A Novel Chassis Structure for Advanced EV Motion Control Using Caster Wheels with Disturbance Observer and Independent Driving Motors

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Abstract—This paper presents a novel chassis structure for advanced EV motion control, using caster wheels with disturbance observers, and independent driving motors. The system consists of two independent driving wheels and two caster wheels. The proposed configuration enables the vehicle to have: a low mechanical stiffness against the direct yaw moment input because caster wheels are free to rotate; and high static stability because of the four wheels having a large base geometry. In addition, by introducing disturbance observers, the vehicle was given enhanced mobility and safety characteristics. Many advantages, which include zero-radius turning, understeer gradient control, load transfer estimation, of the proposed system are shown and discussed with experimental results throughout the paper.

Keywords—Caster Wheels, Electric Vehicle, Independent Driving Motors, Motion Control

I. INTRODUCTION

Utilizing the advantages of using electric motor [1], many motion control strategies for Electric Vehicles (EVs), such as anti-slip traction control, and roll and yaw stability control, are introduced [2][3]. These control methods turned out to be reasonably effective that EVs can run more safely than the ICEVs in poor road conditions. In addition to these properties, vehicle electrification enables EVs to excel the conventional ICEVs in terms of vehicle motion, by assigning EVs two kinds of inputs - the steering and the direct yaw moment - while the conventional vehicles have only one input - the steering. However, most of these research works are based on the four-wheeled vehicle chassis structure with the conventional mechanical steering system, which has not been changed from the beginning of the massive production of the Ford Model T in 1908. It is originally designed and optimized for an internal combustion engine to transmit all power to the four driving wheels. Consequently it is clear that to use the conventional chassis structure for the independent motor driven EVs is a waste of ability, which is the motivation for this paper. This work is on the study and proposal of a novel structure of EVs for advanced motion control. Despite the underlying importance, however, it seems that there has been no attempt to provide an appropriate and unique structure for the independent motor driven EVs. In this work a novel chassis structure using caster wheels and independent driving motors is proposed. Provided with four wheels the system is designed to be statically stable, and with caster wheels on the front axle the proposed system is able to use the two kinds inputs - the steering and the direct yaw moment - effectively for two-dimensional motion control.

II. EXPERIMENTAL VEHICLE AND MODELING

A. Experimental Vehicle, CIMEV

CIMEV (Caster-wheeled Independent Motor-driven Electric Vehicle) is designed to run unmanned. It is controlled by a digital signal processor (S-BOX) with two input signals transmitted through a radio controller. The PWM signals interpreted by the receiver are sent into the DSP, where they are linearized to drive the motors – both driving and steering – to run the vehicle. Four independently controlled electric motors are used. Two are used for steering and the other two for driving. The vehicle is powered by a 24V Ni-MH battery. System configuration is shown in Fig. 2. More details about the experimental vehicle are shown in [4].

B. Mathematical Modeling

As the experimental vehicle having been provided with two steering motors, equations can be written as below, considering the torque inputs of the steering motors, and regarding that the liaison moments and the equivalent forces are given by the motors:

\[
I_w \ddot{\delta}_L + eC_f \dot{\delta}_L = eC_f \beta + \frac{el_f C_f}{V} \gamma + T_{mL} \tag{1}
\]

\[
I_w \ddot{\delta}_R + eC_f \dot{\delta}_R = eC_f \beta + \frac{el_f C_f}{V} \gamma + T_{mR} \tag{2}
\]

\[
I_c \gamma = \frac{1}{e}(T_{mL} + T_{mR}) - 2I_c C_r (\beta - \frac{I_r}{V} \gamma) + M_c \tag{3}
\]

\[
mV(\dot{\beta} + \gamma) = \frac{1}{e}(T_{mL} + T_{mR}) + 2C_r (\beta - \frac{I_r}{V} \gamma) \tag{4}
\]

where
\[
\delta_L: \text{the steering angle of the left wheel;}
\]
Caster wheeled electric vehicle CIMEV: Two rear wheels are driven via belt and pulley by two independent driving motors (90 Watts each). Two front wheels are casters, connected via gears to two independent steering motors (60 Watts each).

Fig. 1. Caster wheeled electric vehicle CIMEV: Two rear wheels are driven via belt and pulley by two independent driving motors (90 Watts each). Two front wheels are casters, connected via gears to two independent steering motors (60 Watts each).

