Wheel Speed Control Algorithm for Rear Wheel Motor Driven Vehicle

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Abstract – *The conventional vehicles in the past had consisted of mechanical differential which converts the engine torque in to two directions. Due to the introduction of electric vehicle the vehicle propulsion system has changed from combustion engine to electric motor. Since the concept of differential is a must have component to drive a vehicle, it is still used in electric vehicles as well. Common method is a motor generates the torque and transmit it to the wheels through a mechanical differential. It is possible to connect two small motors to each wheel rather than making a large motor and connects a mechanical differential. In order to drive two motors independently it is required to set the correct speeds when the vehicle takes a turn. This research has been conducted to find a control algorithm using a mathematical model to set the ratio of wheel speeds of inner and outer wheels to make a smooth turn while maintaining the desired speed of linear motion. The algorithm has been tested using a prototype model and proved the calculation of wheel speed ratio and actual scenario.*

Keywords: *Control Algorithm, Electric Vehicle, Electronic Differential, Mathematical Model*

Nomenclature

EV -Electric vehicle
GUI – Graphical user interface
V - Linear speed
PID - proportional–integral–derivative
PWM – Pulse width modulated
RPM - Revolutions per minute
R_d – Radius of the wheel
V_{read}– Linear speed measurement
V_{Rread} – Right wheel measuredspeed
V_{Lread}– Left wheel measured speed
V_L – Left wheel set speed
V_R– Right wheel set speed

Greek Letters
ω - Angular velocity

Subscripts
inner-inside of bend
outer-outside of bend
read – measured value

1 INTRODUCTION

Electric vehicles are the latest trend in automobile industry. As per the decay of fossil fuel resources in the world, the automobile manufacturers attempted on manufacturing electric vehicles (EV). These are powered by internal battery and the propulsion system is electric motor. Due to the increment of electronic components in vehicles, several electronic control systems such as automatic parking guidance, dynamic breaking and energy controlling are installed in these vehicles. This area has rapid outcomes with the introduction of new technology to the market.

The differential is a device which splits the engine torque in to two ways, allowing each output to spin at a different speed. When the vehicle takes a turn, the inner wheels rotate at a lower speed than the outer wheels. This concept is clearly explained in the next section of this paper. The differential is found in all vehicles including rear-wheel, front-wheel and all-wheel-drive vehicles. This component individually controls the outer and inner wheels of the vehicle and let the vehicle take a turn properly. Conventional differential is a mechanical component and this has been assembling in vehicles for decades. Still almost all the commercial vehicles employ the conventional mechanical differential. Electronic differential is an innovative concept in electric vehicle technology research areas. In here, wheels are powered by individual motors and the electronic controlling performs the functionality of the differential. There are many advantages by using an electronic controlled differential in a vehicle.

The objective of this research is to develop a control algorithm for an electronic differential. This paper will illustrate the concept of electronic differential, discuss the advantages compared to conventional differential and discuss future improvements. A mathematical model is developed to validate the input-output relationship of the algorithm. The algorithm is simulated and tested with a prototype model.

2 ADVANTAGES OF ELECTRONIC CONTROL SYSTEMS OVER MECHANICAL CONTROL SYSTEMS

Upon the emergence of large-scale electrical vehicle manufacturing, the controlling units of vehicles are converted to electronic means. Mechanical control systems used for engine controlling, applying brakes and transmission are now being replaced by electronic control systems. Due to that, precise and smooth controlling can be achieved and could reduce the use of bulky mechanical components.

As an example Internal Combustion Engine, transmission system, differential system of a traditional vehicle could be replaced with two independent motors connected directly to rear wheels with a precise control mechanism. As presented in (Haiihosseinlu et al., 2014) the advantages of electronic control systems over conventional methods are listed below.

1. Avoided heavy, bulky mechanical arrangements. Energy efficiency of the vehicle is increased due to this.
2. Maximum turning angle of a normal vehicle is around 40 degrees. New model can support higher turning angles which gives more mobility options for the vehicle.
3. Due to the possibility of individual controlling of each wheel, it can provide better torque considering the traction surface for each wheel.

4. It is evident that adaptation of electronic controlling for a vehicle could provide above benefits.

2.1 The drive system of an EV

An Electric Vehicle's drive system performs the same functions as that of a vehicle powered by an internal combustion engine. The drive system is the part of the electric vehicle which transmits mechanical energy to the traction wheels causing the electric vehicle to move. Electric vehicles utilize an electric motor to rotate the wheels of the vehicles. There are several different drive system designs in use today. These include vehicles with a single large electric motor coupled to the rear wheels through a differential housing. Other designs utilize two smaller motors to power-up each wheel separately through independent drive shafts (Hashemnia & Asaei, 2008). As presented by (Draou, n.d.) and (Haiihosseinlu et al., 2014) this method is known as electronic differential system.Though the electronic differential system can be directly applied for electric vehicles, it is not widely found in available electric vehicles in the market (Madaras et al., 2013). Most of the EV employs mechanical differential connected to electric motor method as depicted in Fig. 1.

