Establishment and research of state model of intelligent vehicle bend system based on Kalman filter

Fan Gong¹, Chaoda Chen²*

¹Tianhe College of Polytechnic Normal University, Guangzhou, Guangdong, 510540, China
²Guangdong AIB Polytechnic College, Guangzhou, Guangdong, 511365, China
*Corresponding author’s e-mail: 28477850@qq.com

Abstract. In view of the problems of route selection and driving stability of intelligent vehicle in the process of turning, a state model of intelligent vehicle turning system control based on Kalman filter is proposed. Taking intelligent vehicle as the research object, according to the route of intelligent vehicle passing through a certain bend at uniform speed, the corresponding state transition model of intelligent vehicle's speed and position is established, and the state model of intelligent vehicle's bend system is analyzed, and the system state equation of intelligent vehicle in the process of bend movement based on Kalman filter is obtained. According to the state equation of the system, it can effectively monitor the speed, position and trajectory of the intelligent vehicle on the bend. Combining with Kalman filter algorithm, it can effectively reduce the noise of the control process and observation noise. It can be used to achieve more stable and accurate control of the intelligent vehicle in the bend movement.

1. Research status of intelligent vehicle bend model

Unmanned vehicle has become a research direction of modern automobile development. It senses the surrounding road environment through the on-board sensor system, and automatically plans the driving route of the vehicle. At the same time, according to the perceived road environment factors, it automatically identifies the obstacles existing in the road and plans the new driving route. The driverless vehicle can control the steering and speed of the vehicle according to all kinds of data collected during the driving process, so that the vehicle can travel safely and smoothly on the planned route. The design of driverless vehicle integrates many technologies such as automatic control, architecture, artificial intelligence and visual computing. It is the product of the high development of computer science, pattern recognition and intelligent control technology. It is also an important symbol to measure a country's scientific research strength and industrial level. It is in the field of national defense and national economy. It has broad application prospects.

Domestic research on curve control algorithm of driverless vehicle is more and more extensive. Among them, image sensor and corresponding algorithm are used to control the curve motion of driverless vehicle[1]. For example, the structural road lane recognition algorithm based on vision sensor and the intelligent vehicle longitudinal and horizontal joint control method based on dynamic two-point preview strategy, etc[2]. Among them, Kalman filter, edge detection, wavelet filter and other filtering algorithms are used to complete the control analysis of the intelligent vehicle bend, or even the whole road section[3].
This paper will take the Enzhipu Smart Vehicle model as the research object to study the speed and displacement changes of the Smart Vehicle in the process of turning. According to vehicle dynamics and kinematics, a four-wheeled vehicle will move around a point without any axial motion while maintaining the steering angle of the front wheel unchanged. Therefore, according to the rule, the kinematics model of intelligent vehicle is established under certain constraints.

2. Establishment of intelligent vehicle bend model
Before establishing the kinematics model of intelligent vehicle, it is necessary to define the constraints of the model. Because the intelligent vehicle is affected by many factors in the course of its movement, in order to facilitate the analysis, we will simplify the intelligent vehicle motion model without greatly affecting the establishment of the model. By means of bicycle model theory, we will analyze the movement process of the intelligent vehicle and propose the constraints in the process of model establishment. Pieces[4].

(a) Intelligent vehicle controls the steering of intelligent vehicle by steering engine controlling the steering angle of left and right wheels in front. It is assumed that the steering angle of intelligent vehicle will remain unchanged during the course of passing the bend (the unstable steering angle caused by the problem of steering engine itself will be included in the error analysis).

(b) It is assumed that the intelligent vehicle keeps uniform motion during the whole driving process (according to the results of the model, it can be extended to other modes of motion such as uniform acceleration).

(c) The influence of the structural parameters of the intelligent tire and the model itself on the model analysis during the driving process of the intelligent vehicle is not considered for the time being (which can be summarized into the error analysis process).

2.1. Static geometric model of intelligent vehicle
Firstly, according to the structural parameters of the intelligent vehicle model, the static model of the intelligent vehicle is described[5]. Assuming that the spacing between front and rear axles is $L_1$, the spacing between left and right wheels is $L_2$, the angle $\alpha$ between the left front wheel and the center of the circle and the extension line of the left and right rear axle of the intelligent vehicle.

According to the knowledge of vehicle dynamics, four-wheeled vehicle will move around a point without any axial motion while maintaining the steering angle of front wheel unchanged. As shown in Figure 1. The center of the circle is at the intersection of the extension line of the left and right rear axle centers of the intelligent vehicle and the vertical line of the front wheel direction with a certain steering angle. When the steering angle $\theta$ of the intelligent vehicle remains unchanged, its traveling route will move along the center $O$ with a certain radius.

![Figure 1. Static parameter model of intelligent vehicle.](image-url)

During the driving process of the intelligent vehicle, depending on the actual situation, there are different situations of the steering angles of the left and right front wheels. There will be differences in...
the corners of the left and right front wheels. The driving process model analysis of the steering angle of the front left wheel angle $\theta$ is briefly discussed.

