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Article

Development and Validation of an Arduino-Based Control Algorithm for an Electronic Differential in Quad In-Wheel Hub Motor Electric Vehicles

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Abstract: This paper presents the development and validation of a control algorithm for an Arduino-based EDS EV. The main goal of this system is to improve the speed and torque distribution between the wheels while maneuvering, focusing especially on cornering. The suggested algorithm regulates the throttle signal supplied to each wheel based on the steering angle, using a mathematical model derived from the Ackermann-Jeantand geometry. Initial simulations were run in MATLAB/Simulink to validate the theoretical approach before its real-world implementation. Arduino Uno board was used to adjust the throttle pedal voltage signal for each wheel at low, medium, and high acceleration performance. The response of the voltage supplied to the inner and outer wheels while changing the steering angle had been analyzed. The voltage on the inner wheels decreased when increasing steering angle, while it increased on the outer wheels. Compared to the simulation results, the experimental results indicate minor differences, which can be referred to the effect of noise and the limited accuracy of the hardware used. The results indicate that the Arduino-based EDS system can achieve precise torque distribution of EVs. This study forms a basis for the implementation of the system on a full-scale prototype for performance evaluation under actual driving conditions.

Keywords: Electric Vehicle; Electronic Differential System; In-wheel Motor; Independent Drive; Ackermann

1. Introduction

The global need for cleaner and more efficient transportation has become a research priority in electric vehicle (EV) sector. Electronic Differential System (EDS) moves beyond the familiar gear-based differentials. The EDS takes full advantage of electric propulsion by using independent motors for each wheel. This allows real-time control over wheel speed, which improves torque distribution, traction and vehicle stability [1]. The use of EDS has become a key trend in electric vehicle transportation science today, offering higher efficiency and performance than conventional electronics can achieve. Studies show that single-inverter EDS can achieve up to 97.5% of the accuracy of dual-inverter systems, which reduces cost and complexity [2]. Furthermore, EDS frameworks that use torque vectoring effectively solve the problems of traditional differentials, which are often too bulky, mechanically limited and difficult to integrate into modern EV platforms [3]. Research shows that design of EDS for EV depends on the control architecture. A centralized system uses one computer to control all wheels, while independent architecture uses local control units for each wheel. This makes the system respond faster and more flexible when things change. Future improvements are moving toward more advanced systems that use torque control and combine complex algorithms, artificial intelligence, and real-time optimization strategies to improve performance levels [4]. Independent control system in four-wheel-drive electric vehicles makes the system more fault-tolerant and redundant. This architecture allows sending power to the wheels based on real-time sensor signal, which keeps the system running smoothly even if there are problems [5].

The idea for an EDS was first explored for a simple two-wheel-drive electric car that used powerful in-wheel motors, known as Permanent Magnet Synchronous Motors (PMSMs). In this setup, the EDS has one crucial job: to instantly manage the different speeds of the left and right wheels as the car turns, much like a mechanical differential does, but entirely through electronics. It pulls data from the vehicle's steering angle and speed and uses a proven mathematical model (the Ackermann-Jeantand model) to calculate the exact speed each wheel needs. To make this control incredibly precise, researchers proposed a Direct Torque Control (DTC) system, which allows the car to adapt smoothly to various road surfaces. This entire approach wasn't just theoretical; it was proven to work through both computer simulations (MATLAB/Simulink) and real-world tests, confirming that it successfully manages wheel speed while keeping the car stable, efficient, and easy to handle [6].

This push for an EDS was driven by a clear goal: to outperform clunky mechanical differentials by using smart electronics to boost both control and energy efficiency. Instead of being limited by physical gears, the EDS uses a network of sensors to constantly adjust power to each wheel. This results in smoother driving when steering and significantly better traction, especially during sharp turns or on challenging roads [3, 7]. By incorporating advanced models like the Ackermann steering model, the system can precisely calculate the ideal speed for each wheel by factoring in the car's rotation (yaw) and the driver's steering input [8,9]. The latest evolution in this technology involves making the EDS genuinely intelligent. Researchers are now integrating sophisticated algorithms, like Proportional-Integral-Derivative (PID) controllers enhanced with neural networks, to make the hub motors respond more efficiently and quickly. These smart systems are a win-win: they drastically cut down on mechanical complexity by eliminating heavy hardware, while also making the vehicle's performance more adaptable to any driving situation [9,10].

The increasing environmental pollution and the shrinking supply of fossil fuels have motivated the global shift toward electrification of transportation. However, many of today's EVs are still using mechanical parts carried over from traditional gas-powered cars, including clutches, gearboxes, and differentials. While these components are needed to transfer power and manage wheel speed, they come with significant disadvantages, they waste energy, create noise and vibration, and require more maintenance [11]. These disadvantages don't just reduce the vehicle's efficiency; they also make the drive less comfortable and add to the long-term cost.

In-wheel motor (IWM) considered a promising solution to these problems. IWM does away with the need for heavy, complex parts like clutches, gears, and differentials by placing a dedicated electric motor directly inside each wheel. This results in higher overall efficiency, precise control over each wheel, simpler mechanics, less noise and vibration, and minimal maintenance [12–14]. IWMs also allow for finer control of the vehicle's handling and stability, which is especially valuable for advanced electric vehicle designs. The catch? Making this work reliably requires motors that are both incredibly powerful and compact enough to fit in a wheel while enduring tough conditions like heat, shocks, and constant vibration. Motor types like Surface-Mounted Outer-Rotor Permanent Magnet Synchronous Motors (SM-OR-PMSMs) and Axial Flux PMSMs (AF-PMSMs) have emerged as most suitable solutions because they are compact, easy to cool, and excel at delivering high torque [15].

