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New Method Proposal for Vehicle Speed Estimation Using Inertial Sensor

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Executive Summary

The traction motors in electric vehicles play an important role in the motion control due to their precise torque control performance. As a control technology utilizing this characteristic, traction control based on slip ratio has been proposed. Specifically, regarding AWD vehicles, accurate slip ratio calculation requires high-precision vehicle speed estimation. GPS-based methods suffer in poor signal environments. This study focuses on a vehicle speed estimation method using IMU and wheel speed, known as the Leveling Calculation. This method corrects integration errors of the Inertia Calculation, maintaining accuracy over time. On the other hand, it becomes unsuitable when tire grip reduces, causing divergence between actual vehicle and wheel speed. We propose a new method that detects tire grip conditions using acceleration excluding gravitational effects and wheel speed, switching between the Inertia Calculation and the Leveling Calculation based on grip state. The effectiveness of the proposed method was confirmed through vehicle experiments.

Keywords: Drive & Propulsion Systems, Electric Motor Drive, Vehicle Motion & Stability Control, Measuring Methods & Equipment, Advanced control of EVs

1 Introduction

Electric vehicles (EVs) have long been attracting attention as a potential solution to global warming and fossil fuel depletion issues. Initially, the development of EVs was focused on environmental challenges. In recent years, vehicle motion control technologies using the precise torque control capabilities of the traction motor have been proposed successively. As a control technology utilizing this characteristic, traction control systems based on the slip ratio between driving tire and road surface have been developed, contributing to improvements of safety and comfort [1].

On the other hand, precise calculation of the slip ratio, a critical parameter in traction control systems, fundamentally relies on accurate estimation of vehicle speed. In general, for traction control in 2WD vehicles, the driven wheel speed can be considered equivalent to the vehicle speed. However, in AWD (all-wheel drive) vehicles, all wheels are susceptible to loss of grip [2], rendering the method used in 2WD vehicles inapplicable. Moreover, vehicle speed estimates based on GPS signals tend to lose accuracy in environments where GPS reception is compromised or unavailable. Therefore, this study focuses on a vehicle speed estimation method utilizing IMU (inertial measurement unit) and wheel speed, known as the Leveling Calculation [3]. An IMU, comprising a tri-axial acceleration sensor and a tri-axial angular velocity sensor, is widely studied in vehicle attitude and trajectory estimation [4][5]. While the Leveling Calculation effectively corrects integration errors in the Inertia Calculation, it is not applicable when tire grip reduces. Thus, a key challenge lies in developing an appropriate switching mechanism between the Inertia Calculation and the Leveling Calculation.

In this paper, a vehicle speed estimation method based on the Inertia Calculation and the Leveling Calculation is proposed. First, the acceleration excluding gravitational effects is calculated through the Inertia Calculation. Subsequently, based on the wheel speed and the aforementioned acceleration, a tire grip detection method is designed in which the Inertia Calculation is selected during non-grip conditions and the Leveling Calculation is selected during grip conditions. Finally, the accuracy of the proposed vehicle speed estimation method and its applicability to traction control are evaluated through vehicle experiments.

2 Traction Control Systems

When a vehicle accelerates on a low-μ road surface, if the driving force of the wheels exceeds the friction force, the wheels begin to skid. Traction control systems aim to enhance vehicle stability and safety by preventing tire slip during acceleration. In conventional internal combustion engine vehicles, traction control is achieved by engine torque and hydraulic brakes. This study focuses exclusively on traction control achieved solely by electric motor torque. By monitoring wheel speed and adjusting the motor torque accordingly, traction control systems ensure optimal tire grip on various road surfaces.

Figure 1 shows the system overview of the traction control. The Traction Control Judgement determines the ON/OFF status of the traction control system based on the vehicle speed estimate, motor speed, driver torque demand, and motor torque setpoint. The Motor Speed Setpoint Calculation computes the optimal motor speed setpoint corresponding to the slip ratio, allowing the tires to achieve maximum grip from the road surface based on the vehicle speed estimate. The Motor Speed Control calculates the speed control torque necessary for the actual motor speed to follow the motor speed setpoint. The Torque Select switches between the driver torque demand and the speed control torque based on the traction control flag, thereby calculating the motor torque setpoint. When the traction control flag is equal to “1”, the speed control torque is selected, and when the traction control flag is equal to “0”, the driver torque demand is selected as the motor torque setpoint.

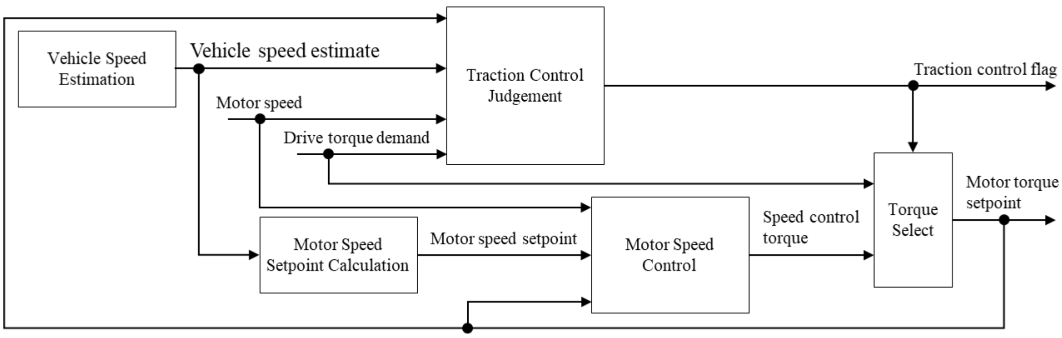

Figure 1: System overview of the traction control

In the following chapters, we will describe the method for calculating the vehicle speed estimate, which is a key factor in realizing this traction control system.