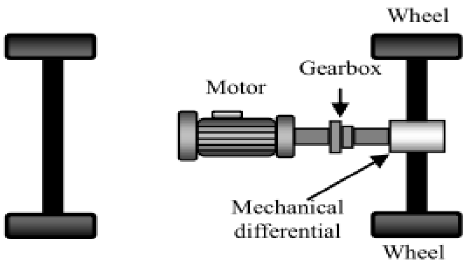

Figure 1: Arrangement of mechanical differential of a vehicle

3 DEVELOPMENT OF MATHEMATICAL MODEL FOR WHEEL SPEED RATIO CALCULATION

The relationship between steering angle, vehicle speed and speeds of rear wheels have to be derived by a mathematical model. The Ackerman Steering Principle (Yildrim et al., 2015)defines the geometry that is applied to all vehicles to enable the correct turning angle of the steering wheels to be generated when negotiating a corner or a curve. The intention of Ackermann geometry is to avoid the need for tyres to slip sideways when following the path around a curve. In order to ensure an ideal rolling of the wheels during cornering all wheels need to have their axles arranged as radii of a circle with a common centrepoint.

As the rear wheels are fixed, this centre point must be on a line extended from the rear axle. In order to intersect this rear wheel axis with the axes of the front wheels it requires the inside front wheel is turned, when steering, at a greater angle than the outside wheel. This is depicted in Fig. 2. Note that the angle of inner front wheel (β) is greater than the angle of outer front wheel (α).

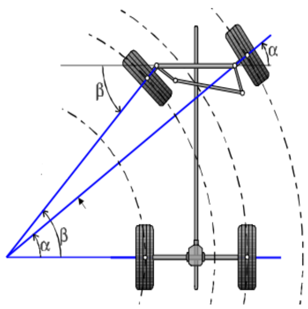

Figure 2: Geometrical arrangement of wheels in a turn (Vehicle is taking a left turn)

3.1 Relationship between inner and outer wheel speeds

Mathematical model will address the relationship of speeds of inner and outer wheels of the vehicle considering the turning angle of the vehicle. Fig. 3 depicts the parameters we consider upon construction of the model. The detailed geometry of a vehicle, presented by (Fu et al., 2012) for slide slip control is used here.

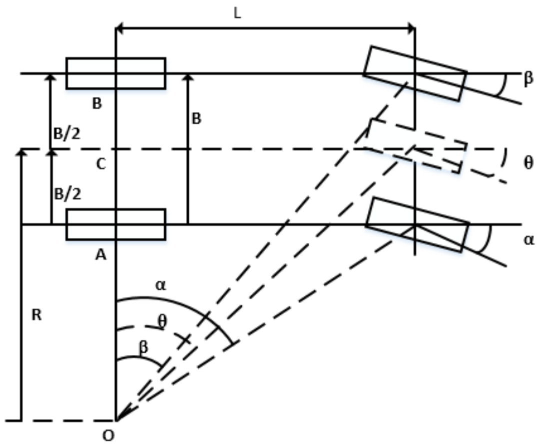

Figure3: Geometrical representation of wheels in a turn with parameters

R – Cornering radius B – Track width of the rear axel

L – Wheel base 0 – Centre of cornering

α – Angle displacement of front right wheel β – Angle displacement of front left wheel

θ - Angle of displacement of imaginary middle wheel also the steering angle of vehicle

The diagram shown in Fig. 3 illustrates a vehicle having four wheels. When the vehicle is steered by angle θ, the inner and outer wheels should be turned by α, β angles respectively. This is accommodated by the steering rack of the vehicle. It should be noted that the steering angle is changed by the driver and inner-outer wheel angles depend on that steering angle. Therefore θ is an independent variable and α, β are dependent variables.

When the vehicle is moving forward

$\theta = \alpha = \beta = 0^{o}$

When taking a turn it is

$\beta < \theta < \alpha$ for right turns or $\alpha < \theta < \beta$ for left turns.

3.2 Derivation of equations for wheel speeds

Step1

Referring to the diagram shown in Fig. 3, the radius of the curve can be expressed by the angles of the front wheels.

$$\mathrm{R} = \mathrm{OC} = \left(\mathrm{OA} + \frac{\mathrm{B}}{2}\right) = (OB - \frac{\mathrm{B}}{2})$$

$$\mathrm{OA} = \mathrm{L\ COT}\ \alpha\ ,\ \ \mathrm{OB} = \mathrm{L\ COT}\ \beta$$

$$\therefore \mathbf{R} = \mathbf{L\ COT}\boldsymbol{\alpha} + \frac{\mathbf{B}}{\mathbf{2}} = \mathbf{L\ COT}\boldsymbol{\beta} - \frac{\boldsymbol{B}}{\mathbf{2}} = \mathbf{L\ COT}\ \boldsymbol{\theta}$$

It is clear that both inner and outer wheel angles have a relationship to steering angle. The steering angle can be represented by a single imaginary middle wheel angle. The control algorithm for rear wheel motor driven vehicles is developed based on this imaginary middle wheel concept. As presented by (Sharma & Pegu, 2015) this method can replace the initial four wheel model; hence reduce the complexity of calculations. This replacement model is illustrated in Fig. 4.

