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Driving Control Architecture for Six-In-Wheel-Driving and Skid-Steered Series Hybrid Vehicles

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Abstract

This paper presents a driving control method including torque distribution, slip control and regenerative-hydraulic brake control to maximize maneuverability for six-in-wheel-drive and skid-steered series hybrid vehicles. Wheel torque command to each wheel, to track both net longitudinal force and net yaw moment, is distributed based on control allocation method. Because regenerative brake torque does not satisfy desired deceleration under certain speed condition, hydraulic brake system is controlled to obtain suitable brake force rapidly. The maneuvering performance of the six-wheeled and skid-steered vehicle with the proposed driving controller has been compared to that of an Ackerman-steered vehicle with even-distribution controller via TruckSim & Matlab-Simulink co-simulations.

Keywords: list 3-5 keywords from the provided keyword list in 9,5pt italic, separated by commas

1 Introduction

The six-in-wheel-drive systems are being developed to enhance mobility of a vehicle or a robot with the wide range of applications such as a pathfinder, surveillance and light combat operation. Unlike the conventional Ackerman-steered wheeled vehicles, the skid-steered vehicle system is not equipped with steering linkages. Instead, it is steered through differential traction force which is created from in-wheel motor at each wheel. On the other hand, maneuverability on off-road surfaces for skid-steered vehicle is better and the volume in the front hull is almost the same as the rear hull. However, skid steering reduces considerable life cycle of pneumatics particularly on road and it shows quite poor mobility at high speed due to limitation of motor torque and traction force.

Many skid-steering control methods have been studied and actively developed to improve maneuverability of the skid-steered vehicle [1],[2],[3]. However, their tire force distribution strategy for skid-steered vehicles considered a general driving condition only and mechanical characteristics of driving motors and brake systems are not considered as well. In this paper, a driving control method including torque distribution, slip control and regenerative-hydraulic brake control is proposed to improve maneuverability in various driving conditions for six-in-wheel-drive and skid-steered series hybrid vehicles. To satisfy the driver's accelerating, braking and steering command, the proposed driving controller determines distributed driving and regenerative braking torques based on control allocation method. Using this method, torque command can be decided with consideration of motor-torque characteristics and slip limitation. Also, hydraulic brake system is controlled to obtain suitable brake force rapidly, because regenerative brake torque does not satisfy desired deceleration under certain speed condition.

2 Vehicle System Model

The skid-steered six-in-wheel-drive vehicle is equipped with a series hybrid power system, independent mechanical brake systems and six in-wheeled motors without any steering system. In this research, a vehicle dynamic model is developed using "TruckSim" in order to analyze dynamic behavior of the six-wheeled skid-steered vehicle and to conduct a numerical simulation studies. A hybrid power train model including motor torque-speed characteristics and mechanical brake system delay is developed using MATLAB/Simulink.

2.1 Vehicle Dynamic Model

The six-wheeled skid-steered vehicle dynamics as shown in Fig. 1 has been modeled using TruckSim. Table 1 shows specifications of the six-wheeled skid-steered vehicle such as a sprung mass, moment of inertia, tread and distance from c.g. to each axle.

Table1: Specification of the six-wheeled skid-steered vehicle

Sprung mass (m)	6000 [kg]
Moment of inertia (I_x, I_y, I_z,)	x-axis : 3300 [kgm^2], y-axis : 45000[kgm^2], z-axis : 42600 [kgm^2]
Tread (t_f)	2.5 [m]
Distance from c.g. to front/mid/rear axle (l_f, l_m, l_r,)	1.75 [m] / 0.25 [m] / -1.25 [m]
Tire radius (r_f)	0.473 [m] (325/65R20 XLT tire)

