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The Design & Implementation of a Self-adaptive Hybrid Electric Skateboard

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ABSTRACT

This paper proposes a novel electric skateboard control architecture to hybridize the skater's manual operation and electric motor drive. The proposed scheme does not need a handheld remote controller for steering; hence provides better man-machine coordination and enhances the safety of new skaters. For this purpose, a torque-speed control algorithm is designed to compensate for the manual acceleration force and rolling resistance by sensing the motor's speed, acceleration, and torque outputs. The compensation level is configurable according to the skater's comfortableness. The proposed electric control solution also enhances the battery mileage per charging and can be applied to various electric skateboards since it does not require a dedicated weight/pressure sensor to detect if the skater is on or off the board. The control scheme is simulated in MATLAB/Simulink and experimentally verified by a controller based on C2000 DSP that supports sensorless brushless DC(BLDC) motor drive.

1. Introduction

Along with the surge of EV/HEV, e-mobility solutions are increasing in popularity, and e-scooter is becoming a significant leading player in green transportation [1]. However, its reception is limited in the US [2]. Meanwhile, the US has the largest number of skateboard users across the globe, with 78% of the end users being teenagers and kids [3] and multiple US cities ranked as the top 10 best cities for skateboarding in the world [4][5]. Compared to other e-mobility solutions such as Segway [6][7] or unicycle [8], the electric skateboard features more portability due to its lightweight, compactness, and flexibility for electrical/manual steering options. This makes electric skateboards a unique choice for transportation and sport, allowing skaters to exercise by manually riding or leveraging the electric drive.

Skateboarding is traditionally considered a very hazardous activity and almost entirely dependent on safety gear in the event of accidents. According to [9], approximately 70,000 injuries related to skateboarding requiring a visit to the emergency department occur every year in the US. Many people are switching sports for their safety due to the likelihood of injury by the sport [3]. Most of the current commercial electric skateboards are equipped with a handheld remote, further reducing man-machine coordination. Paper [10] analyzed the mechanical model of the skateboard-skater system, explained the instability of the system, and proposed to vary the control gains with respect to the speed to stabilize the uniform motion for better stability at high speed. The company EUCO recently announced an electric skateboard solution using an intelligent pressure-sensitive pad for cruise control in leu of the handheld remote [11]. All these solutions are making efforts to make skateboarding easier and safer.

Given the slippery nature of the skateboard and the coordination skills demanded being the main challenges for new skaters, this paper proposed a novel electric skateboard control architecture that prevents the skateboard from accelerating unexpectedly and removes the need for a handheld remote completely, without requiring any replacement devices as introduced by the solution in [9]. A speed-torque control solution regulates the electric motor torque to compensate for the manual force for safety purposes and steering by using a single electric control board. The electric board interfaces with the hub motor and utilizes it as a sensing channel to detect skateboard rolling speed, the skater's manual driving force, and the status of the skater on or off the skateboard. Without the need for a handheld remote, a finite state machine in the solution manages the state flow of the control system, taking the speed, acceleration, and electrical torque inputs sensed from the hub motor. At the same time, the speed-torque regulator regulates the cruising speed and the percentage level of electric torque to compensate for the skater's manual propelling force. The cruising speed virtually profiles the skateboard's speed on different road surfaces. By hybridizing the skater's manual operation and electric motor drive, the torque compensation prevents the skater from falling off unexpectedly due to aggressive acceleration.

2. Methods: Torque-speed Controller for Adaptive Steering

The electric skateboards include one or multiple electric hub motors controlled by the ECU embedded into the skateboard. A battery pack powers up the ECU that converts the electrical power to or from the battery for the motor drive, depending on the skateboard's running mode. For example, when the motor propels the skateboard to speed up, the ECU discharges the battery to power the motor and converts battery power to mechanical power. When the skateboard slows down, the motor acts as an alternator by braking control to convert the mechanical energy to electricity and recharges the battery.

Figure 1 is an architectural diagram illustrating an electric skateboard. Figure 1A shows the three components of the self-adaptive electric skateboard: a skateboard, a BLDC hub motor, and an ECU composed of an electric control board and a power battery. The electric control board connects to a battery power source and the BLDC hub motor, as shown in Figure 1B.

