

Efficient Control and Modeling of Autonomous Electric Vehicles

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Abstract

This paper outlines and discusses the fundamental idea behind autonomous vehicles. Following a quick comparison of automotive sensors, more resources are given so that readers who are interested can learn more about the autonomous area. It is concluded that my own contribution will be to incorporate motion control into the suggested model as a future electro-mechanical engineer. This research also reveals that the model's motor drive and Energy Management System are private, inaccessible systems. The speed controller's design is then looked into. It suggests replacing the driver torque regulation with a feedback control loop utilizing a scheduling controller. A data-driven modeling strategy was chosen to approximate a first order mathematical model of the vehicle as a result of the suggested model system analysis. The PI controller settings are calculated for each operating speed using this assessed model. Utilizing LabVIEW simulation, the control loop and dataset creation are implemented.

Keywords: Electric Vehicles, Autonomous Vehicles, Controllers, Throttle Simulation, Torque, Speed

1 Introduction

Intelligent vehicles having the capacity to drive somewhat autonomously (with little human input) are known as autonomous vehicles (AVs). The idea is not new, but now it has moved from science fiction to reality. The majority of auto manufacturers have been won over by the innovative idea of the self-driving vehicle (SDV), which offers promise economic, social, and ecological benefits.

Autonomous vehicles, which were still viewed as science fiction at the turn of the previous century, have quickly advanced into reality during the past ten years. If you're lucky enough to live close to San Francisco, chances are you've seen a Waymo, the Google self-driving vehicle prototype, cruising the streets and offering free rides. With the Model 3, Tesla automobiles are already aiming for the middle class market with its autopilot software, but many accidents also revealed that there are still flaws. Another factor hurting consumer trust in completely autonomous cars is an Uber car's failure to see a pedestrian crossing the street [1].

2 Related Work

This paper presents a comprehensive overview and surveys of the current autonomous electric vehicles, platforms, emphasizing the software-hardware co-evolution to the current technology. Based on technical discussion with leading researchers in this field, the open research challenges are also presented that will guide future researches in this field.

2.1 An Adaptive Constrained Path Following Control Scheme for Autonomous Electric Vehicles

Zhang *et al.* [2] proposed an adaptive constrained path following control scheme considering the influence of parametric uncertainty for autonomous electric vehicles. Firstly, an adaptive feedback control law and its update law are proposed to deal with the variation of tire cornering stiffness during vehicle path following process. Secondly, a constraint function for lateral displacement error during path following process is designed to further improve driving safety. And then, the closed-loop stability of the proposed control scheme is proved. Finally, the validation is implemented by simulation and experiment, the results show that the proposed control scheme is effective under

different working conditions. The maximum lateral displacement error is reduced to 0.0297m by using the proposed scheme in the experiment. The proposed scheme might provide a theoretical reference for control practice of autonomous vehicles.

2.1.1 Motor Drive Model with Faulty Factor

The permanent-magnet brushless direct current (BLDC) motor has been widely used to drive EVs because of high efficiency and high power density. In this paper, the permanent-magnet BLDC motor is selected as the driving in-wheel motor. The mechanical motion of a motor is much slower than the electromagnetic dynamics, implying that the dynamic response of the motor driver can be ignored [3]. Therefore, the motor driver and in-wheel BLDC motor unit can be described simply as a control gain k_i :

$$k_i = \frac{T_i}{u_i} \quad (1)$$

$$= \frac{F_i R}{u_i} \quad (2)$$

where i represents the four in-wheel motors respectively, ($i = fl, fr, rl, rr$).

Some common motor faults, such as the fault in either a motor winding or an inverter phase, can be modeled as a reduction in motor control gain. A faulty factor λ_i which belongs to $0 \sim 1$ is used to describe the degree of motor fault. Then, the control gain after failure can be achieved as

$$\hat{k}_i = (1 - \lambda_i)k_i \quad (3)$$

The motor fault diagnosis and the estimation of the faulty control gain can be estimated by some various fault diagnosis methods [4]. In this research, the fault tolerant control of the 4WID system is focused. Therefore, the control gain and the fault factor \hat{k}_i, λ_i are assumed to be known.