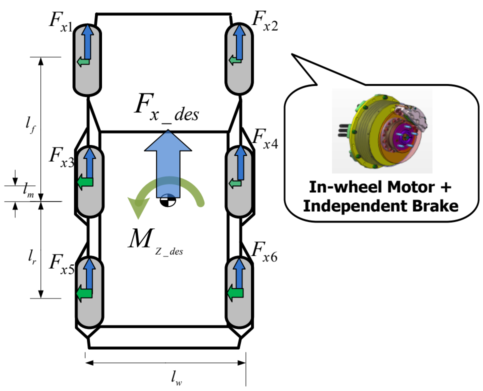


Figure1: Vehicle dynamics of a six-wheeled skid-steered vehicle

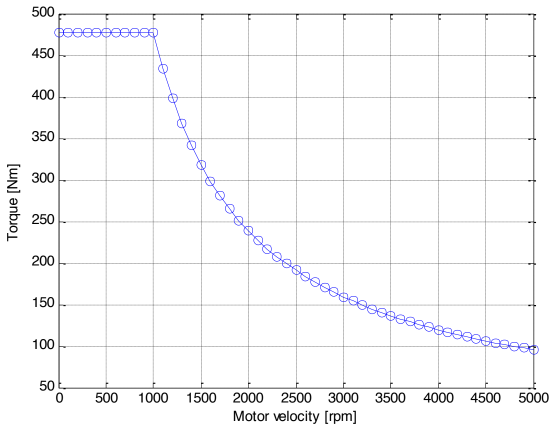


Figure2: Motor torque-speed characteristic

2.2 Power Train Model

The proposed skid-steered vehicle model is equipped with six 40kW in-wheel motors with the motor torque-speed characteristics as shown in Fig.2. Each in-wheel motor is directly connected to the wheel without any reduction gears. Brake actuator of each wheel has been simply modelled using a first-order transfer function with a time constant, 0.2 sec. Hybrid power train system including an engine, an inverter and a battery should be modelled to give allowed driving and regenerative power information to the driving controller [4] but this is skipped in this paper.

3 Driving Control Architecture

A six-wheel-driving skid-steered vehicle equipped with six in-wheel-motors and six independent mechanical brakes is able to operate differential tracking and braking. The driving control architecture is developed to distribute driving torque to each in-wheel motor and braking torque to each hydraulic brake actuator, in order to maximize maneuvering performance and stability. The driving controller consists of desired yaw moment and longitudinal force determination, torque distribution, hydraulic brake control and state estimation. Fig.3 shows the architecture of the proposed driving controller for a six-wheel-driving skid-steered vehicle.

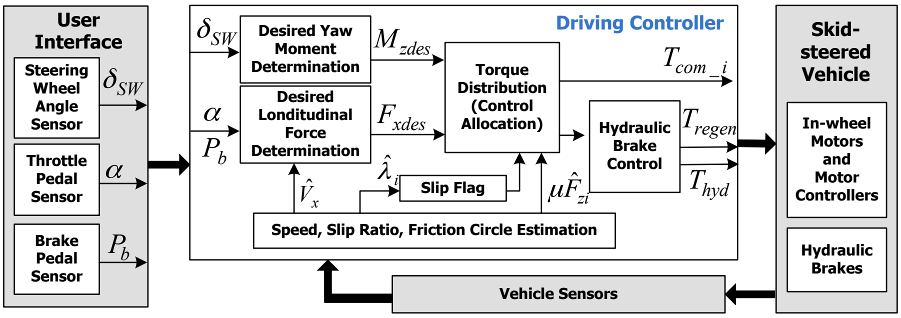


Figure3: Block diagram of driving control architecture

3.1 Desired Longitudinal Force and Yaw Moment

Desired yaw rate which depends on driver's steering angle and vehicle speed is expressed as a first order transfer function.

$$\gamma_{des} = \frac{1}{\tau_{yawrate} s + 1} \cdot \frac{\gamma_{\max}(V_x)}{\delta_{\max}} \cdot \delta_{driver} \qquad (1)$$

where $\delta_{\max}$ is the maximum value of the driver's steering wheel angle and $\tau_{yawrate}$ is time-delay constant of yaw rate. The maximum yaw rate $\gamma_{\max}(V_x)$ is a function of vehicle speed, as shown in Fig.4. This map has been drawn using results of steady-state circular turning simulations at several constant speeds, where the value is the limitation that the vehicle turns stably under 5 deg of side slip angle $\left(\beta = \mathrm{atan}(V_y / V_x)\right)$. Sharp drop of the curve is due to not only the limitation of stability, but also the motor torque characteristic.