3 Vehicle Speed Estimation Methods

Figure 2 shows the system overview of the vehicle speed estimation. The vehicle speed is estimated using tri-axial acceleration a_x, a_y, a_z and tri-axial angular velocity $\omega_x, \omega_y, \omega_z$ measurements acquired by the IMU, in conjunction with external speed data such as wheel speed.

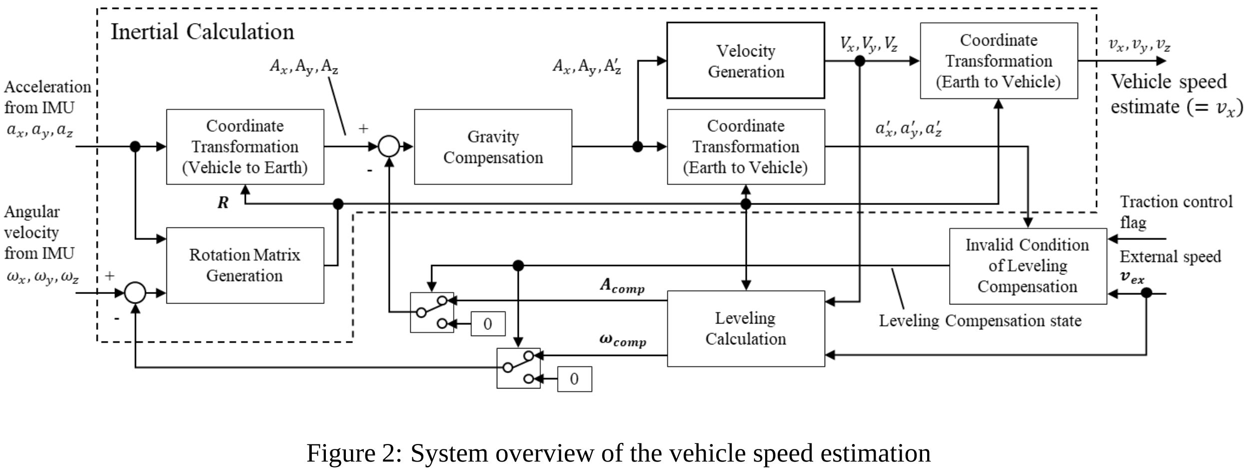

Figure 2: System overview of the vehicle speed estimation

Figure 3 shows the definition of the vehicle coordinate frame and the earth coordinate frame. The vehicle coordinate frame is defined from the viewpoint of an individual situated within the vehicle. In contrast, the earth coordinate frame is defined from the viewpoint of an observer outside the vehicle, referencing the Earth as a whole.

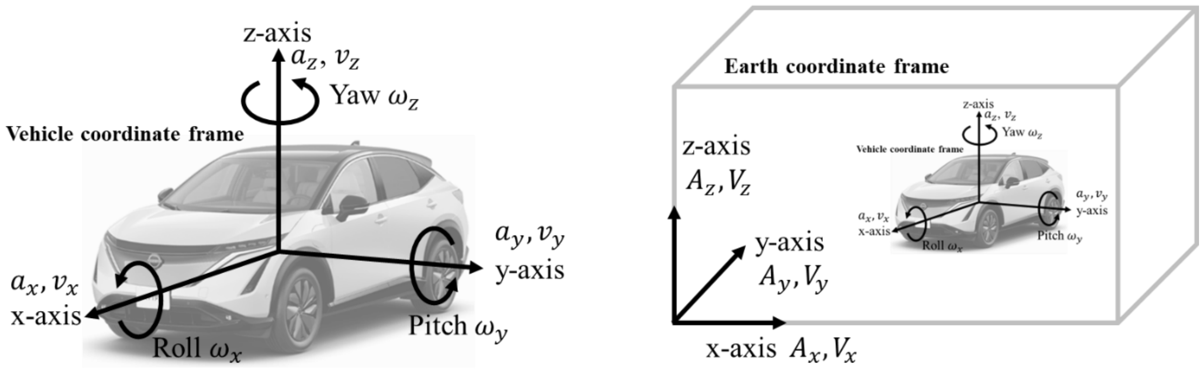

Figure 3: Definition of coordinate frames

3.1 Inertia Calculation

Rotation Matrix Generation

Let ϕ, θ, and ψ denote the roll, pitch, and yaw angles of the vehicle, respectively. The rotation matrix $\boldsymbol{R}$,which transforms any vector from the vehicle coordinate frame to the earth coordinate frame, is expressed as follows:

$$\boldsymbol{R} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \tag{1}$$

During vehicle motion, its attitude changes continuously. The attitude is detected using tri-axial angular velocity $\omega_x, \omega_y, \omega_z$. The IMU data is sampled at a period of Δt. Given that the angular velocity varies slowly relative to Δt, it can be assumed constant over this interval. Consequently, the rotation matrix $\boldsymbol{R_k}$ at time step k can be expressed as follows:

$$\boldsymbol{R_k} = \boldsymbol{R_{k-1}} \boldsymbol{R_{\Delta t_k}} \tag{2}$$

$$\boldsymbol{R_{\Delta t}} = \begin{bmatrix} \cos\omega_z\Delta t & -\sin\omega_z\Delta t & 0 \\ \sin\omega_z\Delta t & \cos\omega_z\Delta t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\omega_y\Delta t & 0 & \sin\omega_y\Delta t \\ 0 & 1 & 0 \\ -\sin\omega_y\Delta t & 0 & \cos\omega_y\Delta t \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_x\Delta t & -\sin\omega_x\Delta t \\ 0 & \sin\omega_x\Delta t & \cos\omega_x\Delta t \end{bmatrix} \tag{3}$$

The initial attitude is determined using tri-axial acceleration a_x, a_y, a_z when the vehicle is stationary. While the initial yaw angle is arbitrarily set, the initial roll and pitch angles are calculated as follows:

$$\phi_0 = tan^{-1}\frac{a_{y_0}}{a_{z_0}}, \theta_0 = tan^{-1}\frac{-a_{x_0}}{\sqrt{a_{y_0}^2 + a_{z_0}^2}} \tag{4}$$

Although the Euler angles are employed for generating the rotation matrix in this study, quaternions could also be effectively utilized.

Coordinate Transformation

The equation for changing the acceleration in the vehicle coordinate frame $\boldsymbol{a} = [a_x \quad a_y \quad a_z]^T$ to the acceleration in the earth coordinate frame $\boldsymbol{A} = [A_x \quad A_y \quad A_z]^T$ can be expressed as follows:

$$\boldsymbol{A} = \boldsymbol{R}\boldsymbol{a} \tag{5}$$

Gravity Compensation

The IMU detects both inertial and gravitational acceleration. Consequently, to isolate the inertial acceleration, gravitational acceleration $\boldsymbol{g} = [0 \quad 0 \quad g]^T$ is subtracted from the total acceleration in the earth coordinate frame $\boldsymbol{A}$, where g is the gravitational acceleration constant $9.81\,[m/s^2]$. Thus, the acceleration excluding gravitational effects $\boldsymbol{A'} = [A_x \quad A_y \quad A'_z]^T$ is obtained as follows:

$$\boldsymbol{A}' = \boldsymbol{A} - \boldsymbol{g} \tag{6}$$

Moreover, in the vehicle coordinate frame, the acceleration excluding gravitational effects $\boldsymbol{a}' = [a'_x \quad a'_y \quad a'_z]^T$ is obtained as follows:

$$\boldsymbol{a}' = \boldsymbol{R}^{-1}\boldsymbol{A}' \tag{7}$$

Velocity Generation

The velocity in the earth coordinate frame $\boldsymbol{V} = [V_x \quad V_y \quad V_z]^T$ is calculated as follows:

$$\boldsymbol{V_k} = \boldsymbol{V_{k-1}} + \boldsymbol{A}'\Delta t \tag{8}$$

As mentioned before, the initial velocity is set to zero, as the attitude is initialized when the vehicle is stationary. In the vehicle coordinate frame, the velocity $\boldsymbol{v} = [v_x \quad v_y \quad v_z]^T$ is calculated as follows:

$$\boldsymbol{v} = \boldsymbol{R}^{-1}\boldsymbol{V} \tag{9}$$

Figure 4 shows the definition of the vehicle speed estimate. In this study, v_x is considered as the vehicle speed for traction control. This approach is adopted because our objective is to control the slip ratio in the direction of the vehicle's longitudinal movement, rather than utilizing the composite velocity vector of the vehicle $\left(= \sqrt{v_x^2 + v_y^2}\right)$. In the following experimental results, which are primarily composed of straight roads, v_x is approximately equal to $\sqrt{v_x^2 + v_y^2}$.

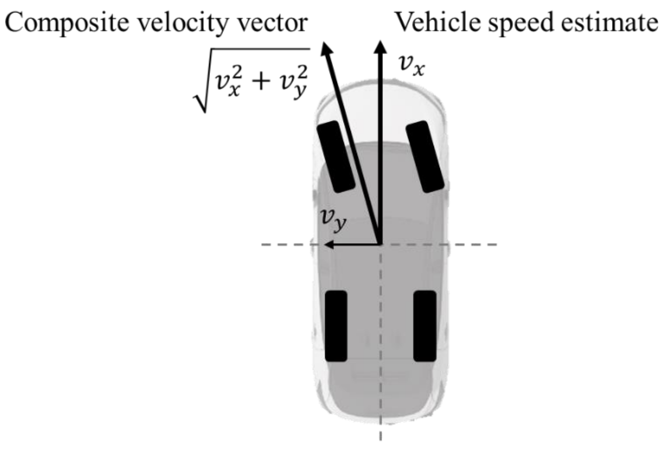

Figure 4: Definition of vehicle speed estimate

A vehicle acceleration/deceleration test was performed on a high-μ flat surface. The experimental results for the Inertia Calculation are presented in Figure 5. The black dotted and blue lines in the upper left panel indicate the true value and the estimated value of the vehicle speed, respectively. The lower left panel shows the estimation error, which is the difference between the true value and the estimated value of the vehicle speed. The right panel shows the true value and the estimated value of the attitude such as roll and pitch angle, respectively.