2.2 Adaptive Tube-Based Nonlinear MPC for Economic Autonomous Cruise Control of Plug-In Hybrid Electric Vehicles

Sakhdari and Azad [5] proposed an adaptive tube-based nonlinear model predictive controller for the design of autonomous cruise control systems. This method ensures the robust satisfaction of the defined constraints in the presence of uncertainty, and also improves the systems performance by adapting to the changes in the vehicle control-oriented model. Therefore, in a way, this method decouples performance and robustness by using separate models one for constraint handling and another one for defining the objective function.

In the modeling step, a nonlinear control oriented model was presented for a vehicle that performs car-following. This model was used for evaluation of the safe sets in the presence of additive disturbance. Moreover, models for fuel consumption and electricity rate were presented to estimate the cost of energy in the prediction horizon and based on them, reduced models for parameter estimation were generated. A high-fidelity model of the base-line PHEV, Toyota plug-in Prius, was used to evaluate the controller.

2.3 Robust Integral Backstepping Control for Unified Model of Hybrid Electric Vehicles

Siffat *et al.* [6] proposed a unified model of fuel cell based hybrid electric vehicle along with robust integral backstepping and robust backstepping controllers for DC bus voltage regulation and motor speed control. Lyapunov stability theory has been used for proving the asymptotic stability. Performance of the proposed controllers for the unified model has been analyzed using MATLAB/Simulink environment. Comparative analysis of the unified model with the conventional model has been done using linear controller. The results show that unified model has significant improvements in voltage regulation and efficiently tracks the extra urban drive cycle (EUDC) speed profile. Also, comparative analysis of nonlinear controllers with each other has been given on the unified model. The results illustrate that robust integral backstepping controller has substantially reduced the overshoots/undershoots, convergence time and steady state error; hence making robust it is suitable for fuel cell hybrid electric vehicle (FHEV). The schematic model of the hybrid electric vehicle is presented in Figure 1.

Future works may encompass implementation of these control methodologies on real platforms, different energy sources and converter topologies or different controllers to further reduce speed tracking and voltage regulation errors.

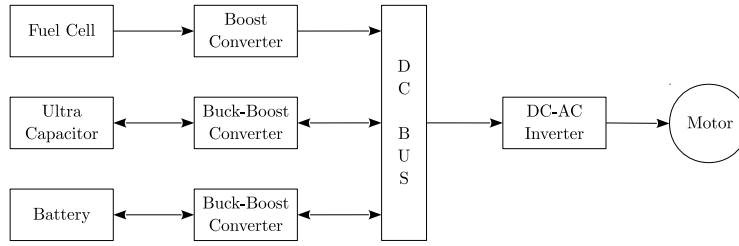


Figure 1: Model of Hybrid Electric Vehicle

2.4 Degradation Control for Electric Vehicle Machines Using Nonlinear Model Predictive Control

Samaranayake and Longo [7] formulated and implemented a multi-objective optimal control problem via a nonlinear model predictive control (NMPC) scheme. By exploiting the inherent redundancy in actuation in electric machines, we have shown how their degradation can be minimized, while closed loop tracking performance maintained, via constrained optimal feedback control. A tuning parameter in the cost function allows to trade off degradation and closed loop performance. It was observed, in simulation experiments using a higher-order model for the plant, that NMPC outperforms the de-facto maximum torque per ampere (MTPA) controller because of its ability of providing an optimal solution rather than a heuristic one. Algorithm optimization for real-world applications could be the subject of future research.

2.5 Explicit Nonlinear Model Predictive Control for Electric Vehicle Traction Control

Tavernini *et al.* [8] presented traction controllers for electric vehicles with in-wheel motors, based on explicit nonlinear model predictive control of the wheel slip velocity. These were compared with more conventional traction control (TC) strategies based on PI control.