Despite these exciting advances, conventional EV designs still face stubborn hurdles that limit their performance and curb consumer adoption. The core of the problem is that even the best batteries hold far less energy than a tank of gasoline, leading to limited driving range and widespread "range anxiety" [16]. Another issue is that most EVs use a single-speed gearbox, which forces a compromise between quick acceleration, high top speed, and efficient cruising. While adding more gears could help, it also brings back the very complexity, energy losses, and reliability concerns that electric drivetrains aim to eliminate [16, 17]. Furthermore, to protect the battery from damage, conservative management systems often limit how much of its stored energy can be used. This can lead to unexpected drops in power when the battery is low, further cutting into the vehicle's range and performance [18].

The search for new electric motor designs is heating up, driven by the high cost and scarcity of the rare-earth materials used in most magnets. This has pushed researchers to seriously consider alternatives like Outer-Rotor Switched Reluctance Motors (OR-SRMs), Synchronous Reluctance Motors (OR-SynRMs), and Outer-Rotor

Induction Motors (OR-IMs). While promising for EVs, these options typically can't match the raw torque power of conventional permanent magnet motors. Another candidate, field-modulated motors, shows potential but is held back by its naturally low power factor and complicated structure. Amidst this search, one thing is clear: using in-wheel motors (IWMs) to precisely manage torque at each wheel is a proven way to boost both the efficiency and stability of an EV. The key is developing high-torque, lightweight motor designs that, when paired with smart suspension systems, minimize unsprung mass. This not only makes for a smoother ride but is a critical step forward for greener EV tech [19].

The benefits of placing motors directly in the wheels are substantial. Most obviously, IWMs remove the need for a complex web of transmissions and differentials. This reduces the overall vehicle mass, cuts down on power losses between the motor and the wheel, and frees up significant space for people and cargo [13,20]. Integrating the power electronics right into the wheel hub also simplifies manufacturing by reducing the total number of parts, giving designers more freedom to create innovative vehicle layouts [20]. From a performance standpoint, IWMs are exceptionally efficient; they can deliver more driving force while using less power and generating less heat, which directly extends the vehicle's range [21]. Even more advanced setups, like using two motors per wheel, have shown impressive gains in both acceleration and energy use, solidifying IWMs as a leading solution for the next generation of electric vehicles [22]. Together, these advantages highlight the truly transformative potential of in-wheel motor technology for the future of electric mobility.

When it comes to building an EDS, engineers have a full toolbox of electric motor types to choose from, including DC, induction, permanent magnet synchronous (PMSM), brushless DC (BLDC), and switched reluctance motors. Each has its trade-offs. Induction motors are a popular choice for their low cost, ruggedness, and proven reliability. However, for most modern electric vehicles, PMSMs and BLDC motors are often the top picks because they pack more power into a smaller size, run more efficiently, and offer sharper dynamic performance—all crucial for a responsive and energy-conscious drive [21]. Even more advanced designs, like axial flux and spoke-type permanent magnet motors, push these metrics further by generating higher power from an ultra-compact and light package, helping designers overcome the tight space constraints in modern EVs [22].

Research comparing these motors within EDS frameworks shows how each enables different innovations. For example, Magnetic Differential systems use a special double-rotor motor to create a differential effect, offering a solution that is more compact, mechanically simpler, and potentially more reliable than traditional gear-based or electronic systems [23]. In another approach, using two five-phase induction motors run by a single inverter allows for precise, independent control of each wheel's torque, enabling the core functions of an EDS and improving traction [24]. Overall, while PMSMs are usually favored for their top-tier efficiency and response, multi-criteria analysis shows that induction motors stay competitive by striking a practical balance between cost, durability, and perfectly adequate performance for many EV needs [25].

Finally, placing the motor directly in the wheel (IWM) itself offers unbeatable advantages for power delivery, maneuverability, and freeing up vehicle space. But this design isn't without its challenges; it introduces new control complexities that require sophisticated and innovative strategies to ensure the vehicle remains stable and reliable [26]. The key takeaway is that there's no single "best" motor. The ideal choice hinges on carefully weighing the target performance goals, budget, and specific demands of the application, guiding the design of efficient and high-performing EDS-based electric vehicles.

Integrating an EDS into multi-motor electric vehicles improves stability, especially when taking corners or changing speed. The core benefit comes from the EDS's ability to intelligently shuffle torque between the wheels in real-time. This active management cuts down on wheel slip and maximizes traction, no matter the driving conditions. To make this happen, engineers rely on advanced control strategies. Techniques like DTC, Fuzzy Logic Control (FLC), and Neural Network-based PID controllers are commonly used to dynamically adjust wheel torque, prevent slippage, and instantly adapt to changing road surfaces [27,28].

But the innovation doesn't stop there. Researchers are developing even more sophisticated methods to make these systems tougher and more adaptable. Multi-agent control frameworks, Active Disturbance Rejection Control (ADRC), and algorithms based on graph theory allow for distributed, coordinated decision-making. This lets the EDS maintain flawless performance even when facing internal uncertainties or external disturbances, like sudden loss of traction [5].