Fig. 2. System configuration of the experimental vehicle CIMEV: The vehicle is controlled by a digital signal processor (S-BOX) with a remote controller. Its dynamic behavior is monitored and recorded through an acceleration sensor unit and four encoders.

\[ \delta_R \]: the steering angle of the right wheel;
\[ T_{mL} \]: the torque output of the left steering motor; and
\[ T_{mR} \]: the torque output of the right steering motor.

III. CONTROLLER STRATEGIES AND ADVANTAGES OF CIMEV

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The global control scheme for CIMEV is shown in Fig. 3. The upper-level controller computes the direct yaw moment reference and the lateral force reference in the form of the steering angles in order to meet the speed and yaw rate requirements. The lower-level controllers which are the driving controller and the steering controller, assign the motor torques to give the vehicle speed, yaw rate, and the steering angles.

Using properly designed controllers, some experiments are done to show the advantages of the proposed system. In this section, the experiment results are introduced, and the corresponding advantages of the system are discussed.

A. High Mobility at Low Speed

Fig. 4 shows the experimental result of the vehicle yaw rate responses to the direct yaw moment input versus the conventional steering maneuver at 90 degrees cornering at a low speed of \(1m/s\). For the conventional steering case, the steering angle was given by Ackermann geometry at 30 degrees which is usually the maximum for passenger vehicles.

It is shown that the yaw rate can go over the maximum rate of the conventional one at a given speed, by applying direct yaw moment to the driving wheels without causing any energy loss from cornering resistance, which corresponds the observation results from the system analyses. This property enables CIMEV to make a more sharp turn than a conventionally steered vehicle does, so that CIMEV can move more freely in restricted spaces. This experiment result also can be associated with the ICR location shown in Fig. 5. Usually a normal passenger vehicle has the minimum turning radius of 5 meters, meanwhile CIMEV can turn with zero radius.

At low speed, the advantage of using caster wheels is obvious: as the way they are defined, they freely rotate and so does the vehicle. Vehicles with the normal steering system, need to run in order to make turns. CIMEV, on
the other hand, can make turns at speed of zero. This property is advantageous not only for the passenger EV applications, but also for the vehicles or the mobile robots which work in restricted spaces.

Note that, as it can be seen in Fig. 4, the yaw rate tends to have higher response over the given reference value when the vehicle is moment steered. This can be explained by the fact that the inertia to be controlled is much larger in the direct yaw moment steer case than the opponent.

B. Making Use of Lateral Force Observer

Since CIMEV is equipped with two independent steering motors, it is possible to apply disturbance observers [5] in the control logic of each wheel. From equations (1) and (2), if we define the disturbance torques for the left and right as:

$$T_{dl} = eC_f\beta + eC_f\frac{eF_f}{V} - eC_f\delta_L = eC_f\alpha_L \simeq eY_L$$ \hspace{0.5cm} (5)
$$T_{dr} = eC_f\beta + eC_f\frac{eF_f}{V} - eC_f\delta_L = eC_f\alpha_R \simeq eY_R$$ \hspace{0.5cm} (6)

the lateral force can be simply calculated by dividing the caster length $e$ without using any special sensors to measure it, and moreover, by controlling the steering angles, the vehicle is allowed to have the controlled lateral forces, which gives a lot of implications to vehicle motion control field.

1) Lateral Force Observer Verification: Fig. 6 compares the lateral forces between the one calculated by using disturbance observers and by using acceleration sensor. Since it is a steady state circle running condition (i.e. $\gamma = 0$ and $M_s = 0$), disturbance torques were converted into lateral forces (red and blue dashed lines), and the lateral acceleration was converted into the necessary net lateral force to make the turn (black solid line). Experimental result shows that the lateral force estimation by using disturbance observer has reliable accuracy although it has some offset, as compared with the calculation using acceleration sensor. For better accuracy of the estimation method, the offset and its implications need to be further investigated.

2) Discussion on Load Transfer: As seen in Fig. 6, the outer wheel has larger value in the estimated lateral force than the inner one. In this thesis, it is assumed that the cornering stiffness $C_f$ has a fixed value, however, in reality the value changes due to the dynamic change in vertical load. It is found, from the experimental result and from the definition of $C_f$ in [6], that the ratio of the vertical load is around 0.63 between the inner and outer wheels.

