System architecture and hierarchical control for in-wheel electric motor vehicles*

Ádám Bakos, Péter Gáspár, and Alexandros Soumelidis

Abstract— **Design of a four-wheel vehicle model using in-wheel permanent magnet synchronous motor (PMSM) based electric drives is outlined in the paper. System architecture, components and basic control principles are presented. The vehicle model is intended to be applied as an experimental platform to support control design processes in association with electric vehicles that use minimized level of mechanics, instead applying the benefits of electronics and digital control solutions. Realization of a 1:5 scaled model is concerned.**

I. Introduction

Electric vehicles have received much attention in the present decade, and there are strong indications that this attention will survive – at least – in the nearest future. Besides the problems of efficient storage of electric energy, improving the efficiency of the electric drives and power train, as well as applying light materials in – both discussed widely in the scientific and technical literature – a significant opportunity to increase the overall efficiency of electric vehicles arises from eliminating the mechanical components of the power train (i.e. gears, clutches, balancers, etc.), substituting them by electronic solutions. The use of advanced digital control methods realized in high performance embedded microcomputers, today, gives the possibility to solve this problem with great success, however working out effective and reliable solutions – suitable for use in real passenger and commercial vehicles – need careful study of the problems arising both in theoretical and technical level. In this paper the design and realization of an experimental small scale physical vehicle model is described that has been constructed to support the development of delicate control methods satisfying the above mentioned principles by realizing a low-cost and safe environment for testing.

Realization of a four-wheel drive 1:5 scaled vehicle model using in-wheel permanent magnet synchronous motor (PMSM) based electric drives has been decided. This construction – with the use of a high performance on-board microcomputer as a global vehicle control unit – gives the possibility of testing several setups – two-wheel or four-wheel drive with or without steering including also faulty cases – providing a widely applicable universal test environment. Besides of testing the electronic control solutions intended to substitute mechanics the experimental electric model can also be used – by eventually complementing it with auxiliary devices – to study general vehicle control and power management solutions.

There are three main methods to use hub motors: front, rear or four-wheel drive. Each of them eliminates the necessity of a central drive unit – realized either by combustion engine or electric motor – and the entire drive train. The reduced number of mechanical connections allows higher steering angles, which increases maneuvering capabilities. Horizontal stability can be improved by integrating the control of the in-wheel electric motors. Also, regenerative braking can be implemented effectively, thus mechanical braking in only necessary for securing the vehicle in a parked position.

The coordination of vehicle control components and the design of an integrated vehicle are in the focus of vehicle companies and suppliers, see e.g., [2,3]. In the in-wheel motor system electric motors are built into the hub of the wheels and they are driven directly. An appropriately balanced in-wheel system is able to improve the yaw dynamics of the vehicle by adapting to road conditions. Comfort usually deteriorates as a consequence of an increase in the weights of the wheels. By using integrated vehicle control the operations of the in-wheel motors can be designed. Some examples have already been published, see e.g., [1,4,5].

The design of an in-wheel motor vehicle is based on a multi-layer hierarchical structure. At the first layer the longitudinal force and the yaw torque are designed based on a bicycle model. In the second layer the designed control signals are converted to construct real physical outputs for the vehicle. Here the feasibility verification is also performed, i.e., construction limits or friction. The function of the third layer is to convert the control signal into real physical parameters of the actuators. This task is carried out by the low-level controllers of the steering system and the in-wheel motors as well.

In the paper the architecture of the in-wheel motor vehicle and the design of the hierarchical control are presented. The structure of the paper is the following. In Section II the system architecture of on-board electronic system is proposed. In Section III the realization of wheel drives is presented. In Section IV the hierarchical design of the control system is presented. Finally, Section V contains some concluding remarks.

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II. ON-BOARD ELECTRONIC SYSTEM ARCHITECTURE

It is recommended to use a modular structure for the on-board electronic system architecture. This way, all the system components can be designed and operated separately. For the experimental vehicle it is to divide the system into the following components: main control computer, wheel drives, steering servo, inertial measurement unit, battery and power management and radio frequency communication.