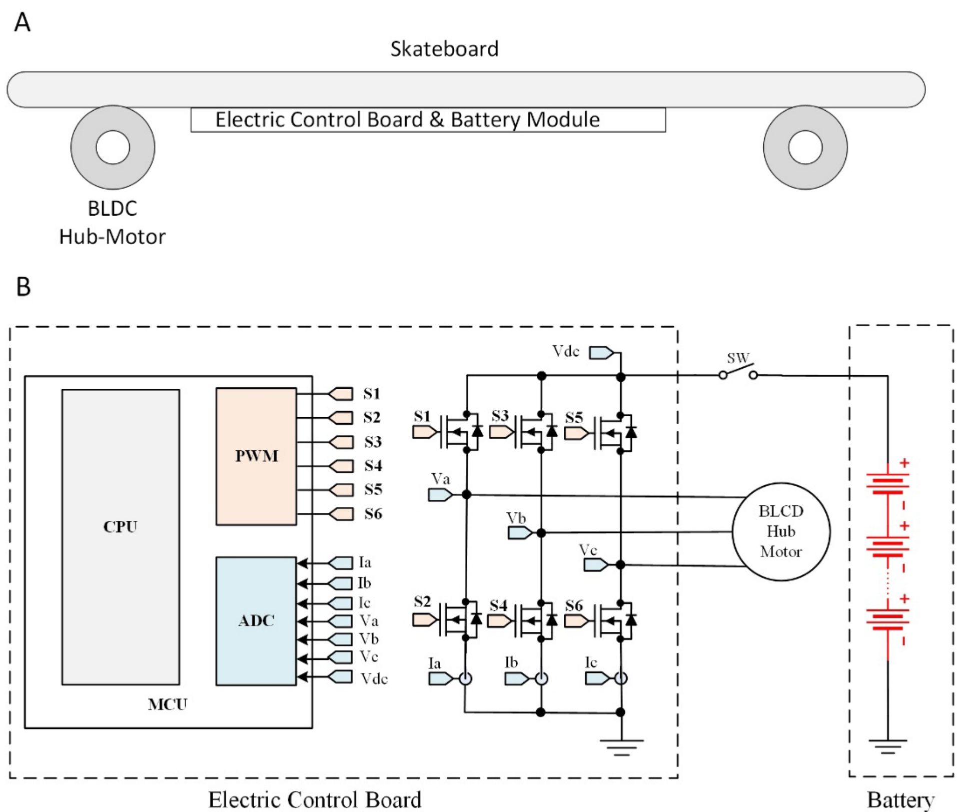

Figure 1. The Electric Skateboard and the Electric Board Signal Chain

The electric control board has an MCU interfacing with a six-switch converter via six pulse-width-modulation (PWM) signals that drive the converter to convert the DC voltage from the power battery to an AC voltage. Meanwhile, the motor's three-phase currents and terminal voltage are fed back to the MCU's analog-to-digital converter (ADC) module. With the signal chain of PWM outputs and ADC inputs, as shown in Figure 1B, various control algorithms for motor control can be implemented to spin the motor, following the commanded torque or speed references and populate the corresponding output data of motor speed, acceleration, and electric torque accordingly.

2.1 Torque-Speed Controller

The skateboard control system diagram is illustrated in Figure 2 and the corresponding signals are listed in Table 1. As shown in Figure 2, the speed-torque controller is composed of 4 modules: modules 1, 2, State Machine, and Gc_V. With the voltage and current inputs sensed, as shown in Figure 1, the outputs for motor speed and electric torque Te can be generated [12][13], converted to the estimated value for skateboard speed V_est, acceleration Acc_est, and electric torque Te_est by module 1.

