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Direct Roll Moment Control for Electric Vehicles Based on Roll Angle Observer and Lateral Tire Force Control

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Abstract-- **This paper presents roll stability control methodology for future personal electric vehicles with 4 wheel steering system and lateral force sensors. Direct roll moment control is realized by 4 wheel steering control based on lateral tire force control. In this paper, the lateral tire force, obtained from novel lateral force sensors, was utilized to estimate a roll angle and to control the vehicle roll motion. In order to estimate roll angle, a linear observer was proposed and implemented in an experimental electric vehicle. The effectiveness of a proposed roll angle observer was verified through field tests. By using an estimated roll angle, a direct roll moment controller for roll stability was designed based on general two-degree-of–freedom (2-DOF) control methodology. Effectiveness of a proposed roll stability control method was verified through computer simulation using CarSim software.**

Index Terms—**Direct roll moment control, Electric vehicle, Four-wheel steering, Lateral force control, Roll angle observer**

I. Introduction

Due to drastically increasing concerns in environmentally friendly vehicles and electrification of vehicle systems, a great deal of research on electric vehicles has been carried out [1]-[3]. Compared with internal combustion engine vehicles, electric vehicles with in-wheel motors have several advantages in the viewpoint of motion control [1]–[3].

1) The torque generation of driving motors is very fast and accurate.
2) The driving torque can be easily measured from motor current.
3) The each wheel can be equipped with driving motors.

Based on above advantages, a roll stability control for safety and driver's ride quality was proposed and verified with experimental results [4]. In contrast to conventional engine vehicles, electric vehicles with in-wheel motors have a low ratio of sprung mass over unsprung mass due to having in-wheel motors installed in each wheel. This implies that ride quality can be deteriorated. In order to avoid deterioration in ride quality, the suspension stiffness was selected as a smaller value. It indicates that the roll motion easily occurs. Thus, a roll stability control system is required and accurate roll angle estimation must be obtained before control design.

Since the goal of stability control systems is to control yaw rate and roll angle, sensor measurements of yaw rate and roll angle are required. Yaw rate is easily measured by a cheap gyro sensor. However, since sensors for roll angle are expensive, it must be estimated from available measurements and vehicle models. Over the last few years, several estimation methods were proposed to estimate a roll angle based on a vehicle roll model without using additional sensors (e.g., roll rate sensor) [5]-[7]. In [7], several methods for roll angle estimation were discussed based on advantages and drawbacks of each method. Moreover, an approach using closed loop adaptive observer for roll angle and roll rate estimation was proposed and evaluated. In [5], a road-disturbance decoupled roll state estimator was designed, by combining the lateral model-based estimation method and vertical model-based estimation method, and evaluated by computer simulations.

Considering that roll motion control of vehicles is very important for driver's ride quality and lateral tire force acting on a vehicle is directly related to roll motion, it is required to control the roll motion using controllable actuators and sensors. In this paper, direct roll moment control by lateral tire force control is realized for roll stability control. Since the lateral tire force can be directly generated by controlling front and rear steering angles, active 4 wheel steering control was chosen in this research.

The proposed control method is based on two-degree of freedom (2-DOF) control [8]. In order to improve robustness against roll disturbance by unstable road condition or side wind, disturbance observer is designed in inner loop. Effectiveness of proposed direct roll moment control using 4 wheel steering system is verified through computer simulation using CarSim model, which is made based on parameters of the actual experimental electric vehicle. In simulation, actual driving motor torque, obtained from field tests, is used as a driver's driving command. Simulation results show the good roll angle control performance having a small tracking error.

II. Vehicle Roll Dynamics and Observer Design

A. Vehicle Roll Dynamics

A commonly used planar vehicle model is introduced to account for roll motion as shown in Fig. 1. The roll

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dynamics for control design is as follows:

$$I_x\ddot{\phi} + C_{roll}\dot{\phi} + K_{roll}\phi = m_s a_{ym} h_{roll} \quad (1)$$

where I_x is the roll moment of inertia, C_{roll}, K_{roll} are the roll damping and roll spring coefficient, m_s is the vehicle sprung mass, a_{ym} is the lateral acceleration measurement, h_{roll} is the distance from roll center to mass center, ϕ is the roll angle. The lateral acceleration measurement has following kinematic relationship and can be expressed with lateral tire force.

$$a_{ym} = a_y + g\phi = \dot{v}_y + \gamma v_x + g\phi = \frac{\sum F^y}{m} + g\phi \quad (2)$$

where a_y is the lateral acceleration at vehicle center of gravity, γ is the yaw rate, g is the gravity acceleration, v_x is the vehicle speed, $\sum F^y$ is the lateral tire force acting on vehicle center of gravity, m is the vehicle total mass.

