

Design of an Adaptive FO-PID Controller for an In-Wheel-Motor Driven Electric Vehicle

Yue Shi, Qingwei Liu, and Fan Yu
 Shanghai Jiao Tong University

ABSTRACT

An EV prototype, with all the wheels respectively driven by 4 inwheel motors, is developed, and undergoes a series of practical measurements and road tests. Based on the obtained vehicle parameters, a multi-body dynamics model is built by using SolidWorks and Adams/Car, and then validated by track test data. The virtual prototype is served as the control plant in simulation. An adaptive fractional order PID (A-FO-PID) controller is designed to enhance the handling and stability performance of the EV. Considering the model uncertainties, e.g. the variation in body mass distribution and the consequent change in yaw moment of inertial, a Parameter Self-Adjusting Differential Evolution (PSA-DE) algorithm is adopted for tuning the controller parameters, i.e. K_p , K_i , K_d , λ and μ . As a modification of traditional DE algorithm, the so-called Variance of Population's Fitness is utilized to evaluate the diversity of the population. In order to avoid the premature convergence problem, a random disturbance is applied on the scaling factor in each iteration step, until the optimal solution is resolved. The simulation tests under some typical handling cases are carried out, and the results show that the proposed A-FO-PID controller is feasible and effective to enhance the handling and stability performance of the vehicle.

CITATION: Shi, Y., Liu, Q., and Yu, F., "Design of an Adaptive FO-PID Controller for an In-Wheel-Motor Driven Electric Vehicle," *SAE Int. J. Commer. Veh.* 10(1):2017, doi:10.4271/2017-01-0427.

1. INTRODUCTION

Electric vehicles (EVs) have been of great interest during the recent decades, among which the ones driven by independently controlled in-wheel motors are considered as one of the most promising configurations for future vehicle design. With such configuration, the overall vehicle weight can be reduced, and there is more space for batteries, electric systems and auxiliary equipment, along with more cargo and passenger space. The merits of adopting electric motors as actuators are remarkable. By replacing the traditional engine-powertrain systems, the control torques, either accelerating or decelerating the vehicle, can be directly applied to every wheel. Thus, the power transmission efficiency can be highly improved, and the goal of zero-emission is ensured. Apart from all the advantages above, such configuration also provides an access for more accurate and flexible control to enhance the vehicle handling and stability performance. With the fast and precise response characteristics of the electric motor, unequal torques can be independently allocated, and adjusted according to the operation limits (e.g. road adhesion, actuator capability, etc.), or the control objectives (e.g. desired yaw motion, optimal path following, etc.).

During the past decades, many optimal control method have been proposed and investigated to enhance the vehicle handling and stability performance based on tracking the desired yaw motion [1, 2, 3, 4]. In literature [5], an optimal controller was developed. The external yaw moment, which is to modify the vehicle handling and stability performance, consists of one feed-forward signal, the input steering angle, and two feed-back state variable, the yaw rate and the

lateral velocity. In [6], an optimization-based yaw rate tracking algorithm was proposed, and implemented by generating unequal torques on the bilateral rear driven wheels via in-wheel motors.

In [7], a PID-based yaw moment control system was designed, with its parameters optimized by genetic algorithm (GA). Comparing to general optimal control method, the PID controller is simpler to implement, meanwhile the robustness and the efficiency are ensured by the adoption of GA method for tuning the controller parameters. As an extension of traditional integer order PID controller, the Fractional Order PID (FO-PID) controllers have received much attention recently [8]. With more design parameters, such controllers possess flexibility and capability to fulfill more design specifications. However, this also raise the demand for an effective and efficient approach to automatically optimize the controller parameters. From the perspective of the design specifications of the closed-loop system, relay feedback tuning method is adopted in some literatures [9, 10, 11]. A more straightforward way is to directly use the optimization methods, e.g. Genetic Algorithms (EAs), Particle Swarm Optimization (PSO), etc., for searching the best set of the parameters. In [12], a new search heuristic named Differential Evolution (DE) is proposed. Comparing to traditional EAs and PSO, the DE algorithm has shown superior performance in some practical applications [13].

In this study, an auto-tuned FO-PID controller is designed to enhance the handling and stability performance of the EV prototype. The major contributions of this work are: 1. building an accurate multibody dynamics model with respect to the unique physical

attributes of the EV prototype; 2. investigating the feasibility and effectiveness of the FO-PID controller in case of improving vehicle handling and stability, and, also, using a modified DE algorithm to auto-tune the parameters of the controller. The rest of the paper is organized as follows. The construction of the EV prototype is introduced and the bench measurements and the track tests carried out to obtain the vehicle parameters are described in Section 2, along with the establishment of the multi-body dynamics model and the model verification. The controller design is presented in Section 3, including the description of the reference model and the algorithm proposed for tuning the controller parameters. In Section 4, the simulations results are presented, and the feasibility and effectiveness of the proposed controller are examined.