Step 2

It is possible to calculate the relationship between θ,α,β

$$\frac{\mathrm{B}}{2} = \ \mathrm{R} - \mathrm{L\ COT}\alpha$$

$$\mathrm{R} = \mathrm{L\ COT}\beta - \frac{B}{2}$$

Substitute R and $\frac{\mathrm{B}}{2}$

$$\mathrm{L\ COT}\ \theta = \ \mathrm{L\ COT}\beta - \mathrm{L\ COT}\ \theta + \mathrm{L\ COT}\alpha$$

$$\mathrm{COT}\ \theta = \frac{(\mathrm{L\ COT}\beta + \mathrm{L\ COT}\alpha)}{2}$$

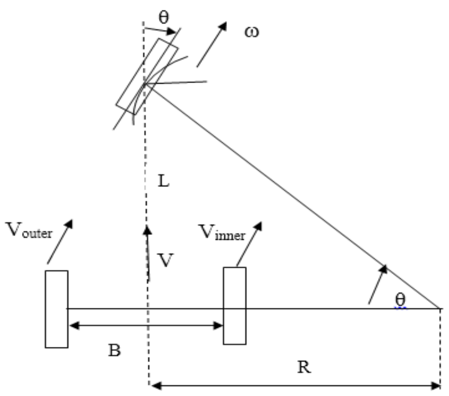

Figure4: Simplified geometric model with parameters

V – Vehicle linear speed   ω – Vehicle angular speed
V_{inner} – Linear speed of inner wheel V_{outer} – Linear speed of outer wheel

Step 3 - The distance between center of rotation and vehicle's center line is given by

$$R = \frac{L}{\tan\theta} \tag{1}$$

Step 4 - The linear velocity equations of the left and right wheels can be derived based on the following equations. From the top view, the centers of both driven wheels of the vehicle are spinning with equal angular velocity about the point 0.

$$V = \omega R \tag{2}$$

Both wheels have the same angular velocity about the point 0, but different distances from the center of rotation. These different distances are creating the angles as discussed in section 3. Therefore when θ ≠ 0,

$$V_{inner} = \omega\left(R - \frac{B}{2}\right) \tag{3}$$

$$V_{outer} = \omega\left(R + \frac{B}{2}\right) \tag{4}$$

By substituting ω from (2) and R from (1)

$$V_{inner} = \frac{V}{R}\left(R - \frac{B}{2}\right) \quad , \qquad V_{inner} = V\left[1 - \left(\frac{B\tan\theta}{2L}\right)\right] \tag{5}$$

$$V_{outer} = \frac{V}{R}\left(R + \frac{B}{2}\right) \quad , \qquad V_{outer} = V\left[1 + \left(\frac{B\tan\theta}{2L}\right)\right] \tag{6}$$

If the wheel radius is R_d, the speed of each wheel in revolutions per minute (RPM) can be calculated as

$$\text{RPM inner} = V_{inner}\left[\frac{60}{(2\pi\, R_d)}\right] \tag{7}$$

$$\text{RPM outer} = V_{outer}\left[\frac{60}{(2\pi\, R_d)}\right] \tag{8}$$

4 FORMULATION OF THE CONTROL ALGORITHM FOR THE MATHEMATICAL MODEL

DC motor has almost linear relationship between speed and torque (Ramesh et al., 2011). For an electronic differential, two motor speeds are equal when the vehicle is running on a straight path and different when taking a turn. In a turn, inner wheel speed is less than outer wheel speed. Another point is that the two wheels may not always travel in identical surfaces of the road. If one wheel moves on an inclined surface on the road, the particular motor has higher load than the wheel moves on a flat surface. Therefore the motor attached to this wheel, has to generate a higher torque than latter one. A speed control algorithm is required to overcome this issue.

4.1 DC motor speed and torque controlling by PWM method

It can be shown that the speed of a DC motor can be controlled by the duty cycle of the pulse width modulated (PWM) signal given to motor (Haiihosseinlu et al., 2014). PWM signals with higher duty cycles will have higher conduction time hence provide higher speeds. If the load on the motor is high, for the same PWM signal, the motor tends to reduce the speed. In this situation, the duty cycle of the PWM signal has to be increased in order to retain the required speed (Haiihosseinlu et al., 2014). Fig. 5 illustrates the DC motor speed torque characteristic curves for three different PWM signals shown as PWM1, PWM2 and PWM3. In this illustration, PWM 3 has the highest duty cycle which is 100%. It is possible to vary the duty cycle under PWM 3 curve region.