A. Main control computer

The primary function of the main control computer is to execute the high-level vehicle control tasks. This module computes the necessary driving torques and steering angles based upon the external references and the inertial measurements. Secondary, it is able to carry out further tasks, e.g. estimation algorithms, vehicle diagnostics, or any data and signal processing based upon any further sensors mounted on the vehicle. As these are mainly computation-intensive tasks, and at this high-level layer of the hierarchical structure it is not recommended to implement special hardware handling tasks, furthermore, all data exchange with the module is achieved via the on-board communication network, it is preferable to use a microprocessor-based system for the main control computer. As, in practice, the cycle time of these tasks is usually in the order of milliseconds, it is also possible to use a real-time operating system. In this case, the implementation and scheduling of these tasks are more comfortable. Furthermore, some tasks e.g. control algorithms, can be designed and tested in MATLAB®/Simulink® and compiled by automatic code generation.

On the experimental vehicle, the functionalities of the main control computer are supplied by a Raspberry Pi microcomputer module with Linux operating system. The use of an operational system offers easy access to the design processes that is useful in the prototyping level of control design, as well as it facilitates the involvement of the experimental setup in the university education. Alternatively a more professional on-board computer system is under development that satisfies strict real-time requirements, and utilizes all the benefits of symbolic control design and automatic code generation.

B. Wheel drives

To produce the desired torque by the hub motors, there are lower-level control systems for each motor. They are responsible for torque reference tracking and supplying wheel velocity information to the main control computer.

Controlling an electric motor is a complex task, which includes hardware-level operations. For example, motor currents, rotor position and angular velocity must be measured, power electronics must be controlled and even control algorithms and mathematical operations with small cycle time must be computed. In this case, it is an obvious choice to use a microcontroller-based system. As many tasks are related to hardware-level functions and require the use of microcontroller peripherals, it is recommended to implement them as native program code.

In the experimental vehicle, wheel drives are realized by Texas Instruments digital signal processors.

C. Steering servo

Required steering angle is realized on the front wheels of the vehicle by a steering servo. This unit also implements a low-level control system.

As the servo mechanism is based on an electric motor, the same facts are true as those related to the wheel drives. Although, the steering servo has considerably less power and it is usually not a direct drive system, it uses a gearbox.

D. Inertial measurement unit

Vehicle state measurements are taken by an inertial measurement unit. These measurements are required by the vehicle control algorithm.

This unit contains accelerometers and gyroscopes to measure three-axis acceleration and angular velocity. The main task of the module is to provide the measurements to the main control computer. In addition, the design of this module fulfills the application's requirements for filtering, signal processing or implementing any estimation algorithm.

E. Battery and power management

This module has two main tasks. First, battery management and protection must be realized. The battery must be protected form deep discharge, thus at a critical voltage level, the system must be shut down. In addition, when the wheel drives are in regenerative braking mode and feeding back energy to the battery, the charging process must be controlled. If the braking energy is higher than it is limited by the charging controller, the surplus must be dissipated.

The second main task of this module is to provide the appropriate power supply to the on-board electronic systems. In addition, this unit can be responsible for some supervisory functions, such as network management, switching on-board devices on and off, emergency shut-down, etc.

The low-level measurement and control tasks associated with battery and power management are implemented in a microcontroller-based environment.

F. Communication

Communication inside the vehicle is organized by using a digital communication bus. All the modules are connected to the bus, and no other module-to-module communication lines are present. Commands, measurements and reference signals are sent via the bus periodically.

Communication between the vehicle and the environment is realized by wireless radio-frequency connection. An on-board radio frequency communication module is applied, which is responsible for transmission and reception. The main computer sends the data to be transmitted via the on-board bus, and the received data is also placed on the bus. The protocol conversion is performed by the communication module.

On the experimental vehicle, the on-board communication network is a Control Area Network (CAN) bus. The radio frequency link uses ZigBee protocol. The block diagram of the system architecture can be seen in Fig. 1.

When the system is switched on, power management is the first to start up. After checking the conditions of the batteries, it enables the power supply to the electronics. If all the on-board modules have started and working properly, power supply is enabled for the wheel drives and the system is ready to use.

III. HIERARCHICAL CONTROL SYSTEM STRUCTURE

To separate the control design steps from each other a suitable strategy is to use a hierarchical control system structure. In this case, the task of the high-level control system is to compute the control signals for the vehicle: the steering angle and the yaw torque. The yaw torque is then distributed between the wheels by a middle-level control system. The resulting individual wheel torque requirements are then realized by the low-level wheel drives.