A key recent focus has been on perfecting steering stability and ensuring the vehicle follows its intended path precisely. For instance, refining the classic Ackermann steering model by adding a tire slip angle correction coefficient has proven to sharpen steering response dramatically. This enhancement boosts high-speed stability, even on slippery roads with poor grip [29].

Unlike modern EDS, the traditional mechanical differentials found in most gas-powered cars have some built-in flaws that hurt both performance and efficiency. The core problem is simple: without a way to differentiate, the inner and outer wheels are forced to turn at the same speed when cornering. This causes the tires to scrub and slip. This isn't just increasing stress on tires and higher maintenance costs, it's also wasteful. The inefficient power distribution increases energy consumption and, most importantly, reduces vehicle stability, especially at higher speeds [30]. Furthermore, in a single-motor EV that uses a mechanical differential, the system adds significant weight and rotational inertia, which drags down the entire drivetrain's efficiency. This is why modern EVs are increasingly turning into multi-motor setups (dual or quad-motor configurations). These systems allow for precise, independent control of the torque sent to each wheel. The results are major gains in energy efficiency, dynamic stability, and overall weight reduction, firmly establishing EDS as a foundational technology for the next generation of EVs [31,32].

EVs with IWMs that use the Ackermann steering model and four-wheel steering (4WS) techniques have a lot of benefits when it comes to handling, stability, and performance. The Ackermann model makes it possible to control vehicle dynamics very precisely, especially at low speeds. This improves stability and helps the vehicle stay at the right speed through differential control methods [33]. Additionally, 4WS systems improve motion performance by controlling yaw motion and sideslip angles, which makes it easier to maneuver without using traditional steering actuators [34]. Adding torque vectoring capabilities to IWMs makes it possible to control the yaw moment directly. This improves vehicle stability by changing how torque is distributed among the wheels, which improves cornering performance and energy efficiency [35]. Also advanced control algorithms can keep the wheels in sync even when the conditions are tough. This cuts down on tire wear and makes sure that the vehicle works well on a variety of terrains [36]. All of these technologies work together to make driving better and reduce the environmental problems that come with traditional cars.

The principles of Ackermann-Jeantand geometry were modeled in MATLAB Simulink and tested with real hardware. To evaluate the system's ability to accurately calculate the correct wheel voltages under various steering angles and acceleration levels was evaluated. The accelerator pedal, with a working voltage range from 0.8 V to 4.2 V, was set to 1.2 V, 3 V, and 4.2 V, corresponding to the low, medium, and maximum acceleration levels, respectively. Crucially, this work doesn't ignore real-world challenges. By using a combined approach of simulation and experiment, this research seeks to prove that an Arduino-based EDS is not only feasible but also responsive and stable under different steering conditions. The results are expected to provide the bases for future optimization of the control system and to support the integration of such affordable EDS technology into working electric vehicle prototypes.

2. Materials and Methods

EDS design based on the Ackermann-Jeantand model, first developed by Rudolf Ackermann [37]. This principle is especially useful for EVs navigating turns at low speeds. The model's rule is to smoothly follow a curve, the outer wheel must turn faster than the inner wheel, with the exact speeds determined by the radius of the turn [38,39]. A diagram of how this model applies to an EV with in-wheel motors is provided in **Figure 1**.

To put this theory into practice, this study uses a multi-turn rotary potentiometer to measure the driver's steering input (δ). This steering angle (δ) is what tells the vehicle which way to go. When the steering wheel is straight ($\delta = 0$), the car travels in a straight line and all wheels turn at the same speed. When the driver turns the wheel ($\delta \neq 0$), the car begins to turn, and the system must instantly create a difference in wheel speeds. This differential speed is crucial. Because the outer wheels have a longer distance to travel on a larger radius, they must spin faster than the inner wheels. This coordinated speed difference is what maintains vehicle stability and prevents tire scrubbing and slip during the turn [40,41].

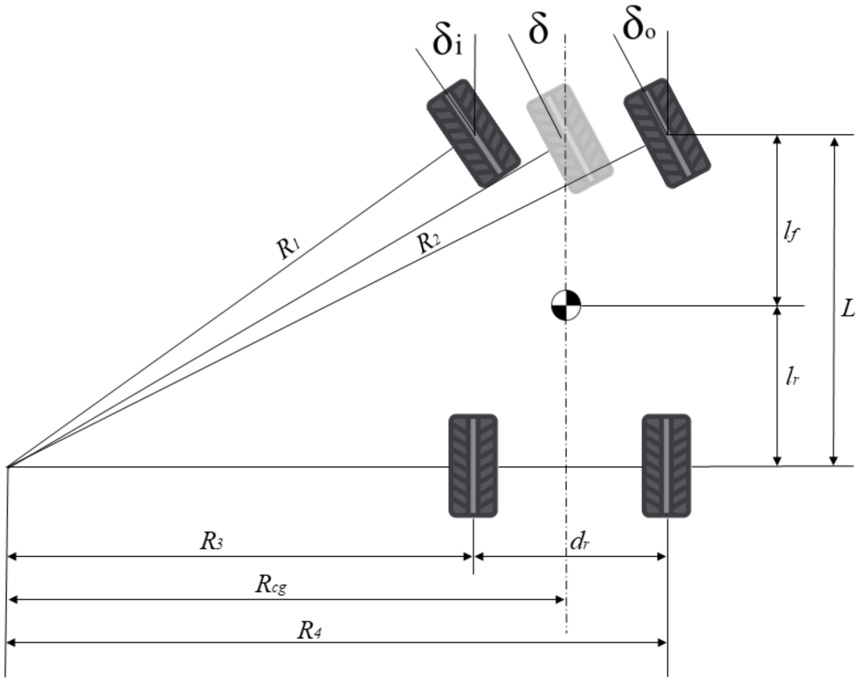

Figure 1. Ackermann steering model.