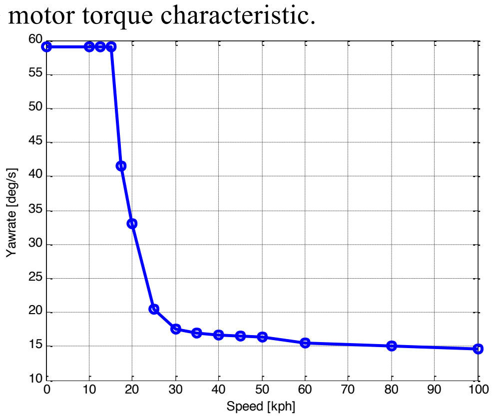


Figure4: The maximum yaw rate curve

The desired yaw moment is calculated to satisfy the desired net yaw rate by yaw rate feedback control method based on sliding mode control theory [#][#], as follows:

$$M_{z\_des} = I_z \cdot \dot{\gamma}_{des} + I_z k \cdot sat\left(\frac{S}{\Phi}\right) \qquad (2)$$

where S is the sliding surface, $S = \gamma - \gamma_{des}$.

Desired longitudinal force control is designed to satisfy a desired velocity controlled by the driver's acceleration pedal, using PID control as follows:

$$F_{xdes} = m \cdot \left\{ K_p (V_{des} - \hat{V}_x) + K_I \int (V_{des} - \hat{V}_x) dt + K_d \frac{d(V_{des} - \hat{V}_x)}{dt} \right\} \qquad (3)$$

3.2 Torque Distribution and Slip Control

Torque distribution algorithm is designed to distribute wheel torque inputs to generate desired longitudinal force and desired yaw moment, using control allocation method. A fixed-point control allocation (CA) method originally proposed by Burcken [5], and then Wang [6] applied this method to optimal distribution for ground vehicles. The control input u (which stands for driving torque T_{com_i}, i =1,…,6) of the fixed-point control allocation is determined to minimize the performance index as follows: [7][8]

$$\min J = \frac{1}{2}\left(Bu - v_d\right)^T W_v \left(Bu - v_d\right) + \frac{1}{2} \varepsilon u^T W_u u$$

$$\text{subject to} \quad u_{\min} < u < u_{\max} \qquad (4)$$

where,

$$u_{\min} = \max\left[u_{\min}, \quad u(t - \Delta t) + \Delta t \cdot r_{\min}\right],$$

$$u_{\max} = \max\left[u_{\max}, \quad u(t - \Delta t) + \Delta t \cdot r_{\max}\right]$$

$$v_d = \left[F_{xdes} \quad M_{z\_des}\right]^T$$

The control input limitation $u_{\min}$ and $u_{\max}$ follows motor torque limitation which is a function of wheel speed. When slip ratio is larger than the threshold, control input limitation has to be zero so that wheel torque input of the wheel becomes zero.

In general, slip control threshold is set to 0.1 or 0.15 to keep stability but this can result in less maneuvering performance.

3.3 Hydraulic Brake Control

Regenerative brake torque cannot always generate desired deceleration. Motor torque limitation is too low at high speed region, and the regeneration energy is not large and the comfort could be deteriorated at very low speed region.[9] Therefore, hydraulic brake controller is designed to assist regenerative brake torque to satisfy desired deceleration.

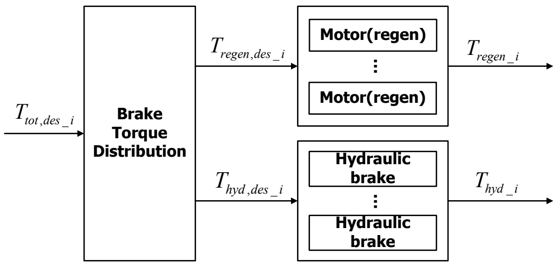


Figure5: Brake Torque Distribution

If state of charge(SOC) of battery approaches to overcharge region, regenerative brake torque should be decreased gradually as shown in the Fig.6.

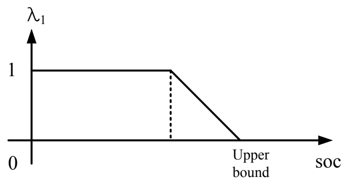


Figure 6: Regenerative brake gain with respect to SOC

If vehicle speed is very low, motor speed is not fast enough, motor cannot generate sufficient regenerative brake torque. Therefore regenerative brake torque should be decreased gradually in low speed situation as shown in the Fig.7.