A. *Control-oriented vehicle model for trajectory tracking*

The design of the high-level control is based upon the dynamic model of the vehicle. The linearized two-wheeled bicycle model (Fig. 2.) with the longitudinal and lateral dynamics of the vehicle is considered. The vehicle motion is described by the following force and moment equations:

$$J\ddot{\psi} = c_f l_f \alpha_f - c_r l_r \alpha_r + M_{br}\,, \tag{1}$$

$$m\dot{\xi}\left(\dot{\psi} + \dot{\beta}\right) = c_f \alpha_f + c_r \alpha_r\,, \tag{2}$$

$$m\ddot{\xi} = F_l - F_d\,, \tag{3}$$

where m is the mass, J is the yaw-inertia of the vehicle, l_1 and l_2 are the distances of the front and rear axles from the center of gravity, c_1 and c_2 are cornering stiffnesses of

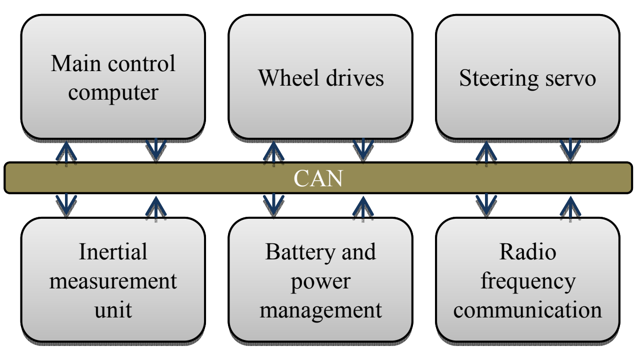

Figure 1. Block diagram of the system architecture

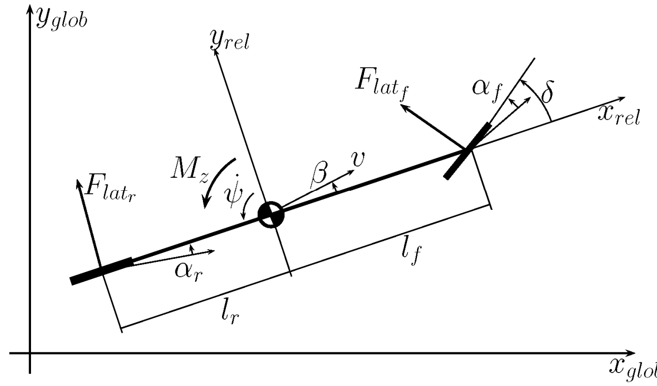

Figure 2. Bicycle model

the front and rear tires, and $\alpha_f = \left(\delta - \beta - \dot{\psi} l_f / \dot{\xi}\right)$ and $\alpha_r = \left(-\beta + \dot{\psi} l_r / \dot{\xi}\right)$ are the side slip angles at the front and the rear. The yaw and side-slip angle are denoted by ψ and β, respectively, while ξ is the longitudinal displacement of the vehicle. Air resistance, road resistance etc. are disturbance forces denoted by F_d. The inputs of the system are the steering angle of the front wheel (δ), the yaw torque (M_{br}), and the longitudinal force (F_l) delivered by the in-wheel motors.

In order to track the predefined trajectory, the longitudinal and lateral dynamics must be taken into consideration. Thus, the vehicle must track reference signals of velocity and yaw rate as well. Velocity tracking is realized by fulfilling the following optimization criterion:

$$Min\left|\dot{\xi}_{ref} - \dot{\xi}\right|. \tag{4}$$

Next, the difference between the reference yaw rate and the measured actual yaw rate of the vehicle must be minimized:

$$Min\left|\dot{\psi}_{ref} - \dot{\psi}\right|. \tag{5}$$

At the same time, in order to avoid actuator saturation, the control signals must be limited. The maximum forces of the in-wheel drive system, the brake system are determined by their construction, as well as the maximum steering angle of the steering system. These limitations are also formulated in an additional performance signal.

The control design leads to a multi-objective optimization task, which can be solved by using Linear Quadratic or H∞ methods.

B. *Distribution of yaw torque*

If the vehicle is moving on a straight path, the wheels are rotating at the same velocity. If the speed of the vehicle must be handled in a bend, the inner wheels must rotate at lower velocity than the outer wheels. Similarly, the inner wheels must produce higher torques than the outer ones. The task of the wheel force distribution in this layer is to define the drive or brake forces of the wheels. It is important to distinguish braking and driving modes of the vehicle motion, since the weight loads of the front and rear axle are different in both cases (Fig. 3.).