The inner steering angle of the front wheel is calculated using Eq. (1).

$$\delta_i = \arctan\left(\frac{\tan(\delta) \times L}{L - \left(\frac{K}{2}\right) \times \tan(\delta)}\right) \tag{1}$$

Similarly, the outer steering angle can be determined by Eq. (2).

$$\delta_o = \arctan\left(\frac{\tan(\delta) \times L}{L + \left(\frac{K}{2}\right) \times \tan(\delta)}\right) \tag{2}$$

Where K represents the distance between the left and right kingpins, and L is the distance between the front and rear wheels.

To calculate the individual wheel speeds, it is necessary to determine the turning radii of the front and rear wheels. The respective expressions for these turning radius are given by Eq. (3), Eq. (4)., Eq. (5)., and Eq. (6).

$$R_1 = \frac{L}{sin(\delta_i)} \tag{3}$$

$$R_2 = \frac{L}{sin(\delta_o)} \tag{4}$$

$$R_3 = \frac{L}{tan(\delta)} - \frac{d_r}{2} \tag{5}$$

$$R_4 = \frac{L}{tan(\delta)} + \frac{d_r}{2} \tag{6}$$

Where dr denotes the distance between the rear wheels.

The radius of the EV's center of gravity is computed by and Eq. (7).

$$R_{cg} = \sqrt{(R_3 + (\frac{d_r}{2}))^2 + (l_r)^2} \tag{7}$$

Where l_r represents the distance between the rear wheel and the vehicle's center of gravity.

The angular speeds of each wheel expressed by Eq. (8).

$$w_x = \frac{\vec{V} \times R_x}{r \times R_{cg}} \tag{8}$$

Where W_x is the angular velocity of wheel x, represents the velocity of the EV, R_x is the turning radius of the respective wheel and r is the wheel radius.

Since angular speed is the ratio of linear speed to the rolling radius, Eq. (8) represents the adjusted angular speed for a target wheel. This is achieved by multiplying the original angular speed by the ratio of the wheel's radius to the radius of the center of gravity. Similarly, the voltage signal from the accelerator pedal of the EV can be adjusted during cornering to achieve the electronic differential performance for each wheel. In this context, voltage can be expressed in place of angular velocity. Therefore, the adjusted voltage signal for each wheel can be calculated using Eq. (9), Eq. (10), Eq. (11), and Eq. (12).

$$V_1 = \frac{V_p \times R_1}{R_{cg}} \tag{9}$$

$$V_2 = \frac{V_p \times R_2}{R_{cg}} \tag{10}$$

$$V_3 = \frac{V_p \times R_3}{R_{cg}} \tag{11}$$

$$V_4 = \frac{V_p \times R_4}{R_{cg}} \tag{12}$$

Where V_p represents the original pedal signal.

The equations derived from Ackermann-Jeantand geometry are implemented in MATLAB Simulink software. The parameters L, l_r, d_r, r, and K, as listed in **Table 1**, are related to the dimensions of the electric vehicle prototype, which will be tested in the future. These parameters are obtained from the vehicle model and are used within the MATLAB Simulink model.

Table 1. EDS model parameters.

Parameter	L	l_r	d_r	K
Value (m)	2.85	0.830	1.35	1.219

To put our proposed EDS to the test, we built a virtual proving ground using MATLAB Simulink. The core of this simulation is a set of adjusted voltage equations rooted in the Ackermann-Jeantand steering model, which defines the precise speed relationship between the inner and outer wheels when a vehicle turns.

As shown in **Figure 2**, the Simulink model uses a mix of fixed parameters and live variable inputs to mimic the real-world behavior of an electric car with in-wheel motors. The model relies on several fixed values, pulled directly from the vehicle's specs and listed in **Table 1**. Where the wheelbase (L), the distance from the center of gravity to the rear axle (l_r), the half-track width (d_r), and a proportionality constant (K) remain the same for all cases to ensure the results are consistent and match our physical prototype.

The dynamic, changing inputs come from the driver: the steering angle and the accelerator pedal position. These variable signals allow the model to dynamically recalculate wheel speeds on the fly, just like a real car would need to do.

The model's internal logic processes the steering angle input first to calculate the specific speed adjustments, known as Δinner and Δouter, required for the inner and outer wheels. Simultaneously, the accelerator pedal input is interpreted as the driver's total torque request. The system then intelligently merges these two data streams—the steering-based corrections and the total torque demand. The final output is a set of four distinct throttle voltage signals (V_1–V_4), each tailored for an individual wheel. This ensures the outer wheels receive more power and the inner wheels receive less during a turn, effectively replicating the desired electronic differential action.