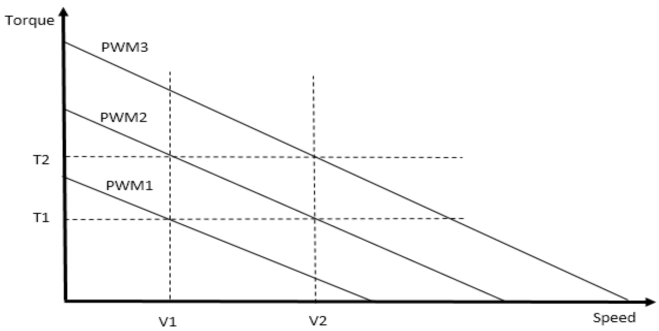

Figure 5: DC motor torque speed characteristics in different PWM signals

As an example, if T2 is the torque for rough road surface and T1 for smooth road surface, the speed V1 can be maintained by changing the PWM duty ratio. By changing the duty cycle; it is possible to move the characteristic curve parallel to each other as PWM 1, PWM 2 and PWM 3 below 100% duty cycle. By considering the above graph it is possible to deduce the required PWM signal for each motor considering the drive pattern, required velocity and the torque. Following table denotes the possible combinations for torque and velocity and the required PWM signal for each motor. Table 1 shows different combinations of PWM signals for inner and outer wheels which will provide the necessary speeds at different requirements of torques for each wheel. It represents two speeds named V1 and V2 and two torques named T1 and T2 which are interpreted as requirements for two different loads on wheels. In the case where the vehicle run on a straight path and the surface is same for both wheels, the required torque will be same. Therefore same PWM will be applied to the motors. If one of the wheels runs on a different surface than the other one, the speed requirement is same for both wheels but the torque is different. Therefore, to compensate the torque it is required to change the PWM of one motor. It will maintain the desired speed by applying different torques on two wheels. The Table 1 shows examples for twelve different circumstances.

Table 1: PWM signal for different circumstances

Drive path	Inner wheel Load	Outer wheel Load	Inner wheel speed	Outer wheel speed	Inner wheel torque	Outer wheel torque	Inner motor PWM	Outer motor PWM
Strait run	Low	Low	V1	V1	T1	T1	PWM 1	PWM 1
Strait run	Low	High	V1	V1	T1	T2	PWM 1	PWM 2
Strait run	High	Low	V1	V1	T2	T1	PWM 2	PWM 1
Strait run	High	High	V1	V1	T2	T2	PWM 2	PWM 2
Turning	Low	Low	V1	V2	T1	T1	PWM 1	PWM 2
Turning	Low	High	V1	V2	T1	T2	PWM 1	PWM 3
Turning	High	Low	V1	V2	T2	T1	PWM 2	PWM 2
Turning	High	High	V1	V2	T2	T2	PWM 2	PWM 3
Strait run	Low	Low	V2	V2	T1	T1	PWM 2	PWM 2
Strait run	Low	High	V2	V2	T1	T2	PWM 2	PWM 3
Strait run	High	Low	V2	V2	T2	T1	PWM 3	PWM 2
Strait run	High	High	V2	V2	T2	T2	PWM 3	PWM 3

From table1, it is evident that different torque and speed requirements can be achieved by providing the correct PWM to the motor. In order to define the correct wheel speed ratio the mathematical model derived in section 3.2 is used. It is then used to generate the correct PWM by an algorithm. Fig. 6 shows the flow chart of the control algorithm.

4.2 PID control method

It is observed that the ratio between outer wheel speed and inner wheel speed depends on steering angle (θ) and does not depend on speed. This can be proved from the equations (5) and (6) since the parameters B and L are constants and only variable is (θ). For smooth functioning of differential, the speed ratio has to be maintained with minimum error.A proportional-integral-derivative (PID) controller can calculate an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through a manipulated variable. In the prototype the error is the difference between set speed and the measured speed of a wheel. In order to minimize the error it varies the duty ratioof the PWM to retain the desired speed of the motors. Arduino® has PID library which could be directly used to get the calculated outputs efficiently.