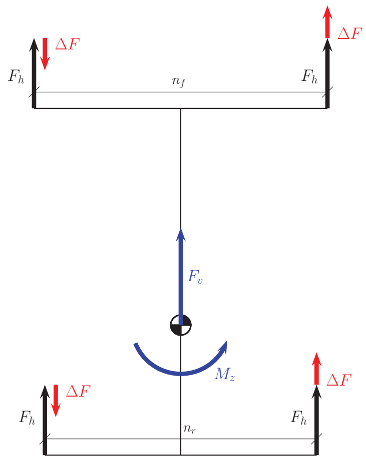

Figure 3. Yaw torque distribution

C. Torque realization on the wheels

The lowest layer of the control hierarchy is incorporated by the wheel drives. The distributed individual torque generation is realized by this layer.

A frequent choice today for wheel hub motors is the use of outer rotor type, three-phase permanent magnet synchronous motors (PMSM). In this type of motors, the stator containing the winding is placed in the inner side of the motor, and the permanent magnets are mounted on an outer ring, which is built together with the wheel. The driving of the wheel is direct, and no gears are used.

The task of the control system in this layer is to realize the required torque by the motor. The most appropriate control method of a PMSM for vehicle drive is the field oriented control (FOC). One of its main benefits is that the highest torque can be generated by the lowest current and it can produce torque even at steady state, which is essential for starting the vehicle.

A simplified dynamic model of the PMSM can be derived if the following assumptions are made: symmetrical winding, fundamental sinusoidal magnetic field distribution and saturation are ignored. In this case, using the space-vector theory, the following expression can be written:

$$\mathbf{u}_s = R_s \mathbf{i}_s + L_s \frac{d\mathbf{i}_s}{dt} + j\omega \boldsymbol{\psi}_p , \quad (6)$$

$$m = \frac{3}{2} |\boldsymbol{\psi}_p| |\mathbf{i}_s| \sin(\upsilon_p), \quad (7)$$

where $\mathbf{u}_s$ and $\mathbf{i}_s$ are the voltage and current vector, respectively, R_s and L_s are the winding resistance and inductance respectively, ω and m are the velocity and torque respectively, $\boldsymbol{\psi}_p$ represents the permanent magnet flux, and υ_p is the torque angle as depicted in Fig. 4.a.

The produced torque is proportional to the motor currents, which is determined by the length of the current vector, thus torque control can be achieved via current control. It follows from (7) that the torque is maximized when υ_p torque angle is 90°. Consequently, the task of the current control is to maintain the $\upsilon_p = 90°$ torque angle during the rotation of the rotor, i.e. orient the current vector perpendicular to the rotor magnetic field.

It is a common method to simplify the control task by applying a linear transformation to (6), which transforms the equations into a rotating reference frame fixed to the rotor. In this frame the expression of the dynamic model and the torque is

$$\mathbf{u}_s^* = R_s \mathbf{i}_s^* + L_s \frac{d\mathbf{i}_s^*}{dt} + j\omega L_s \mathbf{i}_s^* + j\omega \boldsymbol{\psi}_p^* , \quad (8)$$

$$m = \psi_p i_Q , \quad (9)$$

where i_Q is the Q-axis component of the current vector. In this case, the task is to control the Q-axis current according to the demanded torque and control the d-axis current to zero by two current controllers. The method is depicted in Fig. 4.b.

The computed control signals must be inverse transformed before applied to the motor. It can be shown that in steady state these signals and also the motor phase currents are sinusoidal waveform.

Knowing the resistance and inductance parameters of the winding and the magnetic flux of the permanent magnet, the current controllers can be designed by conventional or modern techniques. Note, that the dynamic model and control scheme mentioned above are valid also for the generator operation, i.e. for regenerative braking.

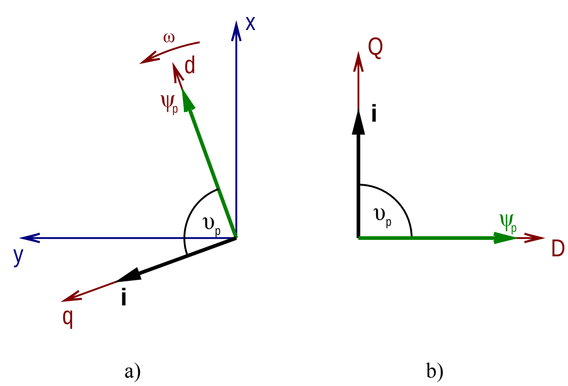

Figure 4. Field oriented control a) normal b) transformed

Using FOC, the produced torque is proportional to the motor currents within a given range. This can be seen in Fig. 5. (blue curve). As the controlled mechanical quantity is torque, velocity is determined by external impacts, such as load torque, rolling resistance, friction, etc., thus the required torque can be produced at any velocities, in a given range