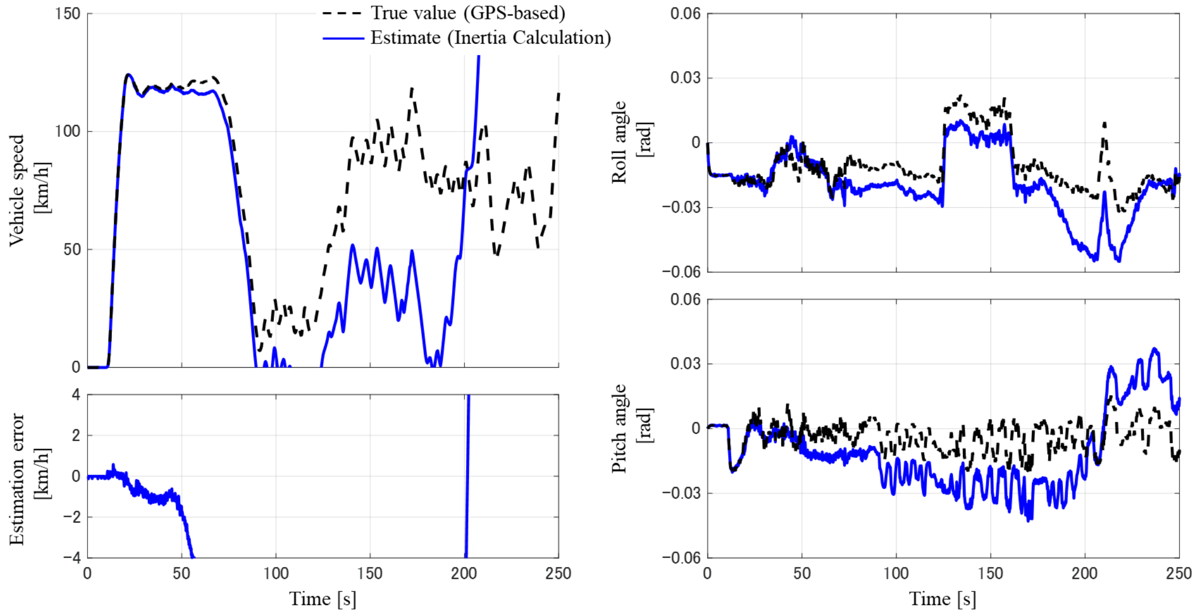

Figure 5: Vehicle test result using the Inertia Calculation

- In a short time frame, the Inertia Calculation accurately estimate the attitude and vehicle speed.
- However, as time progresses, errors due to integration drift accumulate, leading to a deterioration in estimation accuracy.

3.2 Leveling Calculation

The Leveling Calculation corrects the integration error of the Inertia Calculation by utilizing external speed measurements, such as wheel speed. The compensation values for the acceleration in the earth coordinate frame $\boldsymbol{A_{comp}}$ and the angular velocity in the vehicle coordinate frame $\boldsymbol{\omega_{comp}}$ are expressed as follows:

$$\boldsymbol{A_{comp}} = K_1(\boldsymbol{V} - \boldsymbol{R}\boldsymbol{v_{ex}}) \tag{10}$$

$$\boldsymbol{\omega_{comp}} = \boldsymbol{R^{-1}}K_2(\boldsymbol{V} - \boldsymbol{R}\boldsymbol{v_{ex}}) \tag{11}$$

$$K_1 = 2\zeta\omega_n, K_2 = \omega_n^2/g \tag{12}$$

where $\boldsymbol{v_{ex}} = [v_w \quad 0 \quad 0]^T$ is the external speed and v_w is the wheel speed of the vehicle. ζ and ω_n are the damping coefficient and natural frequency, respectively, which are determined experimentally.

Figure 6 shows the block diagram of the Leveling Calculation. The external speed is transformed into the earth coordinate frame, and the difference between this speed and the estimated velocity, as shown in equation (8), is calculated. As indicated in equation (10), the compensation value for the acceleration in the earth coordinate frame $\boldsymbol{A_{comp}}$ is calculated by multiplying the difference with the gain K_1. Additionally, as indicated in equation (11), the compensation value for the angular velocity in the vehicle coordinate frame $\boldsymbol{\omega_{comp}}$ is calculated by multiplying the difference with the gain K_2 and transforming it into the vehicle coordinate frame.