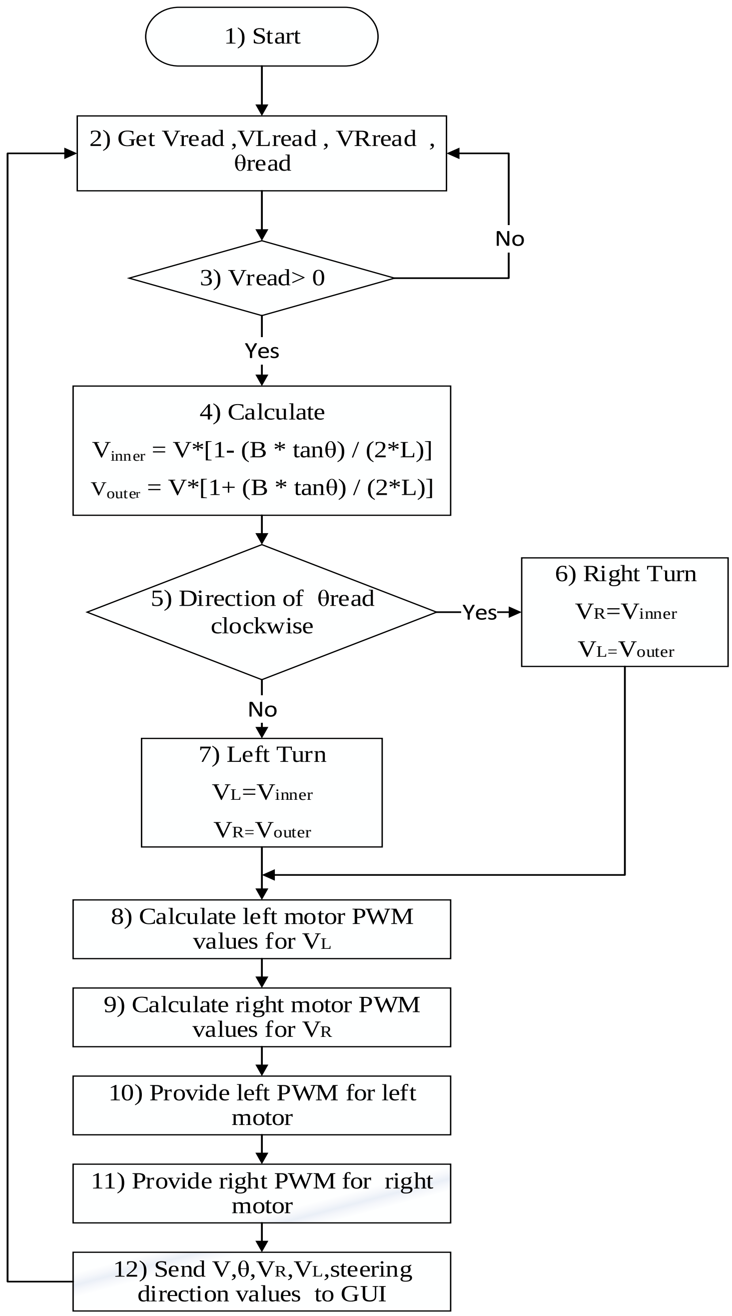

Figure 6: Flow chart of the control algorithm

4.3 Testing of the algorithm using the prototype

The algorithm has been tested on a prototype model of a vehicle. Design of the prototype was based on following facts.

1. Type of the motor – There are several motor types found in electric vehicles. Induction motor is used by most of the vehicle manufacturers considering its characteristics. For the construction of prototype, controllability of the motor is the first priority in selection of a motor. DC motors has the highest controllability and cost of controller is comparatively low. Therefore DC motors have been used for constructions which were controlled by PWM method.

2. Motor drive – The drive for the prime mover of the vehicle. The L298 drive was used as motor drive.

3. Energy source – The battery should be capable to provide power to the prototype.

4. Microcontroller – Prototype works according to the control algorithm. Therefore a microcontroller was required to run the algorithm. This algorithm has mathematical calculations and outputs should be precise. Since the model should be capable of providing results while running the vehicle the microcontroller should have sufficient processing speed.

4.3.1 Control system of the prototype

As shown in Fig. 7 the control system of the prototype consists of speed and steering angle as inputs.