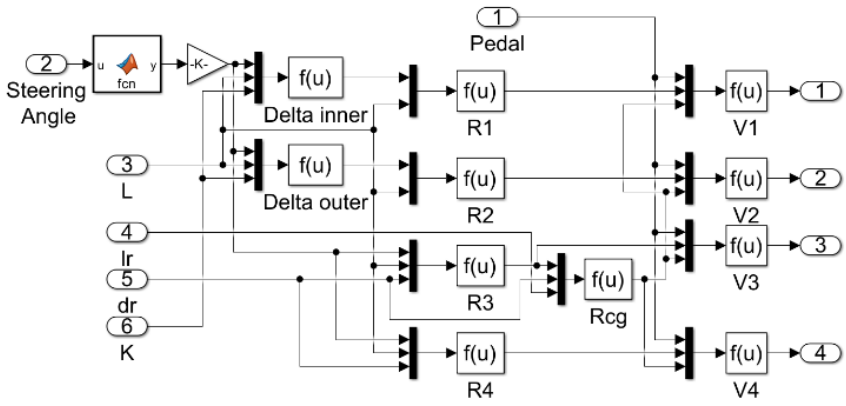

Figure 2. MATLAB Simulink Model of EDS.

By structuring the simulation this way, the model in **Figure 2** does more than just run the Ackermann math; it gives us a practical, powerful tool to see how our Arduino-based EDS would perform under a huge range of driving conditions. This crucial step allows us to validate the entire approach and work out any kinks long before we ever touch the actual hardware.

The experimental setup shown in **Figure 3** was developed to test EDS performance. Arduino UNO microcontroller is the main controller of the system and is responsible for carrying out the control algorithm. A JKH Foot Throttle used to convert the driver's acceleration behavior into an analog voltage signal that operates between 0.8 V and 4.2 V, a multi-turn rotary potentiometer provides precise steering angle measurements.

The experiment aims to evaluate the system control on wheel speeds. To cover all driving scenarios, three different acceleration levels were chosen: 1.2 V (low), 3.0 V (medium), and 4.2 V (maximum). Steering angle and acceleration pedal signals are the inputs for Arduino controller, while the adjusted voltage signal for each wheel will be the output. To measure the system response, the input and output signals were recorded over a range of steering angles from 0 to 15 degrees.

The experimental results obtained from this setup will be compared to MATLAB Simulink results and errors will be calculated.

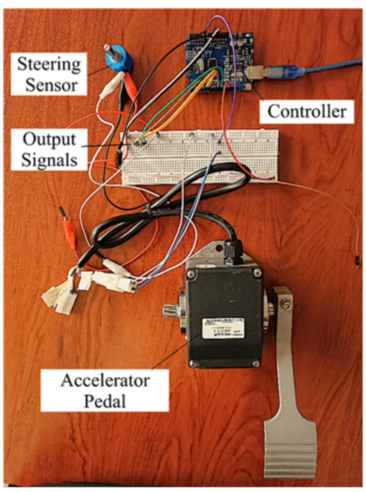

Figure 3. Experimental setup.

The current experimental methodology utilized consistent accelerator pedal inputs (low, medium, and high) to enable efficient analysis. But this method makes it impossible for the results to be truly representative of real-world driving conditions. To better capture how cars behave in the real world, future studies will use different accelerator profiles, such as gradually applying pedal input while turning.

3. Results

Across all three accelerator settings—low (1.2 V), medium (3.0 V), and maximum (4.2 V)—the same pattern was observed: increasing steering angle reduced the throttle-signal voltage applied to the inner wheels and increased the voltage applied to the outer wheels, as predicted by the Ackermann geometry. Simulated outputs from MATLAB/Simulink closely matched the Arduino-based measurements, with discrepancies generally below 0.53%.

At low acceleration as shown in **Figure 4** and **Table 2**, the front inner wheel decreased from 1.200 V at $\Delta = 0°$ to 1.161 V at $\Delta = 15°$, while the front outer wheel increased from 1.200 V to 1.297 V over the same range. The rear wheels exhibited the same opposing trend (rear inner to 1.058 V; rear outer to 1.316 V). Agreement between simulation and experiment was strong across all four wheels, with a maximum deviation of 0.30%, predominantly at small steering angles where sensor noise and potentiometer non-linearity are more influential.

At medium acceleration explained in **Figure 5** and **Table 3**, the front inner wheel declined to 2.904 V while the front outer wheel rose to 3.213 V. The rear axle showed a larger spread (rear inner to 2.684 V; rear outer to 3.263 V), and this case contained the highest observed discrepancy in the study, yet the simulated and measured curves remained closely aligned throughout the steering sweep.

At maximum acceleration as presented in **Figure 6** and **Table 4**, the front inner wheel decreased to 4.062 V and the front outer increased to 4.540 V, while the rear inner and outer wheels reached 3.703 V and 4.606 V, respectively. Errors remained small (≤ 0.44%), with the largest again on the rear inner wheel; the front outer wheel showed the smallest deviations (≤ 0.15%).