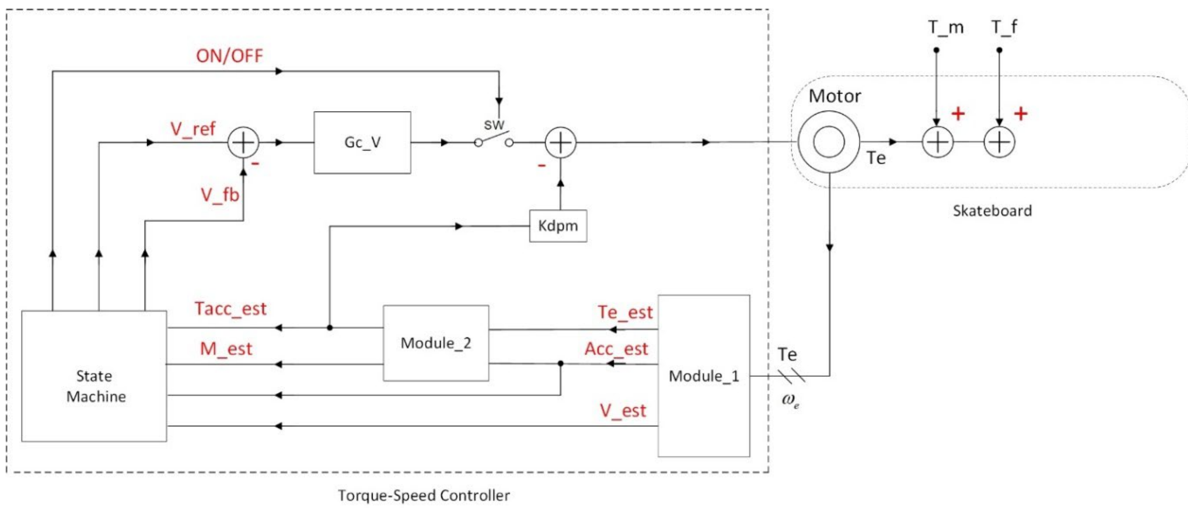

Figure 2. The Skateboard Control System Diagram

Table 1. Signal Variables of the Torque-Speed Controller

Tab	Definitions	Unit
Te	The motor electric torque	N.m
Te_est	The estimated value of the motor electric torque	N.m
Tm	The manual torque for skateboard driving by the skater	N.m
Tf	The resistant torque due to the friction of the riding surface	N.m
Acc_est	The skateboard's acceleration value	m/Sec^2
V_est	The estimated speed of the skateboard	m/Sec
$Tacc\_est$	The total torque contributing to the acceleration value Acc_est	N.m
M_est	The total weight of the skater and the skateboard	Kg
V_ref	The reference speed commanded for skateboard steering	m/Sec
V_fb	The skateboard speed feeds back to Gc_V controller	m/Sec
ON/OFF	The switch signal for torque-speed mode control: OFF for torque compensating control; ON for speed control	Logic
$Kdmp$	The damping ratio to compensate the skater's manual torque	Unitless
ω_e	The electrical angular speed of the motor	rad/Sec

Module 2 populates the estimated skater's weight and the total torque contributing to the acceleration of Acc_est. When the switch SW is put to ON mode, the module Gc_V governs the skateboard speed by referring to the reference speed V_ref and the measured speed V_fb delivered by the State Machine module. In contrast, when the switch SW is put to OFF mode, the electric motor torque Te compensates the skater's manual force T_m according to the damping ratio parameter Kdmp by Equation (1):

$$T_e = -K_{dmp} * T_{acc\_est} \tag{1}$$

Equation (1) shows the controller regulates the electric torque Te in proportion to the total mechanical force Tacc_est that contributes to the acceleration but in the reverse direction. When the value of Kdmp ranges from 0 ~ 1, it acts as a damping factor to reduce the detected acceleration rate Acc_est; therefore, when the skater starts up the skateboard with manual force, the damping factor can be configured to control the acceleration rate of the skateboard to the desired level, making the startup process comfortable and safe. It's challenging for a beginner to jump onto the skateboard because they are prone to slipping out from under the feet, making the skaters fall easily. While the Kdmp is set to a certain level, for example, 0.1, it virtually increases the resistant friction coefficient by 30 ~ 50 times, from an actual level around 0.002~0.003 on a concrete road. It saves the skater from feeling slippery and reduces unexpected falls for beginners.

In addition to safety for beginners, another benefit of the torque compensation scheme is harvesting the manual propelling force to recharge the battery during the acceleration process. In order to maximize battery charging, Kdmp is expected to be set to a value higher than 1. For example, if the Kdmp is set to 2, the total manual force from the skater is mostly used for the battery recharging rather than for acceleration. The electric torque Te from the hub motor cancels out the acceleration in proportion to the skater's manual force until the Te reaches its maximum output, which is usually limited by the current capacity of the DC-AC converter in ECU and the hub motor.