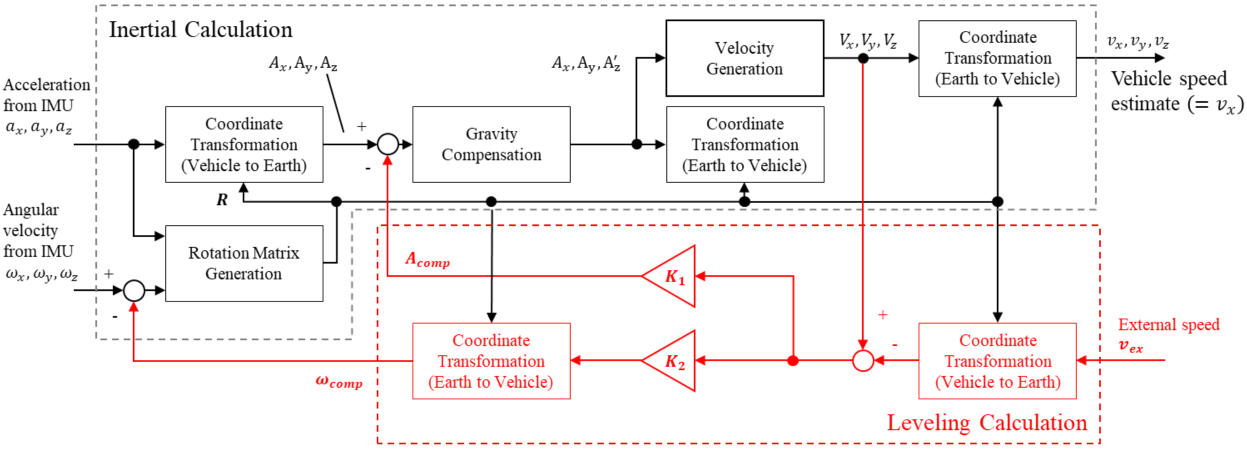

Figure 6: Block diagram of the Leveling Calculation

The experimental results for the Leveling Calculation are presented in Figure 7. The black dotted and blue lines are the same as those in Figure 5. The red lines represent the estimated values, which are calculated using the Leveling Calculation.

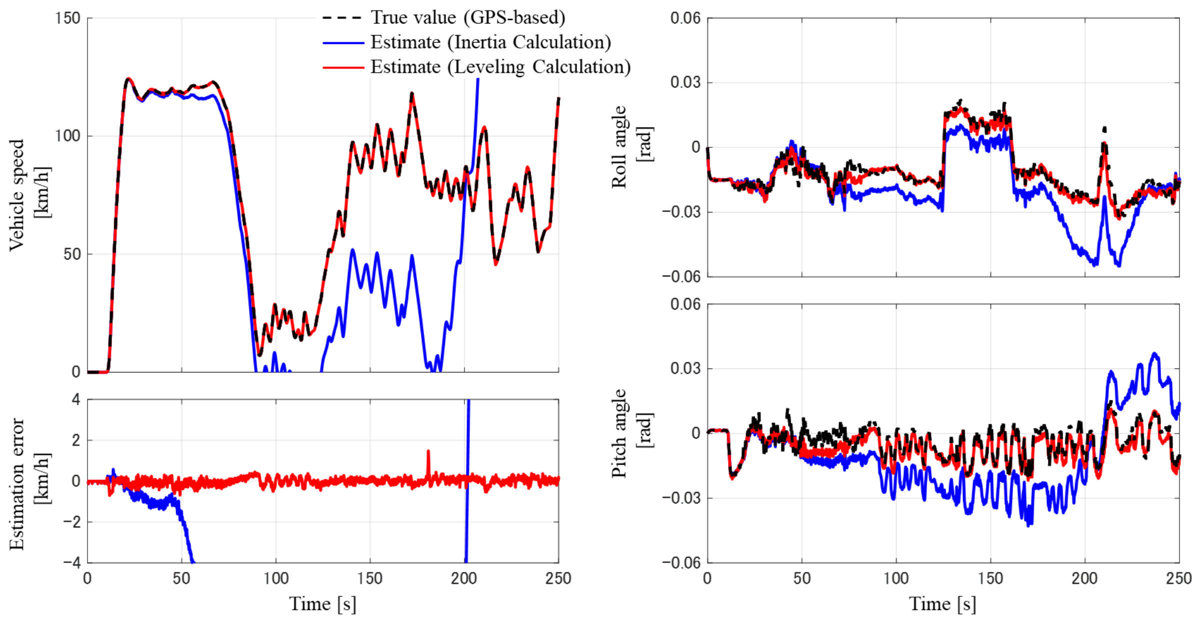

Figure 7: Vehicle test result using the Leveling Calculation

- The Leveling Calculation suppress the accuracy deterioration caused by integration errors, which is a known disadvantage of the Inertia Calculation.
- On the other hand, since the Leveling Calculation relies on external velocity as the true value of the vehicle speed for correction, when wheel speed is used as the external velocity, the correction becomes counterproductive under conditions of reduced tire grip, resulting in a deterioration in vehicle speed estimation accuracy.