To objectively assess the TC performance, a set of performance indicators is identified based on the root-mean square value of the slip ratio error, i.e., a tracking performance indicator:

$$\text{RMSE} = \sqrt{\frac{1}{t_e - t_i} \int_{t_i}^{t_e} (\sigma_x(t) - \sigma_x^{\text{ref}})^2 dt} \quad (4)$$

where $\sigma_x(t)$ is the actual value of the slip ratio during the relevant part of the test, defined by the initial and final times t_i and t_e . The final value of vehicle velocity, V_f , i.e., an acceleration performance indicator. The normalized integral of the absolute value of the control action, which gives an indication of the required control effort:

$$\text{IACA} = \frac{1}{t_e - t_i} \int_{t_i}^{t_e} |\Delta T(t)| dt \quad (5)$$

2.6 Nonlinear Hybrid Impedance Control for Steering Control of Rack-Mounted Electric Power Steering in Autonomous Vehicles

Jeong *et al.* [9] presented an innovative approach to steering control, based on torque overlay, for the smooth and efficient transfer of the steering control from an autonomous driving system to the driver, and to control the pinion angle of the rack-mounted electric power steering for lateral control of an autonomous vehicle. The novelty of their approach lies in the formulation of hybrid impedance control, which employs steering control for both lateral and impedance controls. Their proposed method, nonlinear hybrid impedance controller, consists of desired impedance pinion angle generator and a super-twisting sliding mode controller for pinion angle tracking. The desired impedance transfer function of the driver's torque to the steering wheel angle reflects the driver's torque to the steering control.

The desired impedance pinion angle is generated using the desired impedance transfer function and the desired pinion angle derived by the lateral controller. The sliding mode control method is designed, based on a super-twisting algorithm for the pinion angle, to track the desired impedance pinion angle. Consequently, without the driver's torque, their proposed method is activated as a pinion angle tracking controller for lateral control of an autonomous vehicle. Moreover, with the driver's torque, the proposed method is activated as an impedance controller.

2.7 Autonomous-Driving Vehicle Control With Composite Velocity Profile Planning

Lee and Chung [10] developed a composite velocity profile (CVP) planning and decentralized feedback control for autonomous driving. The CVP that consists of longitudinal speed and lateral velocity profiles innovatively enabled complete lane changes with vehicle speed planning. An autonomous-driving control framework with decentralized speed/lateral control was developed to use the CVP.

The robust stability of the autonomous-driving control system was mathematically proved. A scenario-based autonomous-driving test demonstrated its utility with a splendid lane change. The proposed autonomous-driving control with CVP planning and its design methods are expected to serve as very useful design tools in autonomous driving.

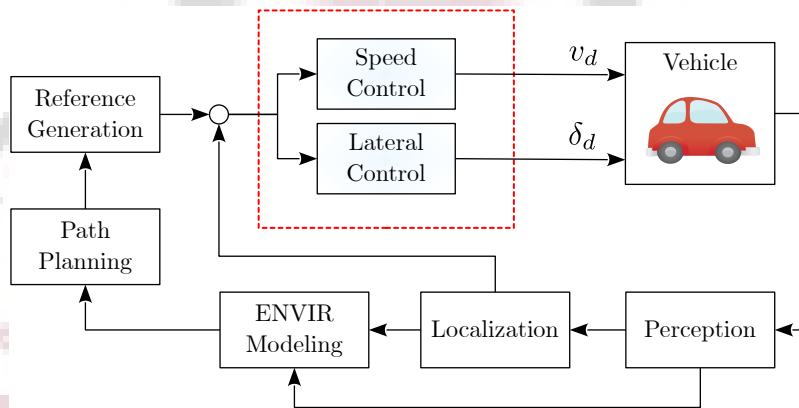


Figure 2: Functional Decomposition of the Autonomous-Driving Vehicle Control System

The autonomous-driving vehicle control system that are interested in proposed work is depicted in Figure 2. This approach is as the figure to dissect a complex automotive system into accessible subsystems with communications between them. These individual function-specific subsystems can be separately designed and implemented but functionally connected for autonomous driving. Maneuver planning is defined as simply determining a gridwise movement in a given occupancy grid environment (ENVIR) model.