As soon as the acceleration rate reduces to a low threshold level, the state machine exits the acceleration mode and switches to cruising mode by capturing the immediate speed value V_est and using it for the reference speed V_ref0 generation. Meanwhile, the V_est signal is connected to V_fb and acts as the feedback channel for cruising control. As shown in Figure 2, the software signal variable is put to ON, enabling speed closed-loop control during cruising mode. The speed reference input Vref is populated in the method as described by the equation below:

$$V\_ref = V\_ref0 + \int(\mu * G)dt \tag{2}$$

G is the gravity constant, and μ is the factor for virtual rolling resistant coefficient control configured in the range of -0.5 ~ 0. In equation (2), the integral can be discretized into different operation forms in accordance with the sampling frequency for speed control. The virtual rolling resistance coefficient can be configured to simulate the resistance coefficient of various surfaces. For example, if μ is configured to a value around -0.0002, the speed control simulates the skating experience on an ice surface; if it is configured to the range of -0.004 ~ -0.002, the skating experience on a concrete surface is simulated, if μ is set to zero, the torque-speed controller steers the skateboard with the constant speed of Vref_0 till the skater gets off the skateboard.

2.2 System State Flow

As a part of the controller, a finite state machine manages the mode switch for torque control and speed control mentioned above. The corresponding state flow for the state machine operation is illustrated in Figure 3. As soon as the system is powered up, the standby mode is enabled to provide housekeeping functions such as ECU self-diagnostic, hub motor speed monitoring, etc. Once a valid acceleration condition is identified, the state flow switches to acceleration mode and the torque control loop is activated and followed by the Cruising Mode, and then the speed closed loop is activated with speed reference and feedback inputs populated from the motor speed, the acceleration, electric torque data derived. Under the Cruising Mode, the weight estimation function runs in parallel with the speed closed loop thread and populates the off-board signal to indicate if the skater is on or off the skateboard. When the off-board signal is validated, the braking mode is activated and stops the skateboard.

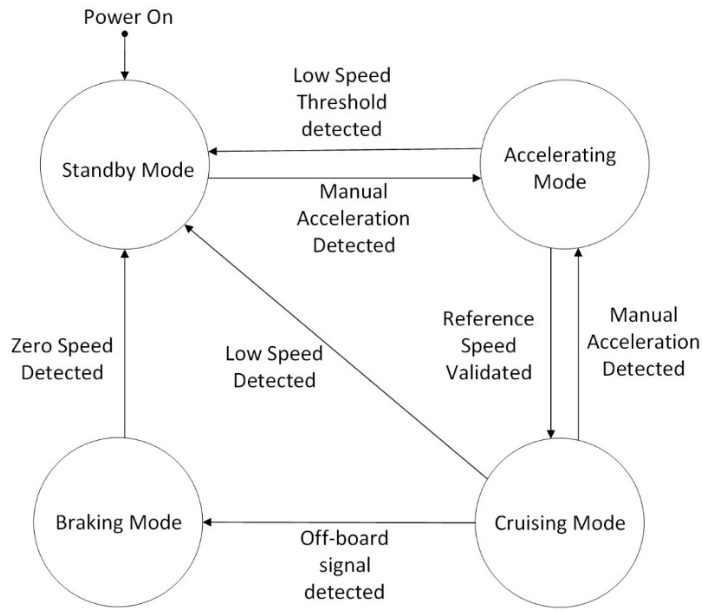

Figure 3. The System State Flow of the Torque-speed Controller

2.3 Weight Estimation for Skater on/off the Board

As mentioned above, the cruising control activates the weight estimating function to estimate the value of M_est for the total weight of the skateboard and the skater riding on it. Equation (3) illustrates the algorithm applied for the estimation, assuming the skateboard runs on a flat road.

$$M\_est = Te\_est / (Acc\_est + \beta * G * R) \tag{3}$$

Where β is the resistant coefficient of the skating surface; G is the gravity constant; R is the radiator of the skateboard wheel. Given that G and R are constants without the need for calibration, the accuracy of β plays a critical factor in impacting the final accuracy of the estimated weight value M_est together with the estimated electric torque Te_est and acceleration Acc_est. Te_est is mostly impacted by the motor parameters and Acc_est by the data resolution defined by the MCU. With a 32-bit based MCU with 12-bit ADC and a preconfigured lookup table for the resistant coefficient β for different road conditions, it is not difficult to have acceptable accuracy for the estimated weight value M_est for the switch function between cruising and braking modes.

3. Results and Discussion

In light of the proposed control method, a simulation model using MATLAB Simulink is presented, followed by the corresponding system implementation on top of the hardware platform released by Texas Instruments [3]. Figure 4 shows the skateboard with one hub BLDC motor connected to the ECU. The motor control kernel InstaSPIN library embedded in the C2000 device is leveraged for sensorless BLDC motor control. InstaSPIN module takes the speed and torque command from the torque-speed controller as discussed above and feedback the motor torque Te andω_e back to the torque-speed controller.