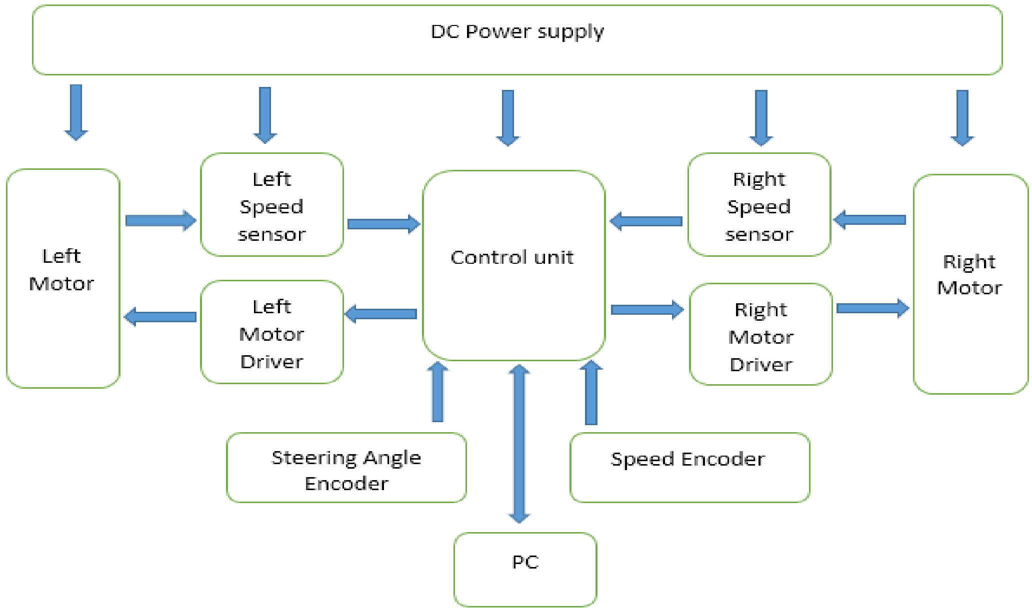

Figure 7: Block diagram of the control of prototype

Two volume control type potentiometers have been used to give the inputs to controller. Those are connected to A0 and A1 analog input pins of Arduino board. The Arduino microcontroller reads 0 – 5 V analog input range with a resolution of 8 bit binary numbers. This means it reads the 0 – 5 V analog range in 28 = 1024 voltage steps. By program code, the read value is mapped to desired range of speed and steering angle parameters. The input denotes the input limits and read values. Table 2 compares the input ranges of the Arduino microcontroller and the relevant input variable.

Table 2: Input variables and relevant ranges of the Arduino microcontroller

Input	Voltage range	Microcontroller pin	Microcontroller reading range
Speed	0 V to 5 V	A0	0 RPM to 350 RPM
Steering angle	0 V to 5 V	A1	40 Degrees to – 40 degrees

As described in PID method the control system requires a feedback from the wheel speed. Therefore a sensor is attached to the drive motors to measure the wheel speed. The sensor is a rotary encoder which has 20 holes on the rotating disc. When the encoder wheel rotates together with the motor drive shaft, it generates a digital pulse train cycled at the rate of wheel speed. For a complete rotation, the encoder generates 20 pulses. Encoder outputs are connected to the interrupt handling pins of Arduino. When the pin receives a rising edge of a pulse, it calls for interrupt handling subroutine of the main program which calculates the speed of the wheel.

4.3.2 Driving of motors

The duty cycle for PWM can be varied in steps of 1 in the range of 0 to 255 in Arduino® PWM output. PWM value for required speed is calculated by PID subroutine. Arduino has a PID library which calculates the required PWM output for the motor drive. The inputs for the PID function are the set speed, measured speed and the P, I, D constants. Values for the constants are determined by manual tuning method. Here the values are changed until the desired performance level is achieved.

4.3.3 Design considerations of PWM generation

Maximum RPM of the selected motors are around 520 rpm. If the motor rotates at this speed, it generates much heat and noise. This reduces the lifetime of the motor. Therefore maximum rpm is limited to 350.

The tested Motors do not rotate for a PWM value fewer than 35. Because the voltage applied at that level is insufficient to overcome the internal losses and start motor rotation. Minimum rpm for the motors has been decided as 40. Speeds from 40 rpm to above could be directly achieved by PWM. Speeds below 40 rpm cannot be achieved by PWM controlling. For a real model these lower speeds could be achieved by applying wheel brakes.

5 REAL TIME TESTING AND RUN TIME MEASUREMENTS

The prototype control system has been tested for two control scenarios. Test 1 was the straight run of the vehicle with varying speeds. The steering input is set to zero for this test run. Test2 was the changing steering angles for constant speed input.

5.1 Real time testing and data acquisition

Data acquisition has been done by using MegaunoLink® (Marketing, 2015) software.

Measurements of each test run are as follows.

i. Left Wheel Speed measured

ii. Right Wheel Speed measured

iii. Speed Input

iv. Steering Input

From the measurements, following information has been calculated.

PWM for inner and outer wheel from equation (7) and (8)

Desired speed ratio = (Inner wheel set speed / Outer wheel set speed)

Actual speed ratio = (Inner wheel measured speed / Outer wheel set speed)

Ratio error = (Desired speed ratio – Actual speed ratio)

Inner or outer wheel speed error = (Set speed – actual speed) / set speed

5.2 Analysis of results

Test1 – Steering input is fixed at zero. Seven different speeds have been given to the input throughout the run. Test has been run for forty seconds. Eighty data points at equal time intervals have been measured using MegaunoLink® data acquisition and recorded on computer. The requirement of this scenario is to maintain the speeds of inner and outer wheels speed ratio at unity when vehicle speed change occurs. The graph in Fig. 8 shows the actual speed change of each wheel along with the set speed variation. It is evident that the controller is taking a time to fix the wheel speed to the desired value. The prototype has been tested with minimum load on vehicle. Therefore the fluctuations of speed measurements have been shown. More loading on wheels will damp the sudden variations in a real model. The PID controller has been tuned to get the step response to an acceptable smooth level.