2.8 Adaptive Sliding Mode Fault Tolerant Coordination Control for Four Wheel Independently Driven Electric Vehicles

Zhang *et al.* [11] proposed an adaptive sliding mode fault tolerant coordination (ASM-FTC) strategy for four wheel independently driven - electric vehicle (4WID-EVs) to maintain the stability and acceptable performance of the vehicle when in-wheel motor driver fault happens. The motor fault information is introduced into a new 4WID-EV dynamic model as the fault factor. The ASM controller was designed to handle the system uncertainties and disturbances. In the 4WID system, the multi-motor was coordinated to accommodate motor fault using the FTC allocation. The physical constraints of the motor and tire-road friction were taken into account and the variation of the control gain of the faulty motor was also considered. When a motor fault occurs, according to the fault information, Hessian matrix H and control effectiveness matrix B were updated automatically. The 4WID-EV model with the front wheel steering is shown in Figure 3.

The simulation and experimental results illustrated that with the proposed ASM-FTC strategy, the operation performance of the vehicle can be improved. The chatting and vehicle lateral deviation were greatly reduced. Meanwhile, the precision and the reach time were also improved. Moreover, it was also can be concluded that one motor fault in the 4WID drive system did not significantly impair the yaw rate dynamic under the drive situations such as small steering angle and low vehicle speed. However, the vehicle trajectory deviated from the desired trajectory obviously. It increased the burden of the driver. In the case of the high vehicle speed on the low friction coefficient road, the serious traffic accident may occur in the event of actuator failures. Therefore, it is important and necessary to design FTC control to improve the maneuverability and the reliability of the 4WID-EVs. In the future, the effects of time delay of online fault diagnosis and the FTC will be studied further.

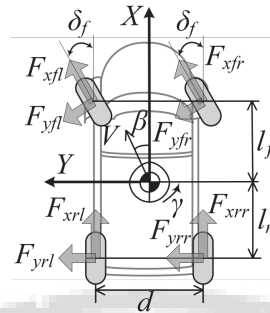


Figure 3: Schematic of 4WID Vehicle Model

3 Proposed Electric Vehicle Model

Nowadays vehicles can be classified into three categories depending on the type of embedded motor/engine used. Most common vehicles are employing “*Internal Combustion Engines*” while *Electric Vehicle* uses electric motors. *Hybrid Electric Vehicle* use both technologies. As this chapter is dedicated on the proposed model prototyping platform which is an electric vehicle, only *Electric Vehicle* will be introduced.

Electric Vehicle use electrical motors for producing the traction effort and chemical batteries, fuel cells or capacitors as its rechargeable energy source. Such vehicles possess advantages over *Internal Combustion Engines* vehicles making them a good alternative choice. *Electric Vehicle* perform with an efficiency above 90% in certain operating regions while an *Internal Combustion Engines* is limited to 40% at best. Additionally to the high efficiency, *Electric Vehicles* produce zero local emissions, low power consumption and enable independence of petrol market. Nevertheless, *Electric Vehicles*’ drawbacks are their higher initial cost, limited driving range, limited battery lifetime, and their long charging time. Those are important disadvantages which need to be solved in order to make *Electric Vehicle* competitive on the vehicle market currently dominated by *Internal Combustion Engines* vehicles. By using both technologies *Hybrid Electric Vehicle* try to combine the advantages of electric vehicles and internal combustion engines by providing higher efficiency and longer driving range.