Figure 4. The Self-adaptive Electric Skateboard Controller

The system parameters for simulation are listed in Table 2. The skateboard's wheel radius is 3.5cm, and the maximum torque output is capped at 5.0N.m. It assumes the skateboard runs on a horizontal paved surface with a resistance coefficient of 0.002. The skater's weight is 67Kg and the skateboard's is 3.8Kg.

Table 2. System Parameters for Simulation

Parameters	Value	Unit
Skateboard weight	3.8	Kg
Skater weight	67	Kg
Resistance coefficient	0.002	(Non)
Wheel radius	0.035	m
Maximum Motor Torque	5.0	N.m

3.1 Acceleration Torque Compensation & Friction Resistance Compensation for Cruising

Figure 5 shows the acceleration process when the skateboard is launched manually by the skater with a kick torque Tm of 12.3 N.m, applied to the skateboard for 0.5Sec. Given the resistance coefficient of 0.002, the actual friction torque is as low as -0.005N.m, which is usually too slippery for a beginner to jump onto the skateboard.

With the damping factor Kdmp being set to 0.1, the hub motor responds immediately to compensate for the manual propelling force with a negative torque Te equaling -1.1N.m, therefore, the total actual torque for acceleration T_acc is reduced down to 11.1N.m. Virtually, it feels to the skater as if they are running on a surface with a resistant coefficient of 0.1, rather than the actual at 0.002. With the compensated negative torque Te, the total resistant torque is increased to -1.1N.m. With this virtual coefficient provided, it then feels to the skater like stepping on a regular surface, not slippery at all.

Figure 6 shows a similar acceleration process but with a higher damping factor Kdmp being set to 1.5. It can be noticed the compensated torque from the hub motor is capped at the maximum torque -5.0N.m, generating the maximum current for the battery recharging.

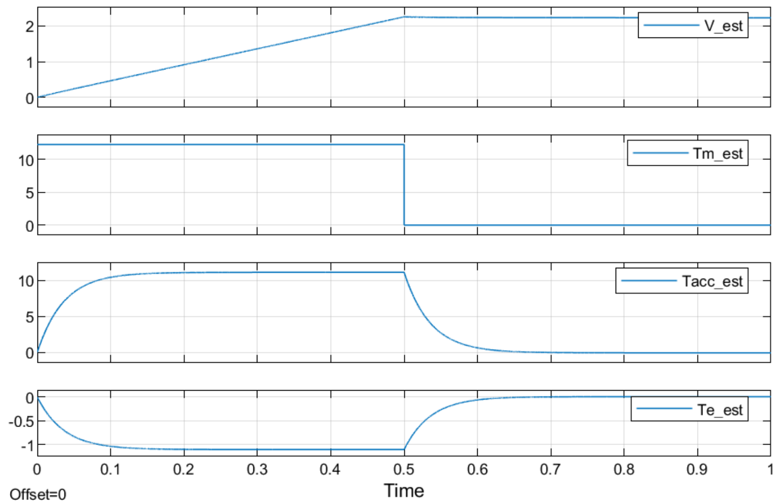

Figure 5. Acceleration with a small Torque compensation rate:
Kdmp = 0.1; V_est = 2.2m/S; Tm_est = 12.3N.m; Tacc_est = 11.1N.m; Te_est = -1.1N.m;