3.3 Invalid Condition of Leveling Compensation

The Leveling Calculation assumes that the wheel speed represents the true vehicle speed. Consequently, when tire grip reduces, corrections using the Leveling Calculation could potentially deteriorate the accuracy of the vehicle speed estimate.

Kinematic equation for x-axis is expressed as follows:

$$a'_x = \dot{v}_x + \omega_y v_z - \omega_z v_y \tag{13}$$

Ideally, the velocities v_y and v_z should be zero. However, when the tires are being steered, a small lateral velocity component v_y is experienced due to the tire cornering stiffness. Similarly, when the vehicle hits a bump on the road, a small vertical component v_z is observed. Given that these components are small and short lived, and that the longitudinal velocity v_x can be approximated to the wheel speed v_w during grip conditions, and the acceleration excluding gravitational effects a'_x is calculated from Equation (7), tire grip conditions can be detected as shown in Figure 8.

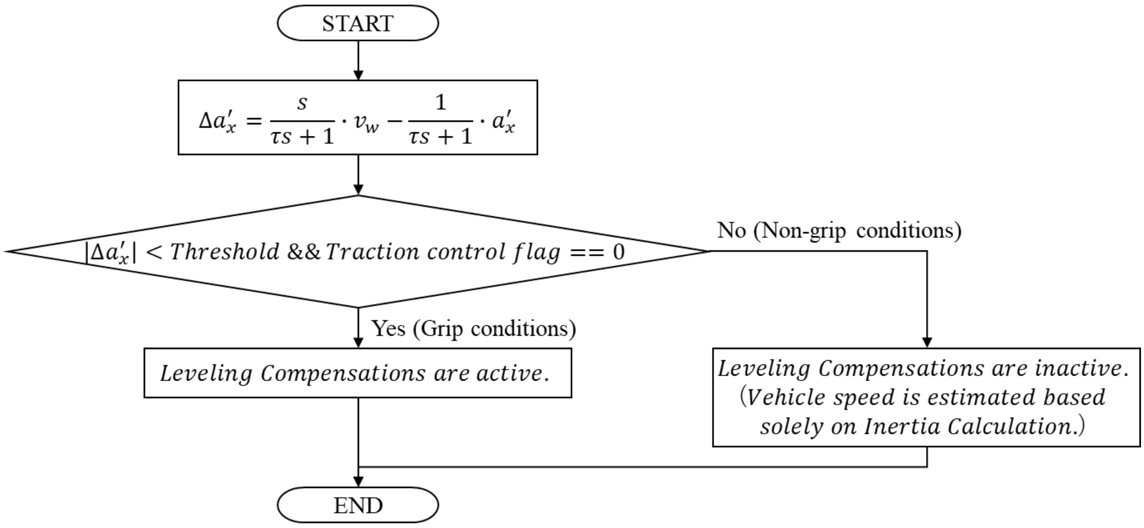

Figure 8: Tire grip detection based on wheel speed v_w and acceleration excluding gravitational effects a'_x

When $\Delta a'_x$ is below a predetermined threshold and traction control is inactive, corrections are implemented using the Leveling Calculation; otherwise, no corrections are applied.

4 Vehicle Test Results

4.1 Experimental Environment

To confirm the effectiveness of the estimation method, experiments were conducted with Nissan ARIYA, a mid-sized sports utility all-wheel drive EV, which is powered by motors located at both the front and rear, as shown in Figure 9. MEMS IMU consisting of a tri-axial acceleration sensor and a tri-axial angular velocity sensor were used for experiments. They were mounted at the rear of the center console. To obtain the true value of the vehicle speed and attitude measurements for comparison, a high accuracy GPS assisted IMU was used. They were mounted on the roof of the vehicle.

Figure 9: Test vehicle

4.2 High-μ Road Surface

A vehicle acceleration/deceleration test was conducted on an uphill/downhill high-μ road with a 26 [%] / 20 [%] gradient. The vehicle started from a stationary position on a flat road, then proceeded to ascend an uphill road, followed by a flat section, and finally descended a downhill road. The experimental results for the proposed method are presented in Figure 10.

In the first left panel, the black dotted line represents the true vehicle speed, while the red line denotes the estimated vehicle speed. The blue and red lines in the second left panel indicate the longitudinal accelerations. The blue line is the low-pass filtered derivative of the wheel speed v_w and the red line is the low-pass filtered acceleration excluding gravitational effects a_x'. The third left panel shows $\Delta a_x'$, which is the difference between the blue and red lines from the second left panel. When $\Delta a_x'$ is less than the threshold, it is determined that the tires are in grip conditions, and the vehicle speed is estimated using the Leveling Calculation. When $\Delta a_x'$ is above the threshold, it is determined that the tires are in non-grip conditions, and the vehicle speed is estimated using the Inertia calculation. The fourth left panel shows the estimation state. When the estimation state is equal to "1", compensations using the Leveling Calculation are active. When the estimation state is equal to "0", the compensations are inactive. The upper right panel shows the estimation error, defined as the difference between the true vehicle speed and the estimated vehicle speed. The middle and lower panel show the true value and the estimated value of the attitude.