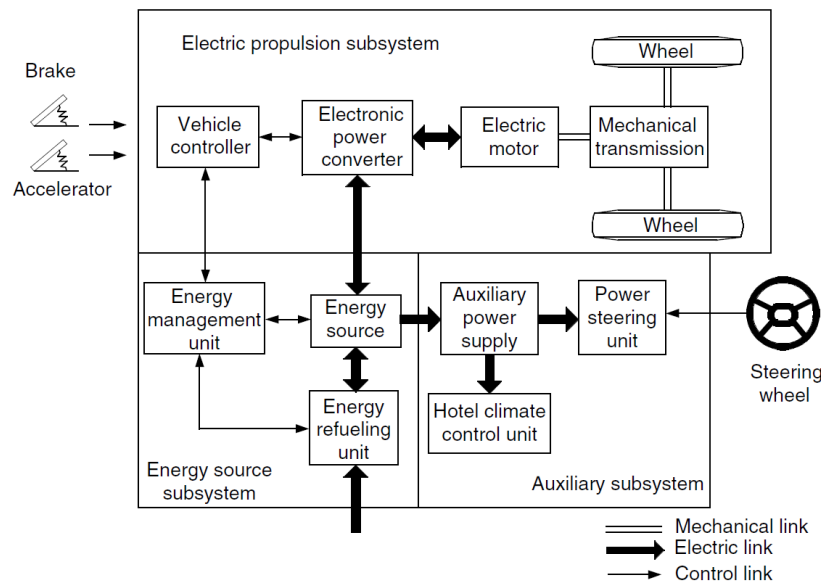


Figure 4: Proposed Conceptual Illustration of Model Configuration

The modern electric vehicle working principle is conceptually represented in FIGURE 4. As shown in this figure, three major subsystems are embedded within *Electric Vehicle*:

- The electric propulsion subsystem,

- The energy source subsystem
- The auxiliary subsystem

Each subsystem is interacting with the others by transferring power through electrical links, or information through control links.

The *energy source* subsystem comprises the energy source itself (like batteries) which supplies the vehicle with electrical power, the refueling unit which enables recharging the energy source, and the Energy Management System which monitors the electrical system state and the power flow. Using its measurements, the Energy Management System regulates the energy flow and optimizes the energy usage. Therefore, the role of the device in *Electric Vehicle* is crucial since its quality affects the vehicle autonomy and general behavior.

The *auxiliary subsystem* is in charge of supplying each auxiliary system such as the headlight, turn signals, the steering helping process, etc.

Finally, the *electric propulsion subsystem* is the main part of an electric vehicle. Given a throttle and a brake pedal input, the vehicle controller computes and provides the electronic power converter with the adequate control signals. The power converter regulates the energy flow from the batteries toward the motor by modulating an electric signal. Additionally, the energy management unit cooperates with the vehicle controller to ensure correct energy transmission with regard to the vehicle state and for safety matter. The energy flows are bidirectional since the electric vehicle can recharge its batteries in a regenerative process. As well, a communication is ensured between the energy refueling unit to ensure proper charging sequence.

There is a variety of practical implementations of electric propulsion system. Early electric vehicles were a derivation of *Internal Combustion Engines* vehicles where the engine was simply replaced by an electric motor and a battery pack while the gearbox and the clutch were kept. Nowadays electric vehicles are equipped with a motor drive that ensures the role of the clutch and the staged gearbox. Actually, the power/torque - speed characteristic of a controlled electric motor allows to remove the traditional gearbox of *Internal Combustion Engines* vehicles, relieving some weight. FIGURE 5 represents a classical drive train topology currently used [12, 13].