From (1) and (2), the roll dynamic equation including direct roll moment input M_x is derived as

$$I_x\ddot{\phi} + C_{roll}\dot{\phi} + (K_{roll} - m_s g h_{roll})\phi = \left(\frac{m_s}{m}\sum F^y\right) h_{roll} + M_x \quad (3)$$

Here, a direct roll moment input is generated from lateral tire force which is controlled by active steering control.

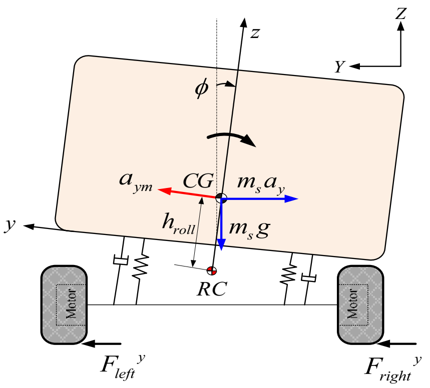


Fig. 1. 2–dimensional roll dynamics for an electric vehicle

B. Roll Angle Observer

In direct roll angle control, it is necessary to know the roll angle. A roll angle observer using lateral tire force measurements and estimated lateral vehicle velocity (see [8]) was proposed and implemented in an experimental electric vehicle as shown in Fig. 2.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u \qquad y = \mathbf{C}\mathbf{x} \quad (4)$$

where $\mathbf{x} = [\tilde{v}_y \quad \phi \quad \dot{\phi}]^T$, $u = [\gamma \quad a_{ym} \quad F^y]^T$, and $y = \tilde{v}_y$

$$\mathrm{A} = \begin{bmatrix} 0 & -g & 0 \\ 0 & 0 & 1 \\ 0 & -(K_{roll} - m_s g h_{roll})/I_x & -C_{roll}/I_x \end{bmatrix}$$

$$\mathrm{B} = \begin{bmatrix} -v_x & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (m_s h_{roll})/m \end{bmatrix}, \quad \mathrm{C} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

Here $\tilde{v}_y$ is a pseudo-measurement of lateral vehicle velocity: In authors' research on vehicle state estimation [8], lateral vehicle velocity is estimated using lateral force measurement of front left and right tires and its estimated lateral vehicle velocity is defined as a pseudo-measurement. By using $\tilde{v}_y$ as a sensor measurement in observer model, $(\mathbf{A}, \mathbf{C})$ is observable (which means that observability matrix has full rank).

From state equation for roll dynamics, a state observer is designed as follows:

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}u + \mathbf{L}(y - \mathbf{C}\hat{\mathbf{x}}) \quad (5)$$

Here $\mathbf{L}$ is a proportional gain defined as $\mathbf{L} = [l_1 \quad l_2 \quad l_3]^T$ and is chosen to achieve satisfactory error characteristics. The error dynamics is obtained by subtracting the estimate (5) from the state (4), to get the error dynamics

$$\dot{\tilde{\mathbf{x}}} = (\mathbf{A} - \mathbf{L}\mathbf{C})\tilde{\mathbf{x}} \quad (6)$$

In this roll angle observer, observer gain $\mathbf{L}$ was chosen so that the error dynamics has triple poles at -30 rad/s. In contrast to conventional estimation methods, a proposed observer uses lateral tire force as an input. This means that the observer can consider not only vehicle roll motion by driver's command but also slight roll motion by road disturbances.

C. Experimental Result of Roll Angle Observer

The designed roll angle observer was implemented on the experimental electric vehicle shown in Fig. 2. Experimental electric vehicle, used in this research, has following special features.