2. EV PROTOTYPE AND VIRTUAL PROTOTYPING

2.1 Development of EV Prototype

An EV prototype is developed by Institute of Automotive Engineering, Shanghai Jiao Tong University, as shown in Figure 1. A pair of Li-Ion battery packages, which are consisted of 64 cells, providing about 120V totally, are equipped to power the 4 in-wheel motors each of which can independently generate driving/braking torque to the corresponding wheel. The steering system is modified with an angular sensor mounted on the steering column to measure the steering wheel angle input by driver. The vehicle motion information is measured by an INS/GPS RT3002. The motor driving algorithm is implemented and running online with the utilization of AD5435, a real-time simulation machine. An uninterruptable power supply (UPS) is utilized to power the aforementioned devices.

The prototype undergoes a series of practical measurements and road tests, as shown in Figure 2. The obtained main vehicle parameters are presented in Table 1.



Figure 1. EV prototype and auxiliary equipment

Table 1. Vehicle parameters

Parameters	Values
Mass m (kg)	352.6
Yaw Inertia I_z (kg·m ²)	844.6
CG height h (mm)	370.0
Wheel base L (mm)	1916
Track width B_f, B_r (mm)	1424
Wheel static load $F_{zs,fl}, F_{zs,fr}$ (N)	858.8
Wheel static load $F_{zs,rl}, F_{zs,rr}$ (N)	869.1



Figure 2. Scenarios of test bench measurement and track test

2.2 Multi-Body Dynamics Modelling

Adams is a commercially available virtual prototyping and motion simulation software which can automatically convert a graphically defined model to dynamic equations of motion, and is powerful in simulation and design. However, it is weaker in solid modelling compared to commercial CAD software [14]. In the current study, a multi-body dynamics modelling method using Adams/Car collaborating with SolidWorks is utilized. The flowchart of the modelling procedure is presented in Figure 3.

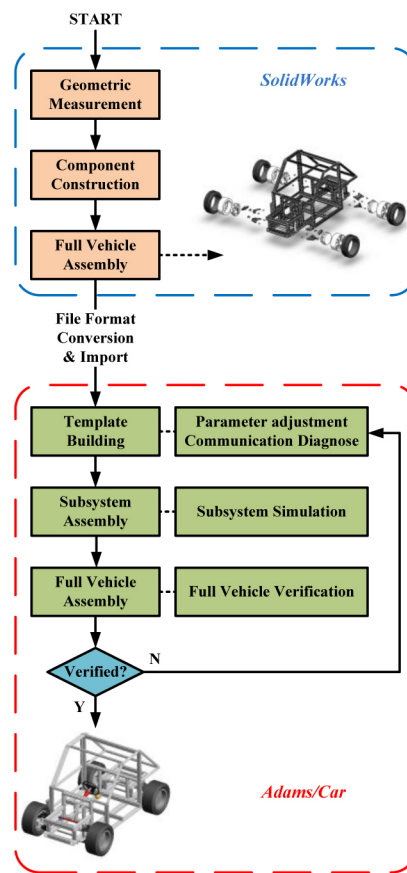
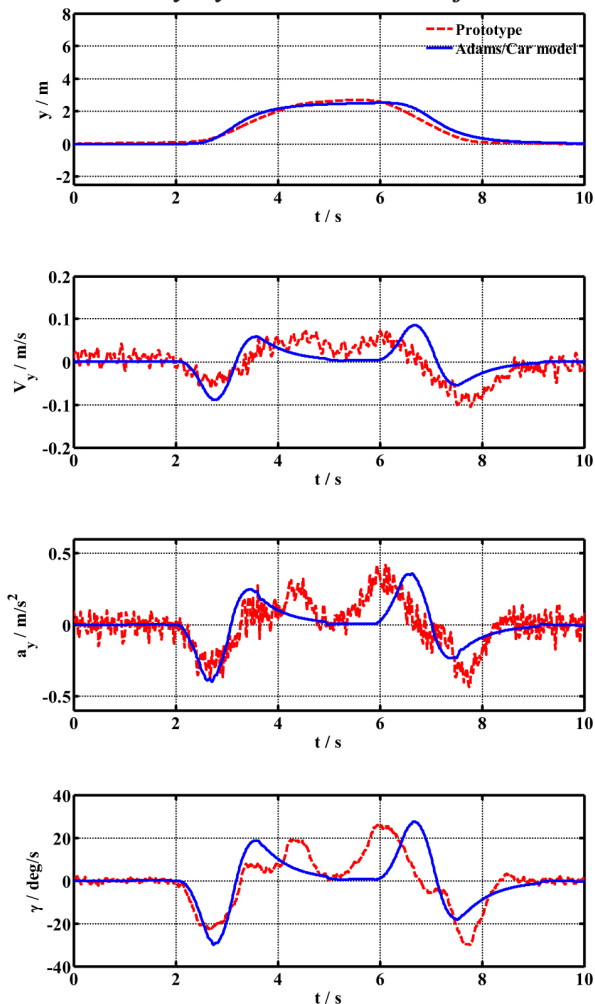