(1) Case 1: Low Acceleration

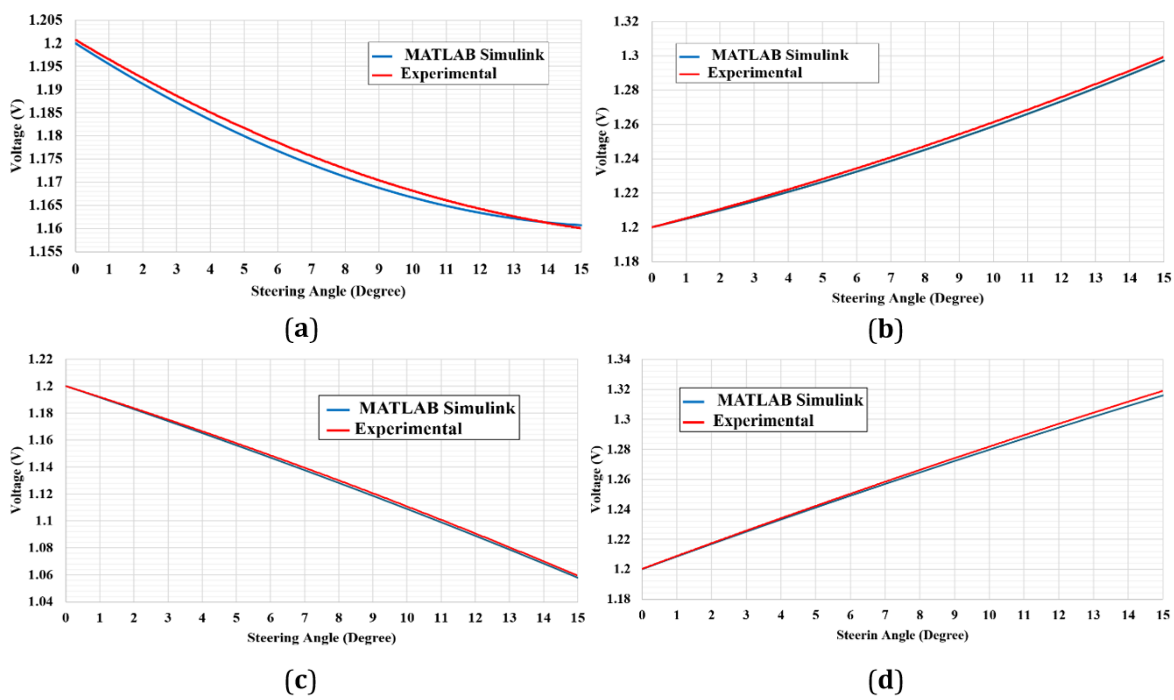

Figure 4. Comparison of simulated (MATLAB/Simulink) and experimental (Arduino-based) throttle signal voltages applied to the front inner wheel during cornering at low acceleration: (**a**) Front Inner Wheel; (**b**) Front Outer Wheel; (**c**) Rear Inner Wheel; (**d**) Rear Outer Wheel.

Table 2. Comparison of MATLAB and experimental voltage signals for Case 1.

Delta Δ	V_1		Error %	V_2		Error %	V_3		Error %	V_4		Error %
	Sim.	Exp.		Sim.	Exp.		Sim.	Exp.		Sim.	Exp.	
0.0	1.200	1.201	0.059	1.200	1.200	0.000	1.200	1.200	0.009	1.200	1.200	0.024
1.5	1.193	1.194	0.086	1.207	1.208	0.051	1.187	1.188	0.065	1.213	1.213	0.039
3.0	1.187	1.188	0.102	1.215	1.216	0.091	1.174	1.175	0.110	1.225	1.226	0.054
4.5	1.182	1.183	0.107	1.223	1.225	0.123	1.161	1.162	0.145	1.237	1.238	0.070
6.0	1.177	1.178	0.099	1.232	1.234	0.147	1.147	1.149	0.171	1.249	1.250	0.086
7.5	1.172	1.173	0.077	1.242	1.244	0.163	1.133	1.135	0.188	1.261	1.262	0.102
9.0	1.169	1.169	0.039	1.252	1.254	0.171	1.119	1.121	0.198	1.272	1.274	0.117
10.5	1.166	1.166	0.016	1.262	1.265	0.173	1.104	1.106	0.200	1.283	1.285	0.130
12.0	1.163	1.162	0.090	1.273	1.276	0.168	1.089	1.091	0.197	1.294	1.296	0.143
13.5	1.162	1.160	0.183	1.285	1.287	0.157	1.074	1.076	0.190	1.305	1.307	0.154
15.0	1	1.157	0.299	1.297	1.299	0.140	1.058	1.060	0.180	1.316	1.318	0.163