On the other hand, from the experiment condition, and the vehicle geometry and parameters, for a given lateral acceleration, the vertical load of the front wheels can be roughly calculated as:

$$N_{FL} = 39.2 + 3.6a_y$$ \hspace{0.5cm} (7)
$$N_{FR} = 39.2 - 3.6a_y$$ \hspace{0.5cm} (8)

where, $a_y$ of this experiment was $1.87m/s^2$, thus the ratio $N_{FL}/N_{FR}$ should be around 0.69, which is fairly close to the value from the experiment result. This observation implies that, by using the lateral force observer, the dynamic load transfer of a running vehicle can be calculated without attaching any special sensors such as a potentiometer. More investigation needs to be done for better accuracy.

3) Understeer Gradient Control: Furthermore, it is also possible at a high vehicle speed to change the understeer characteristics by using the lateral force feedback control. Let us call it the understeer gradient control. The understeer gradient $K_{us}$ is one of the major vehicle dynamic characteristics during cornering.

CIMEV inherently is a severely understeered vehicle due to the free rotation of the casters, however, by using this control it becomes close to a neutral steered one. The understeer gradient controller makes $a_f$ smaller by giving the positive feedback of the estimated lateral force $\hat{Y}$ to

\[\text{Fig. 5. Possible location of ICR (Instant Center of Rotation), colored blue. CIMEV (upper) and conventional one (lower). Vehicle with normal steering has usually 5 meters of minimum turning radius, while CIMEV has zero at zero vehicle speed.}\]

\[\text{Fig. 6. Lateral forces calculated by using disturbance observer versus the one calculated by using lateral acceleration sensor during a steady state circle running. Vehicle speed was 2m/s, and the steering angle was 15 degrees at inner wheel.}\]
the direct yaw moment $M_z$, and thus it virtually makes the cornering stiffness $C_f$ larger: refer to [6]. Consequently $K_{us}$ can be controlled to go closer to zero. The control scheme is shown in Fig. 7, and the experimental results are shown in Fig. 8 and 9. The vehicle ran on a circle and was accelerated from 0 to 4 m/s.

Usually a passenger vehicle is an understeered one, and has a peak in yaw rate gain at a certain vehicle speed – the characteristic speed $V_{char}$, like the red dotted case in Fig. 8 and 9, so the radius of cornering gets bigger as the vehicle accelerates. On the other hand, the neutral steered vehicle can run on a circle of a constant radius regardless of its speed, which gives the driver a natural (linear) feeling during cornering. By using the understeer gradient control, the cornering characteristics of CIMEV can be tuned to the driver’s favor, i.e. the value can be controlled by changing the gain $C_{lat}$ as shown in Fig. 8.

4) Bank Angle Estimation: Another advantage of using the lateral force observer is the estimation of the road bank angle on which the vehicle is running. It is based on a simple kinematic relation between the gravitational force and the lateral force of the front wheels as shown in Fig. 10 without using any special sensors. When a vehicle is running straight on a road which has a bank angle of $\phi$, from the kinematic relation it is written as:

$$\hat{Y} = \frac{l_f}{L} mg \sin \phi \quad (9)$$

thus $\phi$ can be estimated as:

$$\hat{\phi} = \sin^{-1} \frac{\hat{Y}L}{l_mg} \approx \frac{\hat{Y}L}{l_mg} \quad (10)$$

It can be seen in the Fig. 12 that the two lateral acceleration signals agree well, and the estimated and
measured values are acceptable. The bank angle of the road is 10.5 degrees, which assigns 1.79 m/s² of lateral acceleration due to gravity. The vehicle was released at \( t = 2 \) by hand, and the vehicle speed increases up to 2 m/s. As the vehicle starts to run, the lateral force observer works properly.

It is a simple and cost-effective method, however, in order to apply this method in a passenger vehicle application, decoupling the effects of the bank angle and the lateral acceleration during cornering needs to be investigated.

IV. CONCLUSION

In this paper, a novel chassis structure for electric vehicles is proposed using caster wheels and independent driving motors. An actual experimental vehicle is introduced, and its system configuration is shown. Feasibility and the advantages of the system are shown with experiment results. At low speed, CIMEV shows high mobility. It is applicable in various fields such as passenger EVs, mobile robots, military and space rovers which work in limited spaces. Additionally, utilizing lateral force observer, the lateral force during cornering can be estimated and possibly controlled. By doing this it is possible to reduce energy loss from the cornering resistance, or to control the characteristics of the vehicle such as the understeer gradient.

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