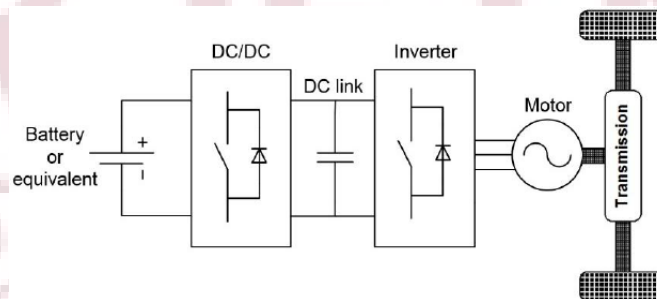


Figure 5: Topology of Battery for Proposed Electric Vehicle

Electric vehicles and hybrid electric vehicles popularity is taking off and are part of the mobility mega-trend like the vehicle automation [14]. *Autonomous Vehicle* is technology based platform which is meant to compute electric signals while electric vehicles can be easily controlled by such signals. It appears that *Autonomous Vehicle* and *Electric Vehicle* are more compatible than would be traditional *Autonomous Vehicle* and *Internal Combustion Engines* vehicles, or at least, they present a better interoperability [14].

3.1 Physical Understanding of Speed Regulation

When someone is driving on the road, the driver constantly pushes or releases the throttle. Indeed, external forces are applied to the vehicle and produce a resistive torque at its wheels. In order to stay in motion the vehicle must produce a forward torque to compensate these external forces.

As the induction motor, the longitudinal dynamic is characterized by a torque - speed curve as illustrated in FIGURE 6. The intersection between the induction motor and the longitudinal characteristic determines the vehicle speed.

However, the desired speed and the external forces applied on the vehicle change constantly and therefore it is necessary to modulate the torque - curve characteristics to drive at any speed; this is the role of the motor drive.

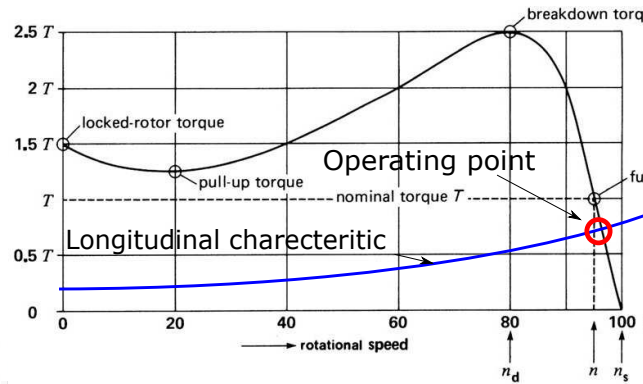


Figure 6: Induction Motor and Longitudinal Characteristic

3.2 Design of Motor Drive

Among multiple vector control methods for induction motor, the proposed model uses an *Indirect Flux Oriented Control* algorithm (FIGURE 7). The idea of such a method is to apply the appropriate coordinate transformation to realize the torque and the flux control independently. In particular, the 3-phase (a, b, c) coordinate system is transformed into 2-phase ($\alpha\beta$) system, which is rotated by an angle θ to obtain a dq coordinate system. The angle θ is chosen to align the flux with the d coordinate simplifying the motor equations, and it estimated using the motor measurement ω . Then, the torque can be controlled using stator current along q axis (i_q) and the flux can be controlled using the current along d axis (i_d).