Fig. 2. Experimental electric vehicle

- In-wheel motors, shown in Fig. 3 (a), are mounted in each wheel and thereby we can control each wheel torque completely and independently for vehicle motion control. And specification of vehicle is described in Table 1.

- 4WS (4 Wheel Steering) control possible through front and rear EPS (Electric Power Steering) systems.
- Lateral tire force sensors are installed in inside the in-wheel motors [10].

Among above features, a last feature, especially, is utilized in this research and authors propose the novel methods for roll motion control using lateral tire force sensors.

In order to evaluate estimation results of the observer, the vertical potentiometers and a roll rate sensor were used to accurately measure the, respectively, roll angle and roll rate.

TABLE I
SPECIFICATION OF EXPERIMENTAL ELECTRIC VEHICLE

Weight	870 kg
Dimension(LxWxH)	2300x1600x1510
Track width	1.3 m
Wheel base	1.7 m
Wheel radius	0.3 m
Maximum torque	500 N (Front) / 340 N (Rear)
Battery	Lithium-ion type

(a) (b)

Fig. 3. (a) In-wheel motor, (b) Electric power steering motor (for 4 wheel steering)

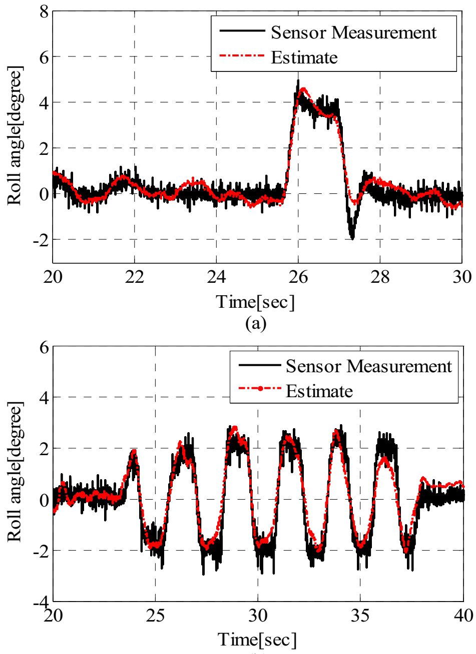


Fig. 4. Experimental result for roll angle observer: (a) Pulse steering test on dry asphalt, (b) Sine steering test on wet asphalt

The pulse steering test with vehicle speed of 40km/h on dry asphalt was conducted. As shown in Fig. 4 (a), estimate (i.e., red dot line) follows the sensor measurement with small error. Similarly, Fig. 4 (b), which is a result of sine steering test with vehicle speed of 40 km/h, shows small estimation error. Here, sensor measurement is obtained from vertical potentiometers. This estimated roll angle is used for direct roll moment control for improving vehicle ride quality.

III. DESIGN OF DIRECT ROLL MOMENT CONTROLLER

Vehicle roll motion generally occurs as a result of lateral motion by steering maneuvers or road disturbances. In contrast to conventional engine vehicles, electric vehicles with in-wheel motors have a low ratio of sprung mass over un-sprung mass due to having in-wheel motors installed in each wheel. This implies that ride quality can be deteriorated. In order to avoid deterioration in ride quality, the suspension stiffness was selected as a smaller value. It indicates that the roll motion easily occurs. Thus, a roll stability control system is required and accurate roll angle estimation must be obtained before control design. In this section, based on estimated roll angle, a direct roll moment control method is presented. A proposed roll stability controller was implemented on CarSim model.

A. Design of 2-DOF Roll Stability Controller

Fig. 5 shows the block diagram of roll stability control based on feedforward and feedback control. The overall control law of a proposed control system is described as follows:

1) The desired roll angle is obtained from driver's steering command and vehicle speed.

2) The roll moment disturbance observer (i.e., inner loop controller) contributes to reject disturbances by feeding a compensation roll moment, which is the difference between roll moment control to the vehicle and filtered output from an inverse model of the nominal roll model $P_{roll,n}(s)^{-1}$.

3) Inverse model-based feedfoward controller, $C_{FF}(s)$, is applied to improve the closed loop stability. The outer-loop tracking controller, $C_{FB}(s)$, is applied to compensate roll moment for estimated roll angle to track the desired roll angle.

