks
  - CAN – the network conventionally used in vehicles
  - FlexRay – a network with increased real-time capabilities and reliability properties
- Realizing different control schemes
  - Hierarchical schemes (global control → local functions control → actuator control)
  - Parallel, concurrent control schemes
  - Cooperative control schemes

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DESIGNING PMSM DRIVES

for Electric Road Vehicles

Control of PMSMs as Vehicle Drives

PMSM – Permanent Magnet Synchronous Motor

Main requirements

- High torque generating capability
- Independent from velocity
- Highly efficient operation

Operating states

- Transient operation in most of the time
- Driving and braking torque is required in either direction (4-quadrant operation)

Modelling of PMSMs as Vehicle Drives

- Dynamic mathematical model for control
  - All the above operating states are modeled sufficiently
  - Reasonable number of equations
  - Reasonable number of parameters
- Determining model parameters
  - Obtaining from finite element analysis of magnetic circuit
  - Measurements
  - Data acquisition and identification

Dynamic model of PMSMs

Theoretical model of PMSMs

- Based on flux, voltage and motion equations
- Nonlinear with varying coefficients

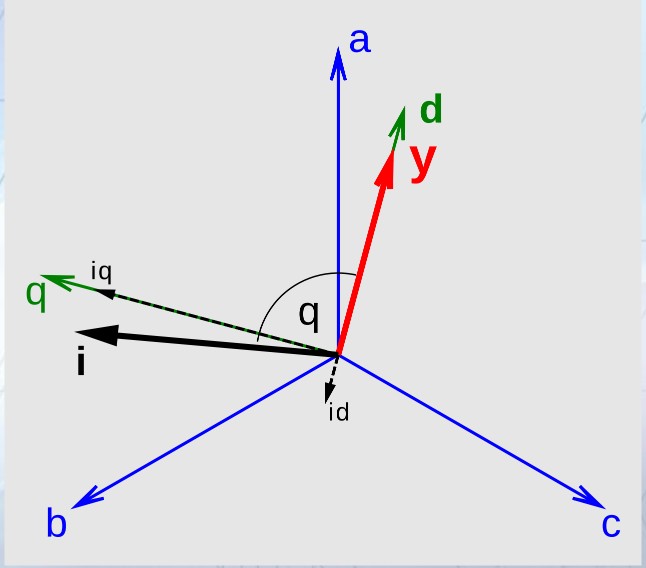
Practical model of PMSMs

- Neglecting some secondary effects
- Using transformation methods

A suitable linear model can be derived.

Field Oriented Control (FOC) of PMSMs

- Commonly used control method
- Principle
  - Torque is proportional to current and torque angle
  - Current vector is oriented to the rotor magnetic filed in every moment



- Realization
  - Voltage can be applied by the power electronic circuit
  - Closed-loop current control is required

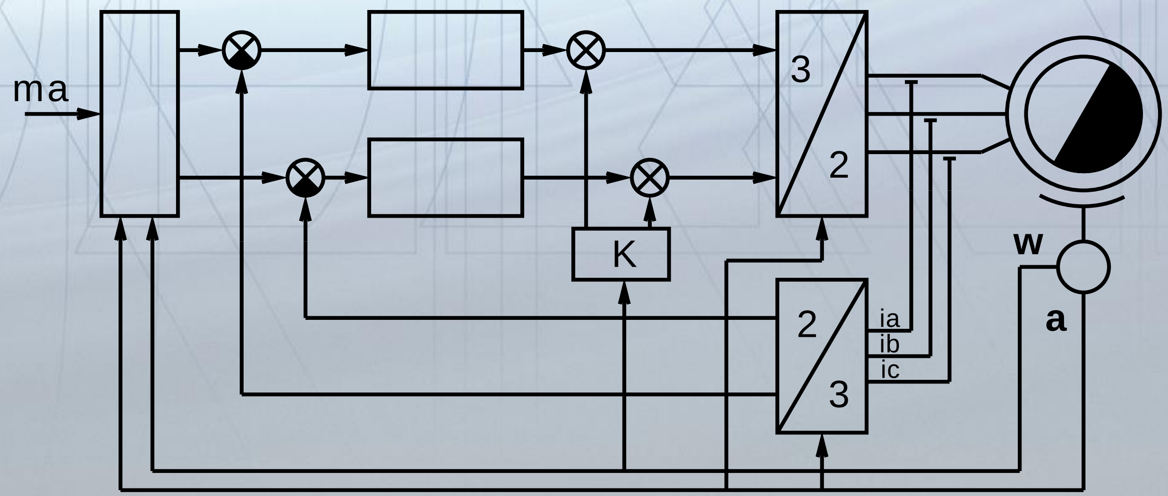
FOC of motor currents

Current reference signal generation

- Torque requirement
- Instantaneous rotor angle and velocity
- Requirement for field-weakening