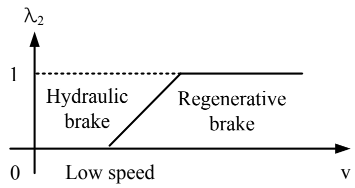


Figure7: Regenerative brake gain with respect to speed

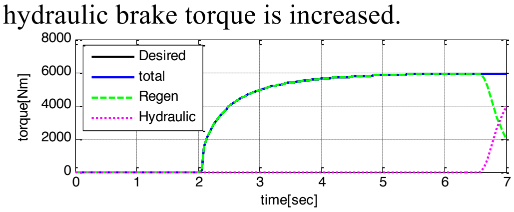
Regenerative brake torque is determined considering battery SOC and vehicle speed as equation (5), corresponding hydraulic brake torque is also determined as equation (6)

$$T_{regen,des\_i} = \min(T_{avail\_i}, T_{tot,des\_i}) \tag{5}$$

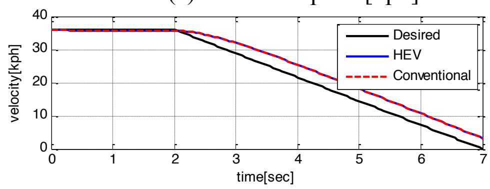
where, $T_{avail\_i} = \lambda_1 \lambda_2 T_{\max}(\omega_i)$

$$T_{hyd,des\_i} = T_{tot,des\_i} - T_{regen,des\_i} \tag{6}$$

Fig.8 shows a result of braking simulation. Under 6kph, regenerative brake gain is reduced and hydraulic brake torque is increased.



(a) Vehicle speed [kph]



(b) Vehicle speed [kph]

Figure8: Result of braking simulation

3.4 State Estimation

For the implementation of the proposed driving controller, it is necessary to know vehicle speed, wheel slip ratio and friction circle of each wheel. Vehicle speed is estimated based on wheel speed, yaw rate and acceleration sensor data, with selection and filtering of wheel speed data to cope with even off-road maneuvering. From calculation of average wheel speed and acceleration of each wheel, the wheel speed in severe slip circumstance is filtered and vehicle acceleration information is used to compensation. The friction circle estimation strategy of the proposed driving controller is based on relationship between friction circles, longitudinal tire force and slip ratio. Slip ratio is a function of wheel speed and vehicle speed. [10]

4 Simulation Results

To improve performance of the skid-steered vehicle with the proposed driving controller, TruckSim – MATLAB/Simulink co-simulation has been conducted as shown in Fig.9. The comparison target of the skid-steered vehicle with the proposed driving controller is the Ackerman-steered vehicle which has the same dimension, as listed in Table 2.

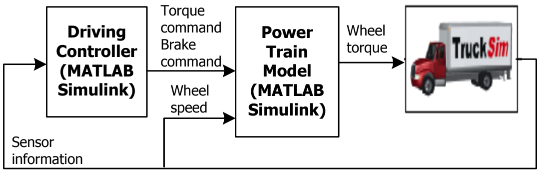
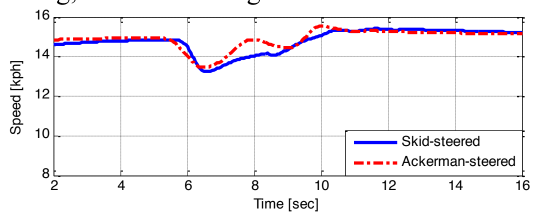


Figure9: TruckSim – MATLAB/Simulink co-simulation

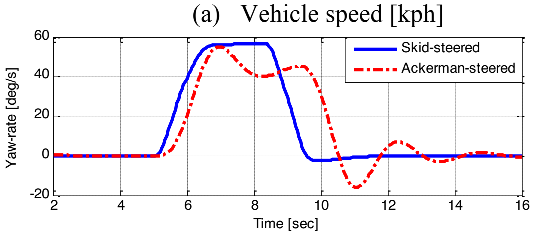
Table2: Specification of the comparable Ackerman-steered vehicle

Lock-to-lock turns of the steering wheel	3.5 turns
Steering ratio	17:1 (Front axle) 8.5:1 (middle axle)
Vehicle dimension	Same as the skid-steered vehicle
Speed control	PID control (Same as the skid-steered vehicle)
Driving torque	Even-distributed (Mechanical diff.)