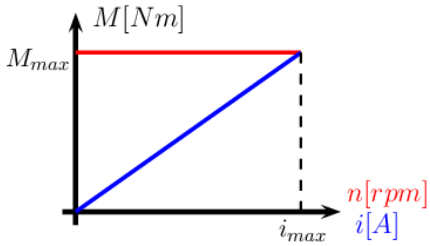

Figure 5. Motor torque curves

(see red line in Fig. 5.) In practice, this range is limited by the saturation of the power electronics circuit, as the voltage of the motor cannot be increased to maintain the constant current when the induced voltage is increased by the increased velocity. In this case, a field weakening method can be used to further increase the velocity.

The algorithm is implemented in an embedded, microcontroller-based control system. The motor driver power electronic circuit is a switch mode, pulse width modulated inverter built from MOSFETs.

IV. Simulation Example

As an illustration the first simulation example presents a yaw rate tracking control for a vehicle using in-wheel hub motors. Here, only the higher-level vehicle control was designed and tested using MATLAB®/Simulink®.

The tracking performances can be tuned by the weighting matrices found in the cost function that is used for the controller design.

The control design is based on the closed-loop interconnection structure, in which weighting functions are designed in order to define performance specifications and specify real environment. This structure is depicted in Fig.6. The role of W_p is to define the performance specifications for the acceptable yaw rate error and the velocity error. W_{act} is defined to guarantee limits of actuator inputs. Weights W_w and W_n reflect the size of the disturbances and sensor noises. The block Δ represents the uncertainties of the system, which are normalized by the weight W_u.

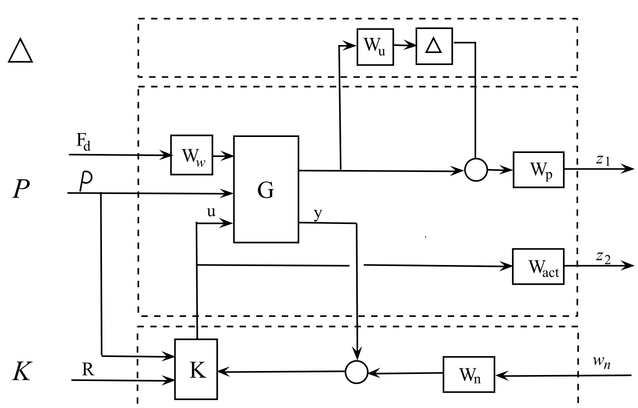

Figure 6. Closed-loop interconnection structure

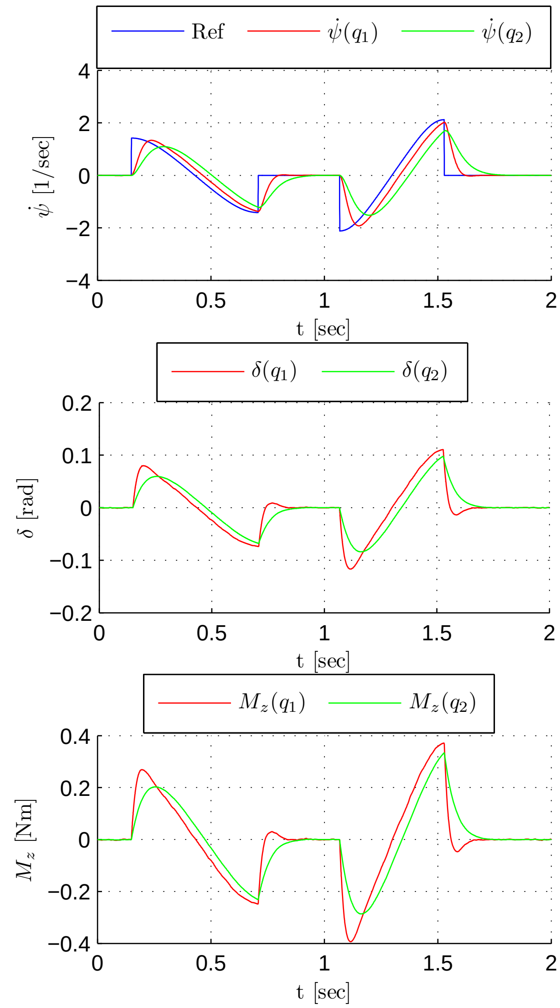

Figure 7. Time responses of the yaw rate and the control signals

In the example two simulation results with different weighting strategies are depicted in Fig. 7. The yaw rate error is punished by different weights. If we apply larger weights for yaw rate error, the tracking performance is better, but both control signals, i.e., the steering angle and the yaw torque, increase. However, if smaller weights are applied the accuracy of the tracking deteriorates.