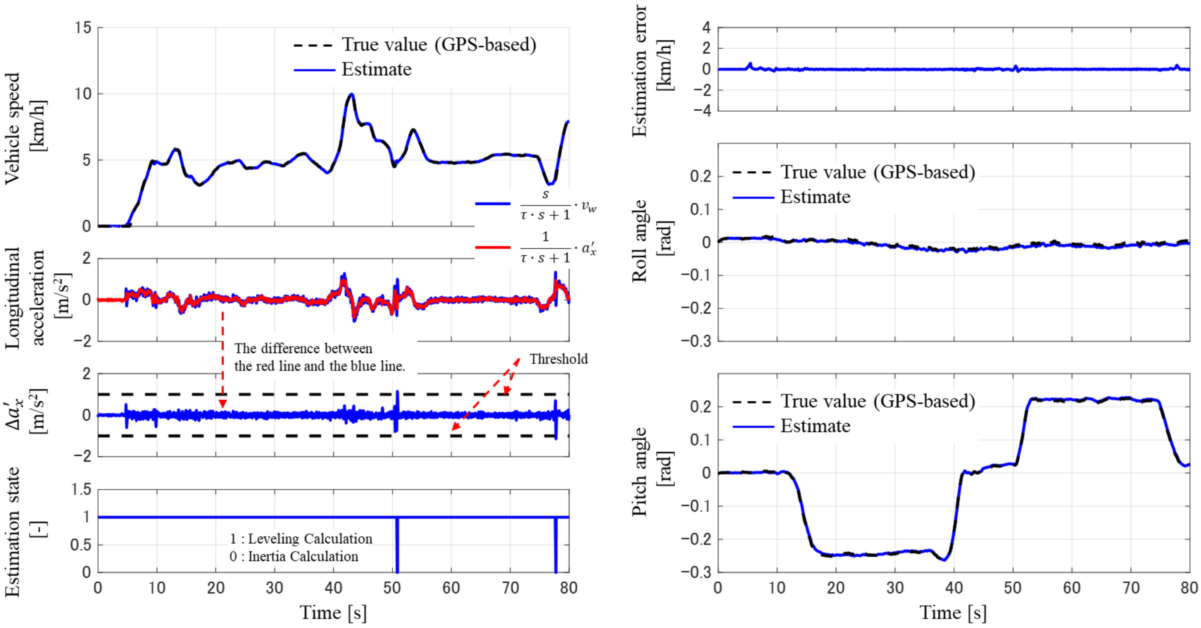

Figure 10: Experimental results on an uphill/downhill high-μ road with a 26 [%] / 20 [%] gradient

- Regarding the second left panel, the blue and red lines are generally consistent regardless of the slopes.
- Regarding the fourth left panel, with the exception of certain scenes, compensations using the Leveling Calculation are active. Since the tires are generally in grip conditions on a high-μ road surface, this operation reflects the desired behavior.

4.3 Low-μ Road Surface

Figure 11 shows the experimental results of a vehicle launch test conducted on a snow-covered uphill road with a 7 [%] gradient, where the vehicle started from rest and accelerated under an accelerator input. Figure 12 shows the experimental results of a vehicle test conducted on an ice uphill road with a 4 [%] gradient, where traction control was alternated between ON and OFF, causing the vehicle to switch between non-grip and grip conditions.

In the first panel, the black line represents the true vehicle speed, while the red line denotes the estimated vehicle speed. The blue and green lines correspond to the average speeds of the front and rear wheels, respectively. The second panel shows the estimation error, defined as the difference between the true vehicle speed and the estimated vehicle speed. The blue and red lines in the third panel indicate the longitudinal accelerations. The blue line is the low-pass filtered derivative of the wheel speed v_w, while the red line is the low-pass filtered acceleration excluding gravitational effects a_x'. The fourth panel shows $\Delta a_x'$, which is the difference between the blue and red lines from the third panel. In the fifth panel, the blue and green lines are the front and rear traction control flags, respectively. The red line is the estimation state. When the estimation state is equal to “1”, compensations using the Leveling Calculation are active. When the estimation state is equal to “0”, compensations using the Leveling Calculation are inactive and the vehicle speed is estimated using the Inertia Calculation.