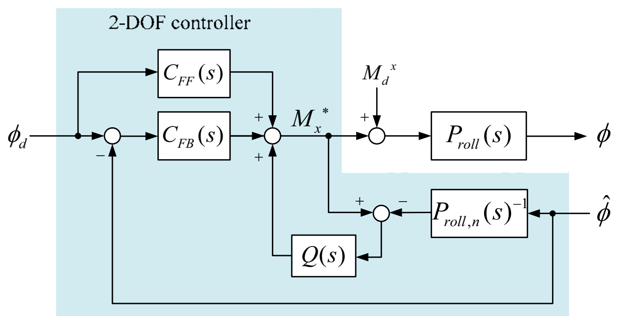


Fig. 5. Block diagram of proposed direct roll moment controller

The desired roll angle is generated from driver's steering command and vehicle velocity.

$$\begin{aligned}\phi_d &= \left(\frac{m_s h_{roll}}{I_x s^2 + C_{roll} s + K_{roll}}\right) a_{y,d} \\ &= \left(\frac{m_s h_{roll}}{I_x s^2 + C_{roll} s + K_{roll}}\right) \frac{K(0)}{1+\tau_a s} \cdot \delta_{cmd}\end{aligned} \tag{7}$$

where desired lateral acceleration, $a_{y,d}$, is obtained from vehicle lateral dynamics: by assuming that desired vehicle motion is under steady state cornering (e.g., $\dot{\beta} = \dot{\gamma} = 0$).

In order to reject roll moment disturbance, a disturbance observer was applied in control system. In this research, a binomial filter was chosen for Q filter (i.e., $Q(s)$) which in the following form:

$$Q_{NM}(s) = \frac{\sum_{k=0}^{M} a_{Nk} (\tau s)^k}{(\tau s + 1)^N} \quad (M = 0, 1, \ldots, N-1) \tag{8}$$

where $a_{Nk} = \dfrac{N!}{(N-k)!}$ *is binomial coefficient*. A filter time constant τ is chosen as 0.05 sec and N =2. Since 2-DOF can completely not reject disturbances and thereby robustness against roll moment disturbance is not ensured, 2-DOF control with a disturbance observer was applied in roll stability control system. Based on roll angle estimation algorithm, a conventional PI-feedback controller was designed and inverse model of linear roll model (1) was used as a feedforward controller.

B. Lateral Tire Force Control

In this paper, novel direct lateral force control is proposed. Fig. 6 shows the block diagram of a lateral force controller including lateral tire force distributor (LTFD) and front and rear EPS controllers. The algorithm for lateral tire force distribution is designed using yaw dynamics, a roll moment equation and expressed as

$$\begin{bmatrix} I_z \dot{\gamma} \\ M_x^* \end{bmatrix} = \begin{bmatrix} l_f & -l_r \\ h_{roll} & h_{roll} \end{bmatrix} \begin{bmatrix} F_f^{y*} \\ F_r^{y*} \end{bmatrix} \tag{9}$$

where I_z is the yaw moment of inertia, l_f, l_r are the distance from center of gravity to front axle and rear axle, respectively, M_x^* is the roll moment for roll angle control, F_f^{y*}, F_r^{y*} are lateral tire force control inputs. In order to design a feedforward controller, a linear lateral tire model is used. Considering that the steering command is realized by only front steering and rear steering is used for roll control, feedforward control is applied to front lateral tire force control only.

For small tire slip angles, the lateral tire forces can be linearly approximated as follows [11]:

$$F_f^y = -2C_f \alpha_f = -2C_f \left(\beta + \frac{l_f \gamma}{v_x} - \delta_f \right) \tag{10}$$

$$F_r^y = -2C_r \alpha_r = -2C_r \left(\beta - \frac{l_r \gamma}{v_x} - \delta_r \right) \tag{11}$$

where C_f, C_r are the front and rear tire cornering stiffnesses, β is the vehicle side slip angle, δ_f, δ_r are the front and rear tire steering angles, respectively. For design simplicity of a feedforward controller, the reference lateral tire force model is defined as

$$F_f^{y*} = -2C_{f,n} \left(\beta_d + \frac{l_f \gamma_d}{v_x} - \delta_{cmd} \right) \tag{12}$$