Figure 3. Flowchart of multi-body dynamics modelling

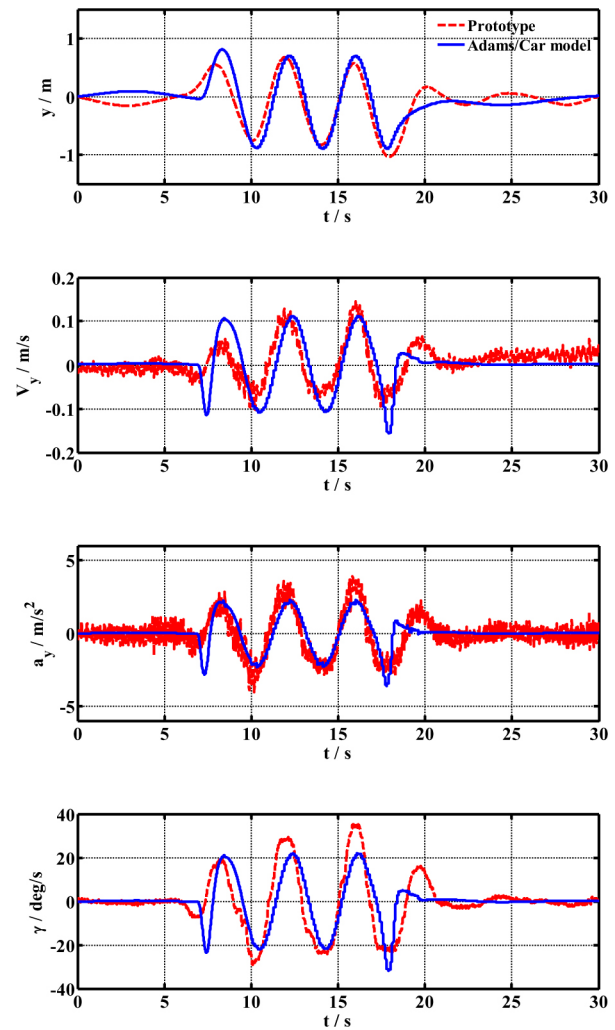
Based on the geometric information of the EV parts, the physical attributes of the movable elements are respectively built and saved. These individual parts are then assembled by defining their relative position to each other, and the designed degree of freedoms of motion are checked. A symmetric diagnose is carried out to ensure the symmetry of the solid structure. The final version of the full vehicle assembly is locked up and got prepared for the modelling in Adams/Car.

Adams/Car provides an access to import a variety of file formats. In this case, Template Building mode is selected, and the SolidWorks files are converted to Parasolid format and imported into Adams/Car. The imported parts are fully created by defining hard points, attachments, feature parameters, mass properties, etc. The templates are built corresponding to the categories of mechanical subsystems, namely the frame, the front and rear suspensions, the front and rear wheels, the steering system, and the braking system. Communicators are defined for exchanging information among the subsystems. A Joint Torque is built and applied to each in-wheel motor respectively, and defined as State Variable which can be controlled through the algorithms outside Adams/Car. Subsystems are then built based on the corresponding templates, and the multi-body model of the full vehicle is finally assembled.

2.3 Multi-Body Dynamics Model Verification



a. Double lane change maneuver



b. Slalom maneuver

Figure 4. (cont.) Comparison of simulation results with track test data

After setting the vehicle parameters and iteratively adjusting the characteristics for crucial force elements, e.g. the spring and the damper, the Adams/Car model is established. A series of simulation are carried out, and the results are compared with the experimental data of the road tests. Two typical examples, i.e. the Double Lane Change (DLC) test and the Slalom test, are presented in Figure 4.

In both cases, the virtual prototype is respectively required to trace the same trajectories as those do in the road tests. The driver model embedded in Adams/Car is adopted. The comparison results of both cases identically indicate that the established Adams/Car model and the physical prototype fit well with each other in characteristics of dynamics responses, with the Root Mean Square Error (RMSE) listed in Table 2, which in turn verifies the effectiveness of the established EV model in Adams/Car environment.

Table 2. RMSE of state variables

	y (m)	v_y (m/s)	v_x (m/s)	a_y (m/s ²)	γ (deg/s)
DLC	0.1857	0.1386	0.0303	0.1174	8.2411
Slalom	0.5691	0.1812	0.0718	0.3547	1.1383

Figure 4.