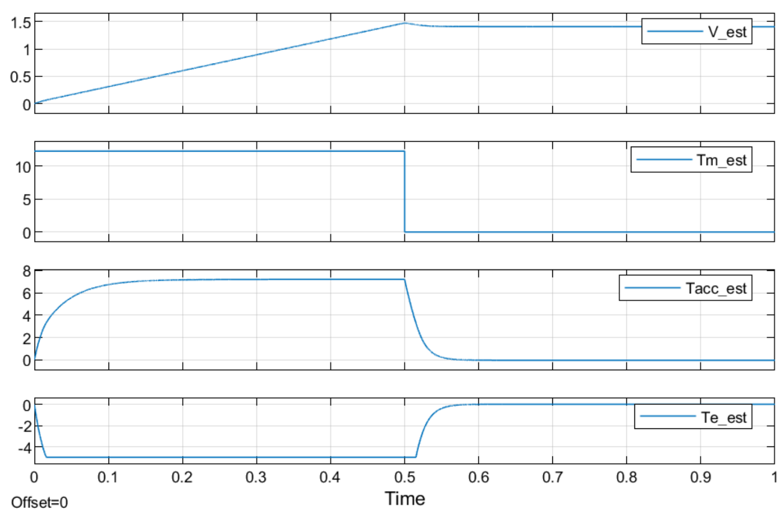

Figure 6. Acceleration with a high Torque compensation rate:
Kdmp = 1.5; V_est = 1.5m/S; Tm_est = 12.3N.m; Tacc_est = 7.2N.m; Te_est = -5.0N.m;

3.2 Weight Estimation

Detecting whether the skater is on/off the skateboard is a critical feature for the ECU to work properly, realized by detecting the skater's weight after they get on/off the skateboard. Figure7 shows the whole weight detecting process with the algorithm proposed in this paper, without needing any dedicated weight or pressure sensors. According to the parameters simulated, when the skater steps on the skateboard, the total weight is 70.8Kg, as shown by the waveform of Weight from start to 20Sec. At the time of 20Sec, the Weight drops down to 3.8Kg, which means the skater jumps off the skateboard at the moment.

The bottom waveform shows the weight estimating process for the total weight Weight_est. During the acceleration process, the propelling torque is the manual force and motor torque combined; therefore, the weight estimating process is not launched. Once the speed saturates after the acceleration, the weight estimator kicks in at around 10sec time point and converges to the actual weight value at about 15Sec time point.

At the time of 20Sec, the skater jumps off the skateboard, the weight estimator responds accordingly with an immediate drop of the estimated weight Weight_est and the skateboard slows down quickly, as shown by the speed waveform V_est in Figure 7, showing the effectiveness of the proposed algorithm.

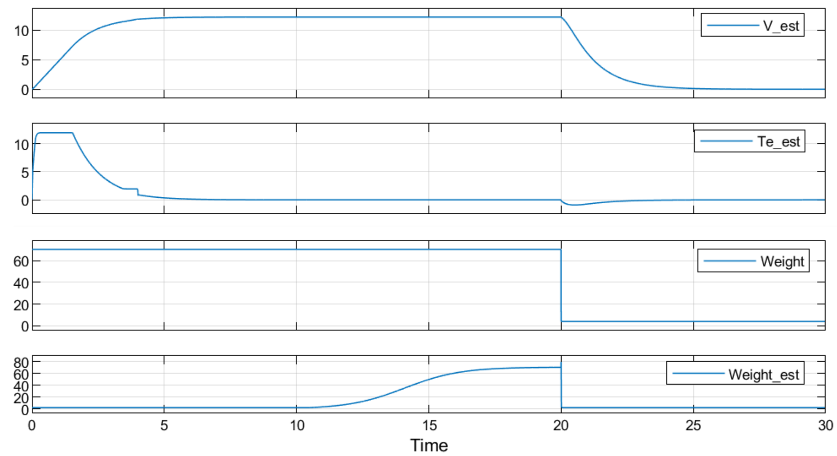

Figure 7. Weight Detection Process: Weight = 70.8Kg; Weight_est = 70.6Kg;

4. Conclusion

Skateboarding is traditionally considered a very hazardous activity and almost entirely dependent on safety gear in the event of accidents. A novel electric skateboard control architecture is proposed for better man-machine coordination with safety considerations that prevent the skateboard from accelerating unexpectedly for a start and removes the need for a handheld remote controller. Meanwhile, it also enables higher power efficiency for longer battery mileage per charge. This control architecture can be implemented using a single electric control board without requiring additional weight or pressure sensing devices, hence a lower cost than conventional electrical skateboards. The proposed speed-torque controller regulates the electric motor torque to compensate for the manual force and steer speed control for cruising with friction adjustability to adapt for various skating experiences from a paved road, ice-skating to cruising, completely hand-free. The solution is validated by the corresponding simulation and system implementation with a control board based on C2000 DSP.

5. Future Study

The solution developed assumes that the skateboard runs on a relatively flat surface without considering the scenario of a high slope. To sense the slope angle, a tilt sensing module is needed for the weight estimation. Due to the limit of the hardware reference, the sensing module is not available. Therefore, the solution for the sloping road is not yet tested and will be planned for the next step after the corresponding hardware is developed.

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