Here δ_{cmd} is the driver's steering command, β_d and γ_d are the desired vehicle responses based on lateral vehicle dynamics and given by [11]

$$\begin{aligned}\beta_d &= \frac{1 - \left(\dfrac{m l_f v_x^2}{2 l l_r C_{r,n}} \right)}{1 + K_s v_x^2} \frac{l_r}{l} \cdot \delta_{cmd} = G_\beta \delta_{cmd}, \\ \gamma_d &= \frac{1}{1 + K_s v_x^2} \frac{v_x}{l} \cdot \delta_{cmd} = G_\gamma \delta_{cmd} \\ K_s &= \frac{m(l_r C_{r,n} - l_f C_{f,n})}{2 l^2 C_{f,n} C_{r,n}}\end{aligned} \tag{13}$$

where $C_{f,n}$, $C_{r,n}$ are nominal values of tire cornering stiffnesses (e.g., cornering stiffnesses on dry asphalt)

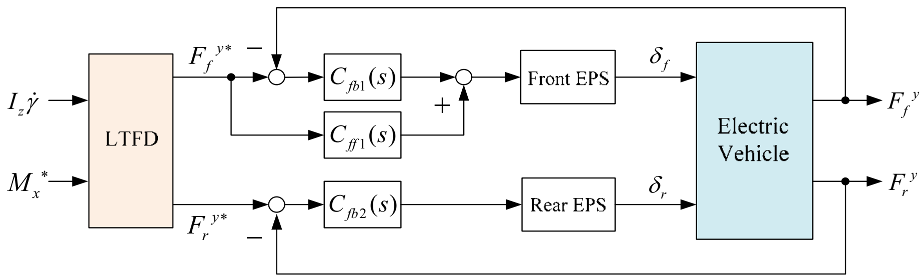


Fig. 6. Block diagram of direct lateral force control

From (12) and (13), a feedforward controller based on inverse tire model is obtained as

$$C_{ff1} = \frac{1}{2C_{f,n}}\left(1 - G_\beta - \frac{l_f}{v_x}G_\gamma\right)^{-1} \qquad (14)$$

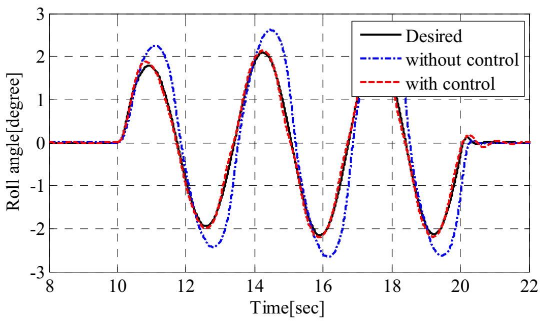
Feedback controllers for front and rear lateral force control are chosen as PI controllers.

IV. Simulation and Experiment

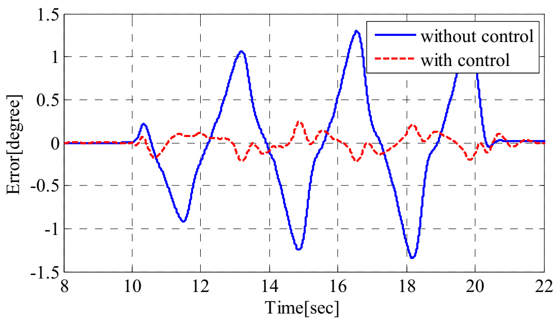
The control performance of the proposed control system was verified through computer simulations using vehicle simulation software, CarSim, and Matlab/simulink. A control algorithm was implemented on a modeled electric vehicle corresponding to an actual experimental electric vehicle (i.e., Kanon). Considering that severe roll motion rarely occurs when vehicles drive on a slippery road, simulation was carried out on dry asphalt road.