Test2 – Vehicle speed is fixed and different steering angles have been given to the input throughout the run. Test has been run for fifty five seconds. One hundred and ten data points have been acquired using the same methodology as test1. The requirement of this scenario is to set the correct speed ratio immediately after changing the steering angle. Fig. 9 shows the actual wheel speed variation for steering input changes with constant vehicle speed. From the results it is evident that the controller follows the desired speed of each wheel and correctly changes the speed at desired point. According to the PID controller values it takes a time to stabilize the speed of wheel.

5.2.1 Average error calculation for the test run

From the results, the error ratio for the wheel speed can be calculated as

Speed error = (set speed – actual speed) / set speed

The average speed error has been calculated for the period of entire test run of test1 and test2 separately. The results show that for the test1 the average speed error is 0.06. For test2 it is 0.07 for left wheel speed and 0.08 for right wheel speed. According to the results it is evident that the controller is capable of setting the desired speed more accurately for speed changes than changes in steering input.

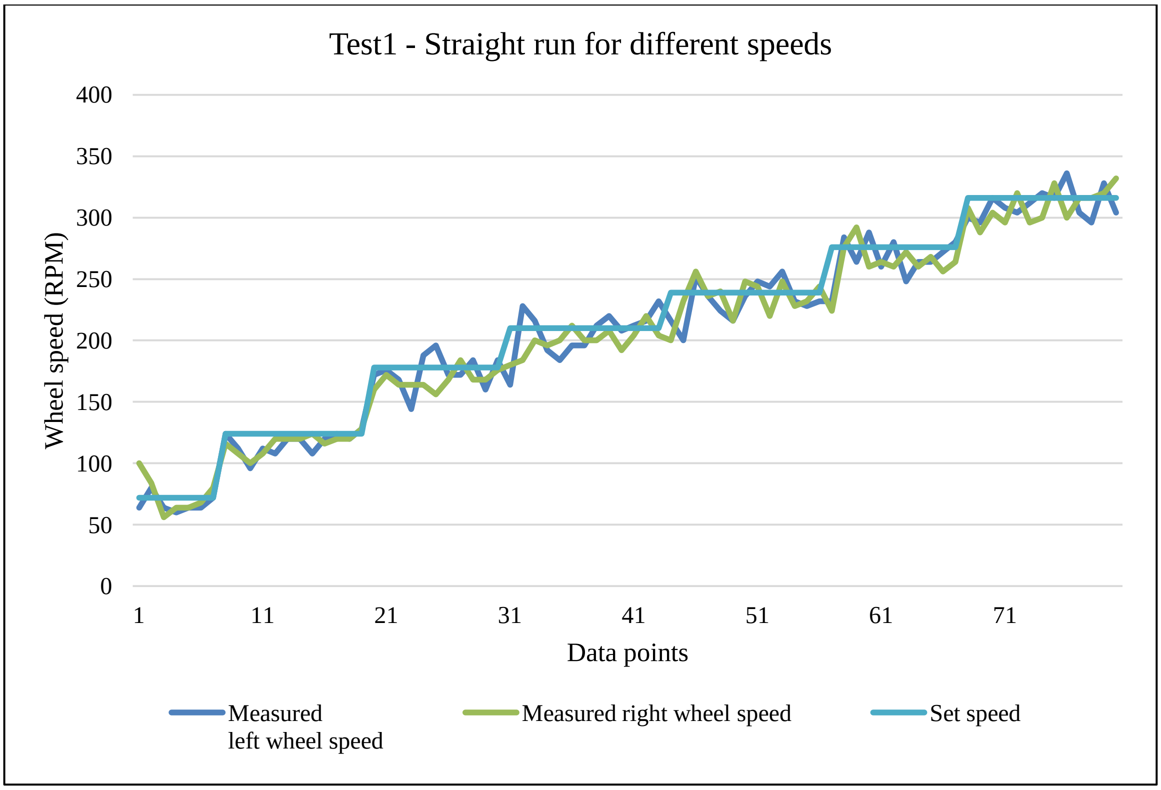

Figure 8: Actual wheel speed variation according to set speed changes

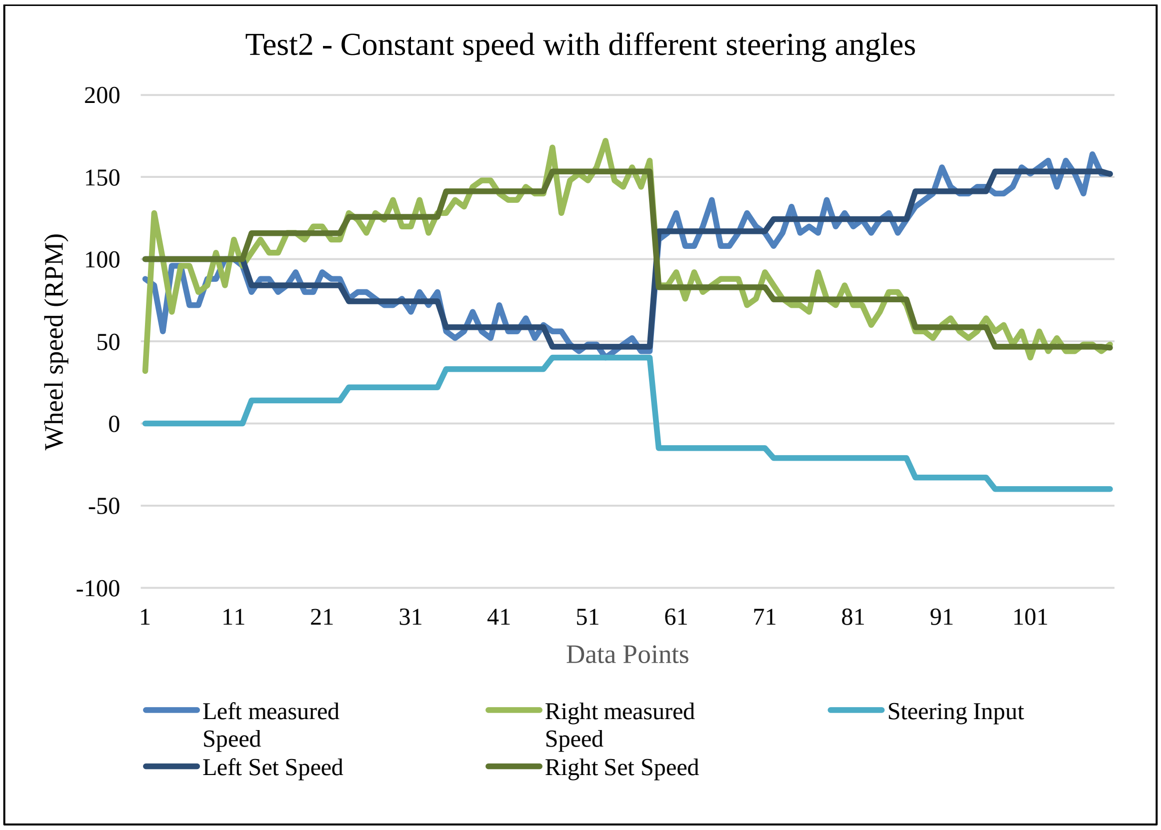

Figure 9: Actual wheel speed variation according to steering input changes

6 CONCLUSION

The mathematical model designed for the electronic differential concept has been tested with a prototype. Test results have confirmed the correctness of the control algorithm hence prove the mathematical model. There are differences between the calculated values and the measured values. A real implementation model can test how much tolerance is acceptable without disturbing traction. Following points have been identified as possible reasons for the error between expected and test results.