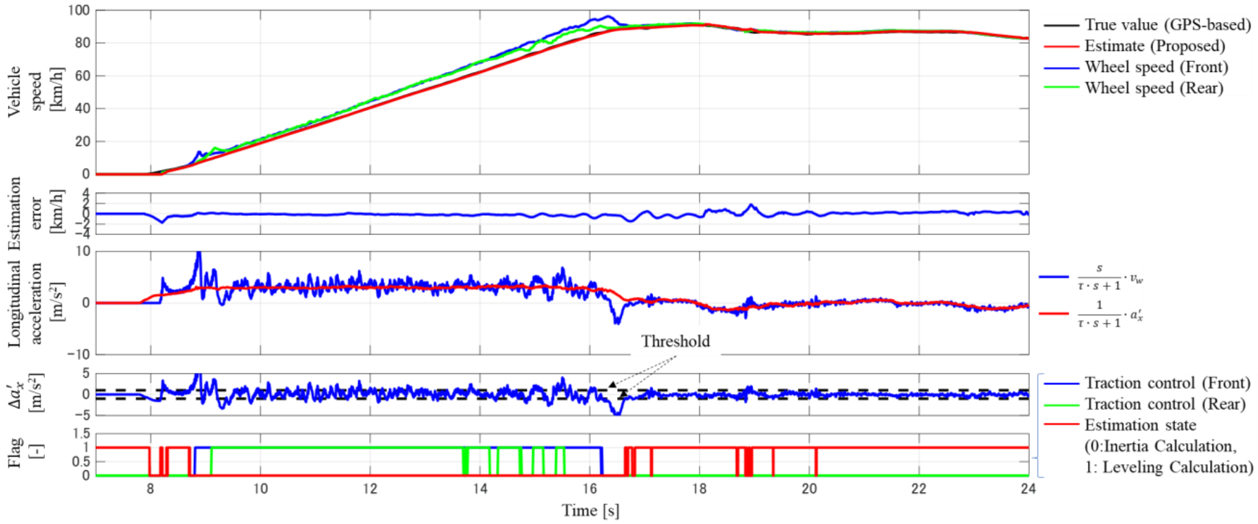

Figure 11: Experimental results on a snow-covered uphill road with a 7 [%] gradient

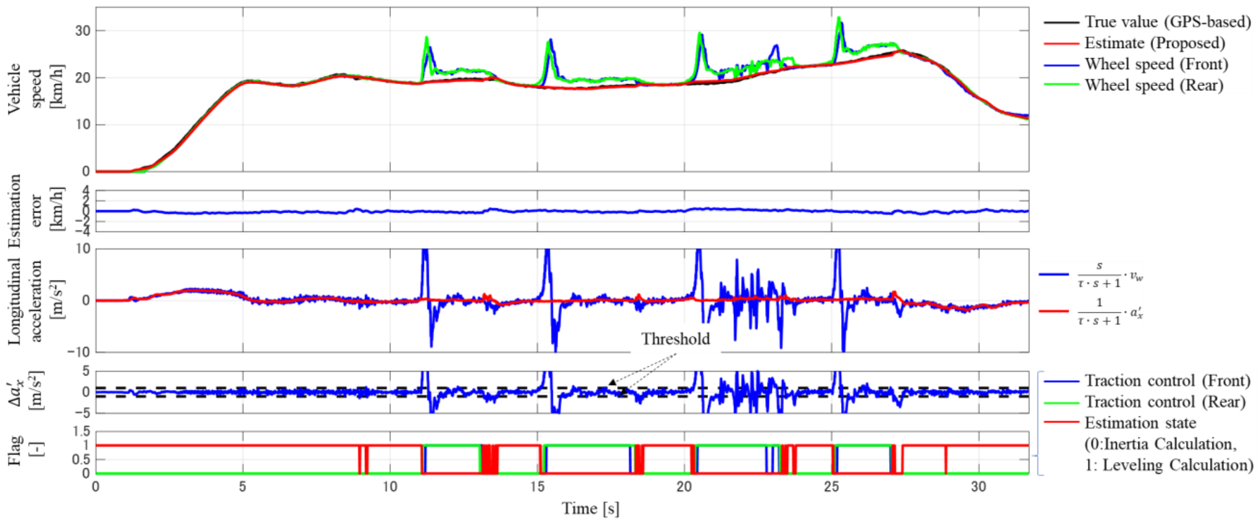

Figure 12: Experimental results on an ice uphill road with a 4 [%] gradient

- The vehicle speed estimate closely matched the true value (obtained from GPS), regardless of the slope. Even when this estimate was applied to the conventional traction control system, the desired acceleration performance was achieved.
- The tire grip detection method functioned as intended, utilizing $\Delta a_x'$ and traction control flag. It successfully selected the Inertia Calculation during non-grip conditions and the Leveling Calculation during grip conditions.
- Furthermore, in the scenario of alternating between the Leveling Calculation and the Inertia calculation, the vehicle speed is estimated with high accuracy.

5 Conclusions

This study proposed the vehicle speed estimation method using IMU and wheel speed for traction control systems in AWD vehicles. Specifically, the tire grip detection method was designed based on the wheel speeds and the acceleration excluding gravitational effects. In this method, the Inertia Calculation is selected during non-grip conditions and the Leveling Calculation is selected during grip conditions. Experimental results using an all-wheels drive EV demonstrated that high-accuracy estimation could be achieved even in scenarios where all wheel experience non-grip conditions. Additionally, favorable results were obtained when this method was integrated with traction control systems. The findings indicate that this approach is highly practical, as it maintains estimation accuracy even in environments where GPS signals are unavailable. Future challenges include verification under various driving conditions and comprehensive evaluation through integration with other vehicle systems.

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Presenter Biography

Hiroyuki Komatsu received his B.S. and M.S. degrees in mechanical engineering from Sophia University, Tokyo, Japan, in 2007 and 2009, respectively.
In 2009, he joined the electric motor control development team of Nissan Motor Corporation and has been working on developing the electric powertrain of Nissan BEV and e-POWER.