Controller design and realization

- Based upon the transformed and decoupled model
- Using linear techniques



Main benefits of FOC

- There are no distinct operating states (e.g. starting, spin-up, etc.)
- Maximum Torque-Per-Ampere control
- The same controller can be used in all four quadrant of power
- Velocity range can be extended by field-weakening

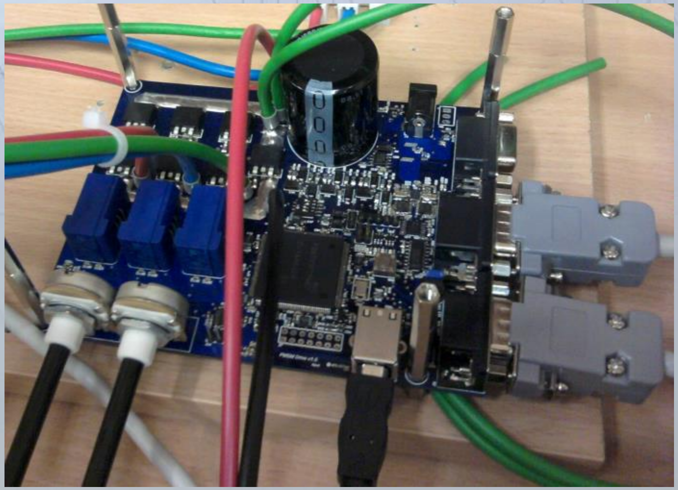
Implementation issues of FOC

- Measurements
  - Accurate measurement of phase-currents
  - Rotor angle
    - Absolute angle is required after switch-on
  - Rotor velocity
  - Voltage of power supply

- Power electronic circuit
  - 3-phase switch mode power inverter
  - Pulse-width modulation (PWM) methods

Case study

- Design and development of a 700W electric drive
  - PMS motor
  - Hardware design
    - Texas Instruments microcontroller platform
    - Power electronics built on MOSFETs
    - 3-phase current measurement
    - Rotor velocity and absolute position measurement
    - CAN communication
  - Software development
    - Unique hardware-level software
    - Motor model identification
    - Implemented filed oriented control



Control perspectives

- Taking secondary effects into consideration
  - Iron saturation
  - Magnetic field deviations
  - Efficiency constraints
- Complex mathematical models
  - Nonlinear
  - Linear parameter-varying (LPV)
- Applying modern/postmodern control algorithms
- Implementing of more sophisticated computational-intensive algorithms

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ACTIVITIES IN JKK

SZE JKK – Research Center for Vehicle Industry of the Széchenyi István University

in collaboration with

MTA SZTAKI – Institute for Computer Science and Control of the Hungarian Academy of Sciences

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Participating in Design and Implementation of Electric Road Vehicle Drives

Topics

- Mathematical modelling of electric motors: control oriented models
- Controller design by using advanced control methods
- Embedded controller realization platforms: tools and methods for hardware and software development
- Embedded realization of electric motor controllers
- Sensors, measurement devices for electric motor control
- Test systems, hardware-in-the-loop (HIL) simulation platforms
- Measurement and identification methods

THANK YOU FOR YOUR ATTENTION.

Alexandros Soumelidis, PhD
leader of research group, MTA SZTAKI
research professor, SZE JKK

Contact

Email:
alexandros.soumelidis@sztaki.mta.hu
soumelidis@sze.hu

Tel.: +36-1-279 6226

Web:
http://www.sztaki.hu/people/008002921

Ádám Bakos
researcher, MTA SZTAKI, SZE JKK

Contact

Email:
bakos.adam@sztaki.mta.hu,
bakos.adam@sze.hu

Tel.: +36-1-279 6148

Web:
http://www.sztaki.hu/people/008007278

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The projects are supported by the European Union
and co-financed by the European Social Fund.

Hungarian Academy of Science
Budapest, 31 January 2014

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