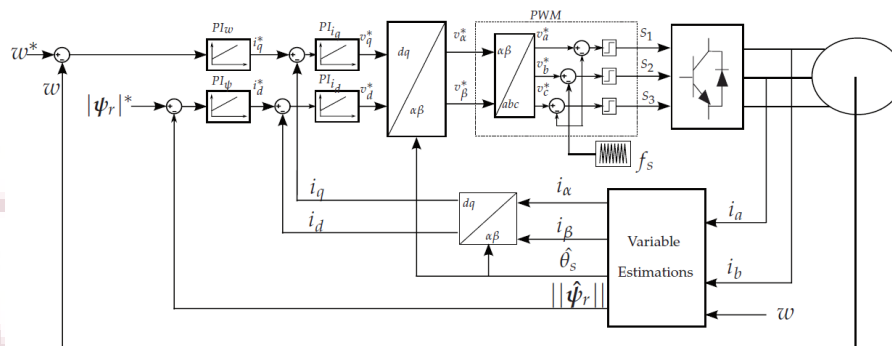


Figure 7: Block Diagram of Indirect Flux Oriented Control

Notice the unique motor feedback (FIGURE 7) is its rotational speed ω which estimates, using i_a and i_b respectively the stator current from phase a and b, the motor flux ψ_r and torque (associated to the value i_d and i_q). This characterizes the behavior of an *Indirect Flux Oriented Control* while a direct FOC, would use a direct measure of those values instead of estimating them. Indeed, placing the required sensors inside induction motor confined volume for such measurements is expensive, and thus *Indirect Flux Oriented Control* is most popular of the two solutions. In FIGURE 7, the *Indirect Flux Oriented Control* is configured in speed control mode and will follow the speed reference ω^* . Such control algorithm is capable of working in torque control by directly regulating i_q^* .

FIGURE 8 illustrates the Curtis diagram which receives the throttle and brake commands and provides the 3-phase voltage to the induction motor. It highlights that the AC controller is a black box system which has software access restricted to proposed model and which has an inaccessible internal processes. It underlines the safety and logical functions ensured by the *Curtis Instruments India Private Ltd* and the communication with the *Energy Management System* which has also a (software) limited access to proposed model.

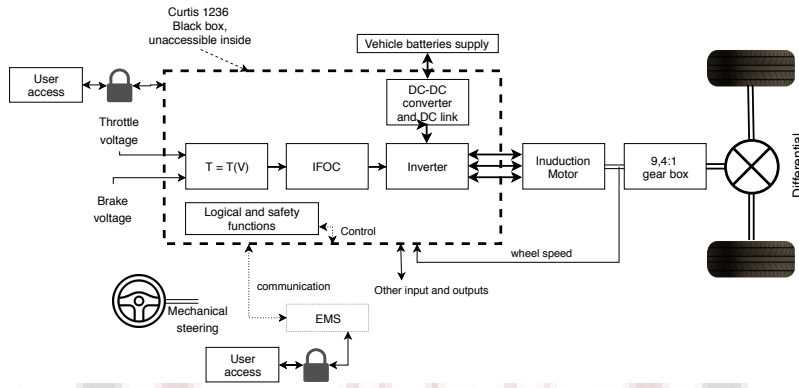


Figure 8: Curtis Instruments India Private Ltd within Model Propulsion System

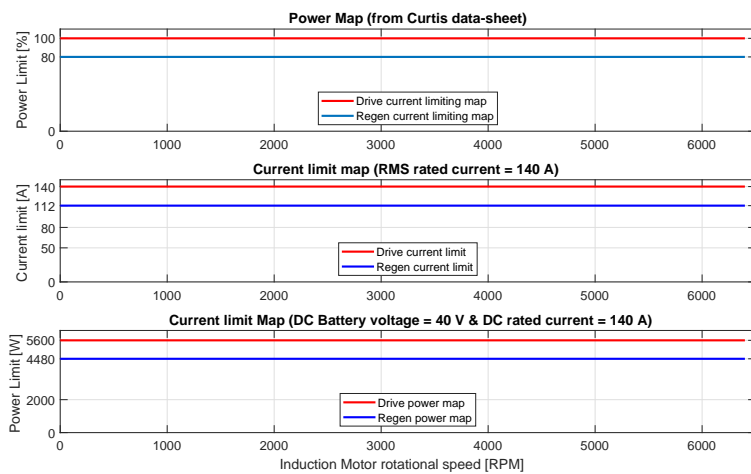


Figure 9: Model's Power Map

4 Simulation Result

The power map of the proposed controller (and its attached induction motor) is given in FIGURE 9 in regenerative process and driving conditions. The power upper limit is constant meaning the model operates at a constant power 5600 W (4480 in regenerative) with the entire speed region. A maximum current of 140 A is taken from the batteries in driving mode.