(2) Case 2: Medium Acceleration

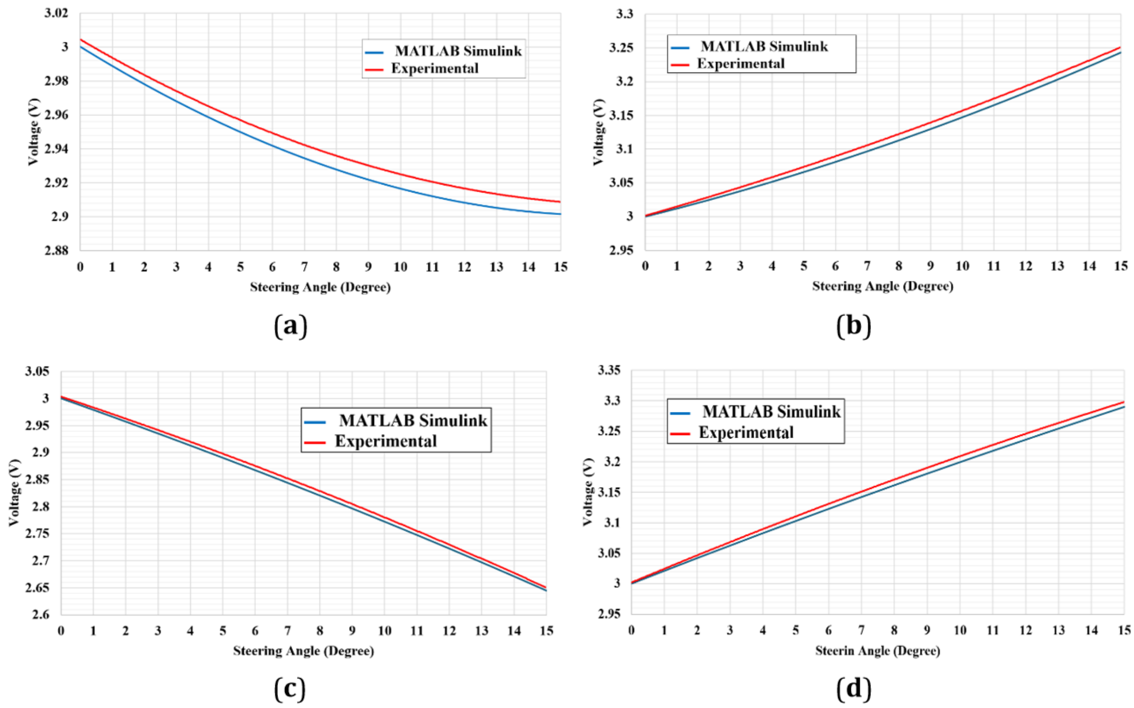

Figure 5. Comparison of simulated (MATLAB/Simulink) and experimental (Arduino-based) throttle signal voltages applied to the front inner wheel during cornering at medium acceleration: (**a**) Front Inner Wheel; (**b**) Front Outer Wheel; (**c**) Rear Inner Wheel; (**d**) Rear Outer Wheel.

Table 3. Comparison of MATLAB and experimental voltage signals for Case 2.

Delta Δ	V_1		Error %	V_2		Error %	V_3		Error %	V_4		Error %
	Sim.	Exp.		Sim.	Exp.		Sim.	Exp.		Sim.	Exp.	
0.0	3.000	3.004	0.147	3.000	3.000	0.004	3.000	3.003	0.114	3.000	3.002	0.069
1.5	2.983	2.989	0.178	3.018	3.021	0.084	2.968	2.973	0.178	3.032	3.036	0.132
3.0	2.980	2.986	0.184	3.022	3.025	0.098	2.961	2.967	0.190	3.038	3.042	0.144
4.5	2.968	2.974	0.207	3.038	3.042	0.145	2.935	2.942	0.235	3.062	3.068	0.184
6.0	2.954	2.961	0.231	3.059	3.064	0.191	2.901	2.910	0.287	3.093	3.100	0.225
7.5	2.942	2.949	0.250	3.081	3.088	0.220	2.867	2.877	0.333	3.123	3.131	0.254
9.0	2.931	2.939	0.263	3.105	3.112	0.234	2.832	2.843	0.376	3.152	3.160	0.273
10.5	2.922	2.930	0.268	3.130	3.137	0.233	2.796	2.808	0.415	3.180	3.189	0.279
12.0	2.914	2.922	0.264	3.156	3.163	0.219	2.760	2.772	0.452	3.209	3.217	0.275
13.5	2.908	2.916	0.249	3.184	3.190	0.191	2.722	2.736	0.490	3.236	3.245	0.259
15.0	2.904	2.911	0.222	3.213	3.217	0.151	2.684	2.698	0.528	3.263	3.271	0.231

(3) Case 3: Maximum Acceleration

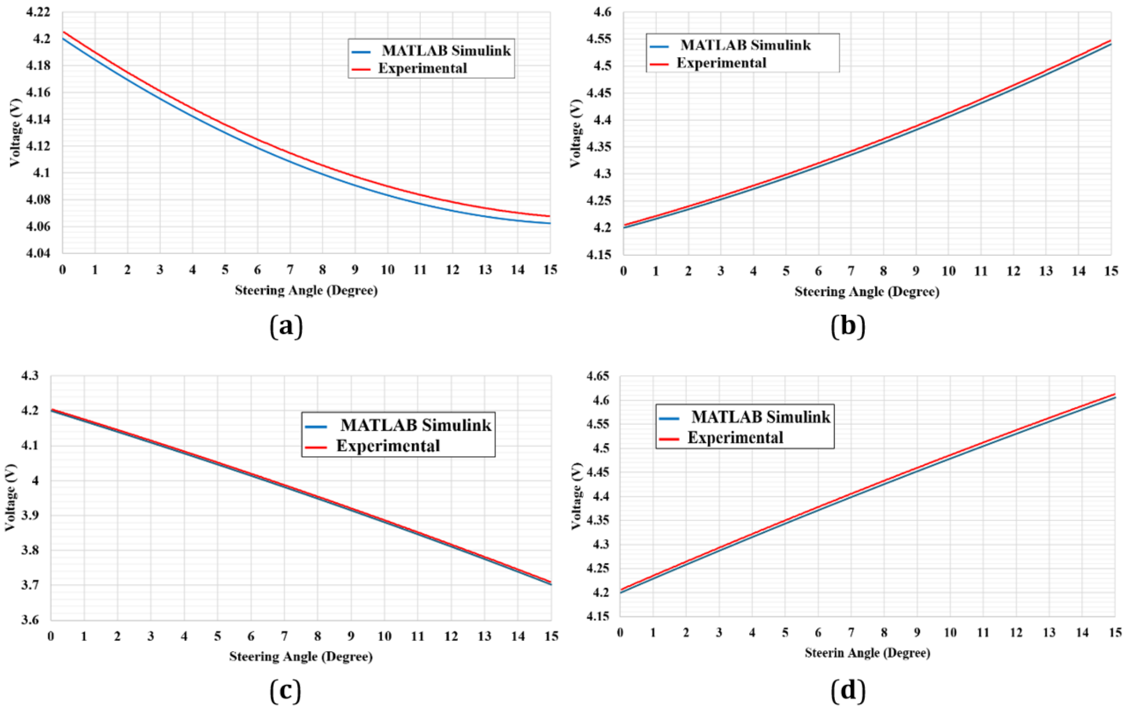

Figure 6. Comparison of simulated (MATLAB/Simulink) and experimental (Arduino-based) throttle signal voltages applied to the front inner wheel during cornering at maximum acceleration: (**a**) Front Inner Wheel; (**b**) Front Outer Wheel; (**c**) Rear Inner Wheel; (**d**) Rear Outer Wheel.