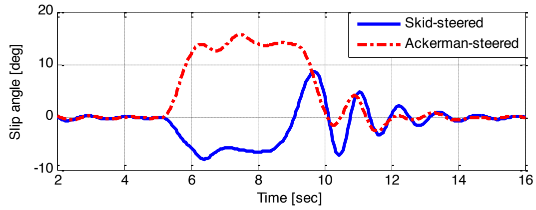
To confirm maneuverability and stability of the skid-steered vehicle with the proposed driving controller, U-turn simulation has been performed. In this simulation, both vehicles are controlled to keep desired speed at 15kph during u-turn behaviour, where μ=0.85. This simulation study shows that the skid-steered vehicle with the proposed driving controller turns with less side slip angle and becomes stable quickly after turning, as shown in Fig.10.



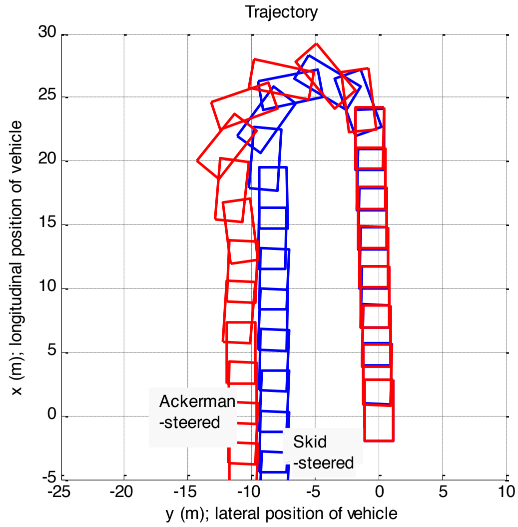
(a) Vehicle speed [kph]



(b) Yaw-rate [deg/s]



(c) Side slip angle [deg]



(d) Trajectory [m]

Figure10: Results of U-turn simulation

The skid-steered vehicle with the proposed driving controller can maneuvers with larger yaw-rate, compared to the Ackerman steering vehicle, at low speed region. However, as shown in Fig.4, maximum yaw-rate of the skid-steered vehicles is sharply reduced as speed is increased. For this reason, maneuvering performance of the skid-steered vehicle can be maximized only at low speed region, compared to that of the Ackerman steering vehicle. Fig.11 shows the maximum yaw-rate curve as a function of speed, compared to that of the Ackerman steering vehicle.

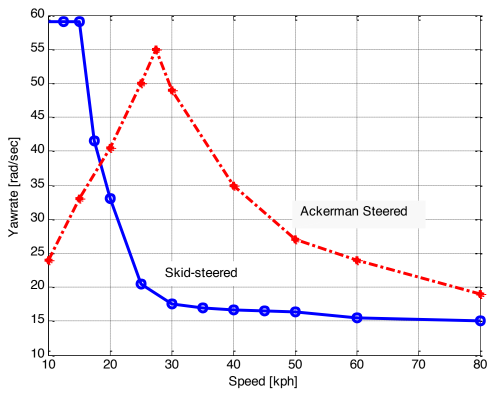


Figure11: The maximum yaw rate curve of the skid-steered vehicle and the Ackerman steered vehicle

5 Conclusion

In this research, driving controller has been designed to maximize maneuverability for six-in-wheel-drive and skid-steered series hybrid vehicles. The torque distribution algorithm determines torque command to each wheel, in consideration of friction circles of all wheels, slip condition and motor torque limitation. Wheel torque command to each wheel is determined to minimize allocation error for longitudinal net force and yaw moment. Hydraulic brake controller is designed to assist regenerative brake torque to satisfy desired deceleration. Vehicle speed is estimated using wheel speed, longitudinal acceleration and yaw-rate signal. The maneuvering performance of the six-wheeled and skid-steered vehicle with the proposed driving controller has been compared to an Ackerman-steered vehicle model via TruckSim – MATLAB Simulink co-simulation. The simulation study shows that severe turning performance of the skid-steered vehicle with the proposed driving controller is much better than an Ackerman-steered vehicle, and it can be maximized only at low speed region due to motor torque limitation and tire force characteristics. An investigation of the drive-ability of the skid-steered vehicle with the proposed driving control algorithm also needs to be conducted via test vehicle in the near future.

Acknowledgments

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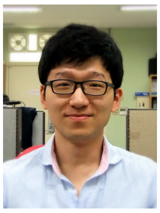

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