A. Simulation Result

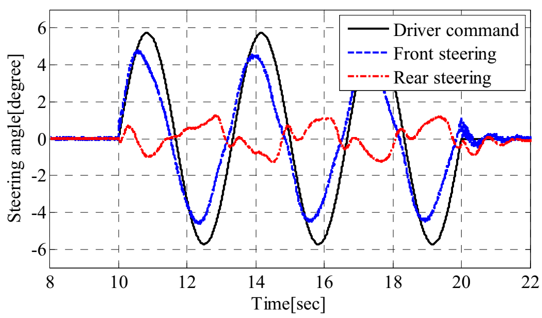
Sine steer driving with vehicle speed of 50 km/h was performed for control performance verification. Fig. 7 (a) and (b) shows the controlled roll angle and roll angle tracking error, respectively.



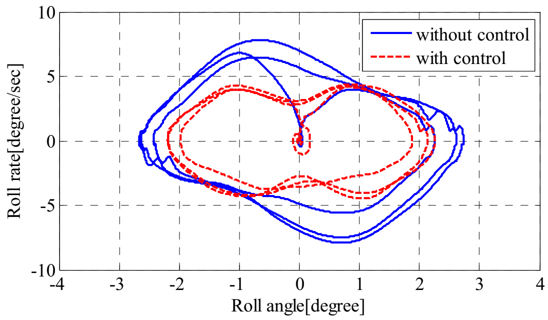
(a)



(b)



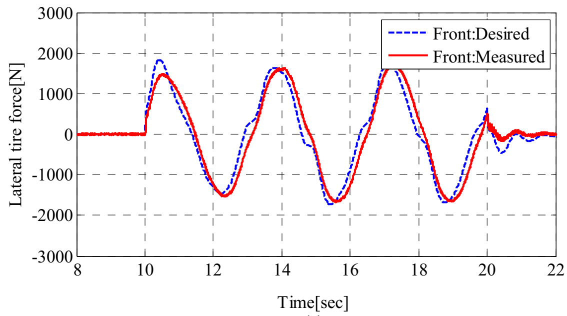
(c)



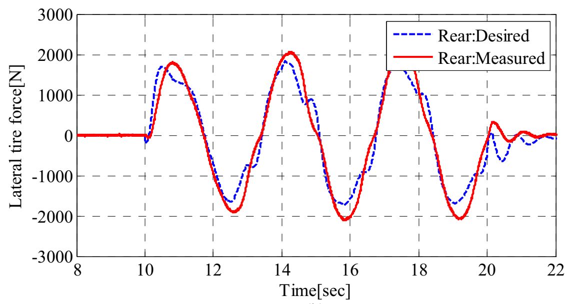
(d)

Fig. 7. Simulation results of a proposed control system: (a) Roll angle, (b) Tracking error, (c) Steering angle, (d) Roll angle-Roll rate plot

Compared with roll angle trajectory without control, a controlled roll angle with a proposed controller follows the desired roll angle trajectory with a small tracking error. Fig. 7 (c) shows the control inputs to the vehicle, which are the front and rear steering angles. In aspect of driving comfortability, it is important to reduce roll rate. As shown in Fig. 7 (d), the enclosed roll angle-roll rate trajectory was to be small by roll angle control. Simulation results of lateral force control are shown in Fig. 8. Measured lateral tire forces track the desired lateral tire force with small errors.



(a)



(b)

Fig. 8. Simulation results of lateral force control: (a) Front tire force control, (b) Rear tire force control

V. Conclusions

In this paper, direct roll moment control based on 4 wheel steering control is proposed and evaluated by simulation results using CarSim software. In order to directly control the roll angle, a roll angle observer is designed using estimated lateral vehicle velocity as a sensor measurement. Cost-effective lateral tire force sensors are utilized in observer design and controller design. In actual, real-time estimation and measurement of lateral tire force are very difficult due to nonlinearities in vehicles and need expensive sensors. A roll angle observer was implemented in an experimental electric vehicle and its estimation performance was verified from field tests. Based on a roll angle observer and lateral tire force measurements, a novel control methodology for roll stability control is proposed. Direct roll moment control is realized by 4 wheel steering control based on lateral force feedback. A proposed control method is verified through computer simulation using CarSim model. In this research, a reliable CarSim model, which can describe dynamic characteristics of an experimental electric vehicle, is made and utilized in simulations. In future works, proposed control methods including lateral tire force controller are implemented in an experimental electric vehicle.

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