In the second example the objective for the in-wheel motor vehicle is to travel along the road with the predefined reference velocity. Here in the simulation the high-complexity vehicle dynamic software CarSim® is used. The specifications, i.e., the reference path with its altitude and predefined velocity are shown in Fig. 8. Fig.9 shows the control signals, i.e., the steering angle and the wheel torques.

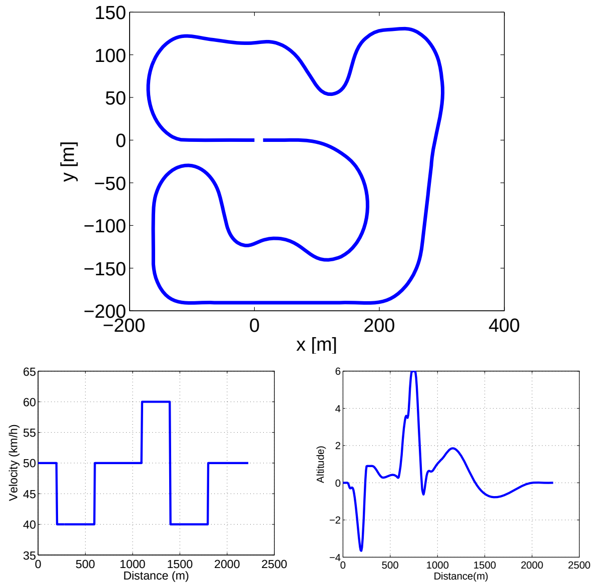

Figure 8. Reference path with its altitude and predefined velocity

As Fig.10. illustrates, both the lateral error and the velocity error are acceptable. These signals increase when the vehicle is travelling in sharper bends, the road slopes change or velocity changes suddenly. Consequently, the velocity and path tracking ability of the designed control system is acceptable.

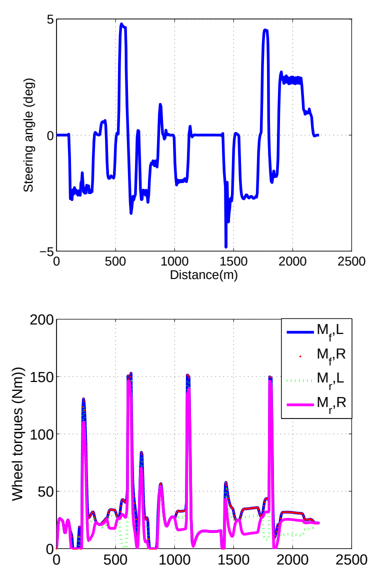

Figure 9. Steering angle and wheel torques

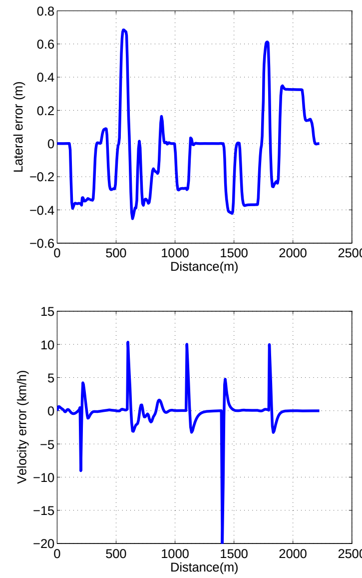

Figure 10. Lateral error and velocity error

V. CONCLUSION

In the paper design and realization of a four-wheel drive 1:5 scaled vehicle model using in-wheel permanent magnet synchronous motor (PMSM) based electric drives has been presented. Main issues of the system architecture, the components applied, the basic control principles, and a hierarchical control scheme have been outlined. The vehicle model is intended to be applied as an experimental platform to support control design processes in association with electric vehicles that use minimized level of mechanics, instead applying the benefits of electronics and digital control solutions. Furthermore the control system incorporated in the model and the on-board electronics is also suitable for studying and testing general vehicle control and power management solutions both for design and educational purposes.

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