Table 4. Comparison of MATLAB and experimental voltage signals for Case 3.

Delta Δ	V_1		Error %	V_2		Error %	V_3		Error %	V_4		Error %
	Sim.	Exp.		Sim.	Exp.		Sim.	Exp.		Sim.	Exp.	
0.0	4.200	4.206	0.136	4.200	4.205	0.121	4.200	4.205	0.122	4.200	4.206	0.135
1.5	4.177	4.182	0.139	4.225	4.231	0.133	4.155	4.161	0.135	4.244	4.250	0.137
3.0	4.155	4.161	0.148	4.253	4.259	0.141	4.109	4.115	0.149	4.287	4.293	0.136
4.5	4.136	4.142	0.161	4.282	4.288	0.145	4.062	4.069	0.165	4.330	4.336	0.135
6.0	4.119	4.126	0.178	4.313	4.320	0.147	4.014	4.022	0.183	4.372	4.377	0.131
7.5	4.103	4.112	0.197	4.346	4.353	0.146	3.965	3.973	0.207	4.412	4.418	0.124
9.0	4.091	4.100	0.217	4.381	4.388	0.144	3.915	3.924	0.235	4.453	4.458	0.115
10.5	4.080	4.090	0.237	4.418	4.425	0.140	3.864	3.874	0.271	4.492	4.497	0.103
12.0	4.072	4.082	0.256	4.457	4.463	0.135	3.811	3.824	0.316	4.531	4.535	0.087
13.5	4.066	4.077	0.270	4.498	4.503	0.128	3.758	3.772	0.372	4.568	4.572	0.067
15.0	4.062	4.074	0.280	4.540	4.546	0.120	3.703	3.719	0.440	4.606	4.608	0.044

4. Discussion

This study developed an Arduino-based EDS for an electric vehicle with four in-wheel hub motors. This research takes a different approach. While many studies only deal with front wheel systems, this study examines all four wheels simultaneously. To make it practical, the control system was tested on a low-cost Arduino platform. The EDS mathematical model was based on Ackermann-Jeantand geometry and was first tested in MATLAB/Simulink. The same equations were then used in the Arduino environment, where real throttle and steering inputs were used to make separate voltage signals for each wheel. The experimental outcomes across three acceleration scenarios (low, medium, and maximum) indicated that the proposed system effectively regulated wheel voltages in relation to the steering angle. As the steering angle went up, the inner wheels voltage decreased, and increased the voltage applied to the outer wheels. This is what Ackermann geometry says should happen. The MATLAB/Simulink simulations and the real-time experimental data showed the same trend, with only small differences between the two sets of results. Sensor noise, potentiometer non-linearity, and hardware response delays were the main causes of these differences. However, they had little effect and did not affect the differential function. The study proves that an EDS running on Arduino matches the performance of its mathematical model. This approach is valuable for prototyping, research and education due to its low cost.

5. Conclusions

This study successfully created and tested a low-cost Arduino-based control algorithm for an EDS used in a four-wheel motor electric vehicle. The MATLAB/Simulink model and the actual Arduino Uno implementation matched up very well, with the maximum voltage output errors staying below 0.53%. These findings validate that the control algorithm can precisely modulate wheel voltage signals in accordance with steering angle. It is important to note that this validation was done at the signal level; physical actuation with motors and torque/rotation measurements is still to come. This kind of integration will make it possible to test the full function of the drivetrain under dynamic load conditions.

The current study effectively validated the proposed Arduino-based control algorithm at the voltage-signal level; however, several limitations must be recognized. Initially, the experiments were confined to open-loop pedal-to-voltage mapping; subsequent research will include closed-loop validation employing motor encoders and torque feedback to comprehensively elucidate drivetrain dynamics. Second, while sensor performance was qualitatively assessed, comprehensive calibration of linearity, noise, latency, and temperature drift was not performed in this initial phase and will be examined in future studies. Finally, the tests were done in a lab with fewer variables, so the battery state of charge, tire pressure, and wheel alignment were not explicitly controlled. All of these things could affect how well the vehicle works. To do full-scale testing on a real electric vehicle platform in the future, it will be important to control these variables.

Author Contributions

Conceptualization, K.A. and Z.T.; methodology, K.A. and Z.T.; software, Z.T. and K.A.; validation, Z.T. and K.A.; formal analysis, Z.T. and K.A,; investigation, Z.T. and K.A.; resources, Z.T.; data curation, Z.T. and K.A.; writing—original draft preparation, Z.T. and K.A.; writing—review and editing, K.A.; visualization, Z.T.; supervision, K.A. All authors have read and agreed to the published version of the manuscript.

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The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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