The two motors which are connected to left and right wheels have to be almost identical in its physical parameters. Otherwise it is not possible to have same measurements as Rise time, Settling time for the two motors. The motors which are used for the prototype are manufactured not exclusively for this purpose. For a real application, DC traction motors has to be uniquely manufactured.

The Atmega® microcontroller in Arduino® board does not support multi-threading operation. Therefore all the functions (read inputs, measure speed, calculate PID outputs) has to be done in same control loop in the program code. The speed measurement subroutine has 750 milliseconds delay for one wheel speed measurement, altogether the control loop delayed for 1.5 seconds interval during speed measurements. This is affecting for the performance of the system. This could be overcome by using a multithreading support microcontroller and measuring the wheel speeds in different threads. This method is useful for a practical Electronic Differential design.

It is clear that the mathematical model is proven for giving correct inner and outer wheel speed ratio when steering a vehicle. By using this model, the conventional differential can be replaced with electronic counterpart hence achieve more benefits for the vehicle manufacturing industry. The differential lock method which is used in heavy vehicles can also be achieved with this electronic differential method. It is required when one of the two rear wheels is on a slipping surface while the other is on rough surface. Then the wheel on the sipping surface tends to run at a higher speed unless the differential is mechanically locked. In this electronic differential method this kind of wheel slip will not be occurred. Because it gets the wheel speed as a feedback and the control system set the PWM to maintain that desired speed. Therefore this kind of wheel slipping will not be occurred with electronic differential method.

Even though the current approach was to design a differential for rear wheel motor driven vehicle, it is possible to improve this technology to drive front wheel and all-wheel drive vehicles as well.

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