An *Indirect Flux Oriented Control* can work either on speed control mode or torque control mode, thus the user select either of them. The proposed model predefined its work in torque control mode, and therefore the input from the pedals are interpreted as an available torque request (FIGURE 10).

5 Throttle Response of the Proposed Model

The model does not drive correctly while using the new batteries, it aims is to analyze and diagnose the problem source. Multiple data measurements have been recorded however only few measurements are provided here to illustrate the model's behavior while the other are omitted. FIGURE 11 represents the final full throttle response of the proposed model.

The model was submitted to a full throttle experiment with the results provided in FIGURE 11.

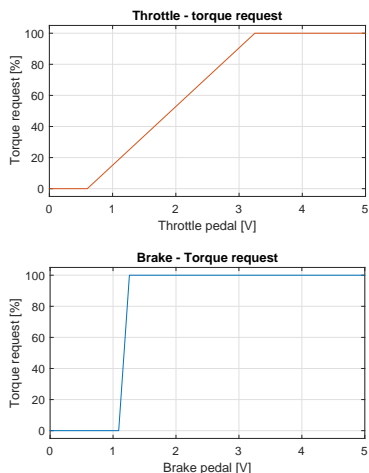


Figure 10: Torque Request vs Throttle and Brake Pedal Voltages

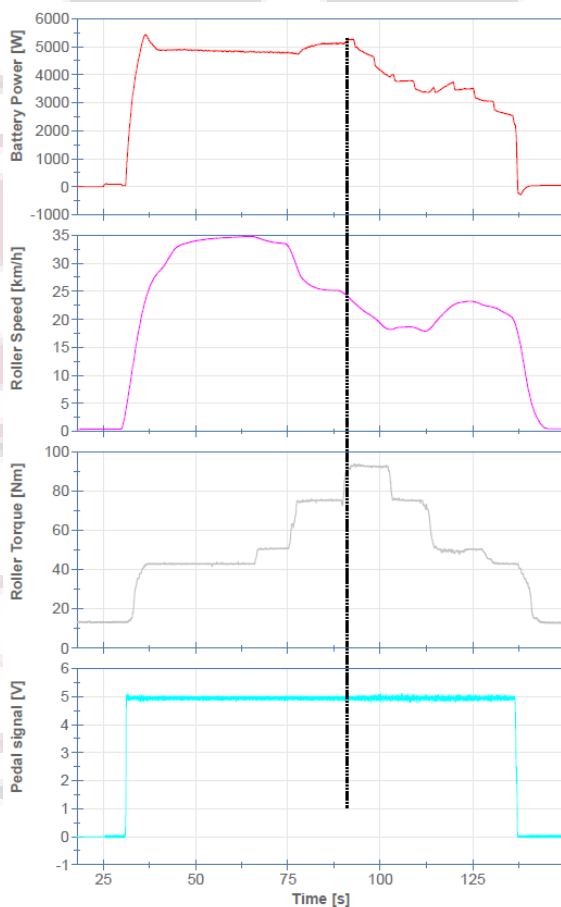


Figure 11: Full Throttle Response of the Proposed Model

6 Conclusion

This paper report presents, analyzes and determines efficient control and modeling of autonomous electric vehicles. The proposed model is an *Electric Vehicle* using an induction motor based controlled by an motor drive. Despite knowing the power maps of the motor, its data-sheet remained inaccessible and the induction motor parameters are

missing. The drive is a motor controller which generates, using the throttle and brake inputs, the appropriate AC signals supplying the induction motor from the DC batteries. The model uses an *Indirect Flux Oriented Control* based algorithm which has additional safety procedures over-layers. This device is a black box process where the main internal sub-processes principles are known but are inaccessible and details about those sub-processes are unprovided. The model is a reprogrammable motor drive meaning a finite set of parameters can be tuned using tools (a software and handler programmer).

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