The relationship of the radius $R$ can be derived from the static model geometry of the intelligent vehicle:

$$\sin \alpha = \frac{L_1}{R}$$

$$R = \frac{L_1}{\sin \alpha}$$

$$\left\{ \alpha + \beta = \frac{\pi}{2}, \ \theta + \beta = \frac{\pi}{2} \Rightarrow \alpha = \theta \right\}$$

$$R = \frac{L_1}{\sin \theta}$$

Equation (1) shows that the turning angle of the left front wheel and the distance between the front and rear wheels determine the turning radius of the left front wheel of the intelligent vehicle.

2.2. Intelligent vehicle kinematics model

According to the static geometry model of the intelligent vehicle, a kinematics model of the intelligent vehicle is developed when the intelligent vehicle moves at a certain steering angle in the curve[6]. As shown in Figure 2, the front wheel steering angle of the intelligent vehicle is $\theta$. (The following discussion is based on the premise that the intelligent vehicle moves in the counterclockwise direction. If the clockwise direction is reversed, the corresponding speed and displacement state are reversed.) According to the previously defined constraints, the intelligent vehicle in the process of motion, the influence of the shape of the car model is not considered. It is only seen as the moving process of the center of gravity, and is used to represent the movement process of the intelligent vehicle (such as the intelligent vehicle moving from Z to M, Z means the intelligent vehicle in K) The location of the moment).

According to the kinematics model of the intelligent vehicle, the speed and position change of the intelligent vehicle through the curve only need to study the speed and position of the center of gravity of the intelligent vehicle in the changing process.$R_0$ is the connection between the center of gravity of the intelligent vehicle and the center of the circle, and it is also the radius of the circular route during the driving of the intelligent vehicle. According to the geometric analysis of its kinematic model, it can be obtained:$R_0 = \sqrt{ON^2 + ZN^2}$.
\[
ON = OH + \frac{1}{2} HN = OH + \frac{1}{2} L_2
\]
\[
tan \alpha = \frac{L_1}{OH}
\]
\[
OH = \frac{L_1}{\tan \alpha} \| \alpha = \theta
\]
\[
R_\theta = \sqrt{\left(\frac{L_1}{\tan \theta} + \frac{1}{2} L_2\right)^2 + \left(\frac{1}{2} L_1\right)^2}
\]

It can be known from equation (2) that the steering radius of the intelligent vehicle is determined by the steering angle of the front wheel of the intelligent vehicle and the body parameters \(L_1\) and \(L_2\) of the intelligent vehicle. When the car body parameters \(L_1\) and \(L_2\) are kept unchanged, the steering angle \(\theta\) is directly determined. The turning radius of the intelligent vehicle, and the steering angle \(\theta\) will be determined by the actual curve road condition analysis.

3. Analysis of velocity and position state transition of intelligent vehicle in bend

According to the kinematics model of the intelligent vehicle, the velocity and position changes of the intelligent vehicle are modeled and analyzed by Kalman filter algorithm, and the state equation of the intelligent vehicle bend system is obtained. Kalman filter is a time-domain filtering method. It introduces the concept of state space into the theory of stochastic estimation. In the estimation process, the system state equation, observation equation, process noise and measurement noise are utilized, and the filtering algorithm is formed by their statistical characteristics to solve practical problems, which is convenient to realize real-time on computer. Application.

The state of the Kalman filter algorithm is mainly based on the state and control variables of the previous moment to estimate the state at the moment. According to the analysis in Figure 2, it is assumed that the state \(K\) is the state of the previous moment and the intelligent vehicle is at the position \(Z\) of the center of gravity. Corresponding speed, position state quantity is expressed as \(V_k\), \([X_k, Y_k]\) and center coordinate is \([X_0, Y_0]\). At the next moment, \(K+1\) is in this state, and the intelligent vehicle moves to the \(M\) point position, and the corresponding speed and position state quantities are expressed as \(V_{k+1}\), \([X_{k+1}, Y_{k+1}]\). Through the change of position between the two times, it is found that the change of the displacement of the intelligent vehicle is 
\[
S_{ZM} = \sqrt{(X_{k+1} - X_k)^2 + (Y_{k+1} - Y_k)^2}
\]
and the change time from \(Z\) to \(M\) is assumed to be \(\Delta t\) and the time required for the intelligent vehicle to move from the \(K\) time to the time \(K+1\) is a short time period. \((\Delta t\) can be determined by the turning angle of the intelligent vehicle at each time. When \(\theta\) increases, the time \(\Delta t\) increases accordingly.)

3.1. Intelligent vehicle speed state transfer strategy

By the precondition, the intelligent vehicle maintains a certain steering angle through the curve at a constant speed. According to the knowledge of vehicle dynamics, the speed of the intelligent vehicle can be decomposed into the horizontal component \(V_x\) and the vertical component \(V_y\). According to Figure 3, \(\delta_k\) is equal to the angle between the instantaneous velocity and the vertical axis at that moment. According to plane geometric analysis, equation (3) between intelligent vehicle and steering angle can be obtained.
Since $\gamma$ can be measured by the actual intelligent vehicle position $L_1$, $L_2$ and $\theta$ are known parameters of the intelligent vehicle, then $\delta$ can be obtained according to equation (3) corresponding to the current time $K$. The velocity component at time $K$ is $V_{xK} = V \sin \delta_k$, $V_{yK} = V \cos \delta_k$. When the intelligent vehicle moves from $Z$ point to $M$ point in a short time, the center of gravity of the intelligent vehicle is $\Delta \gamma$, so the speed component of $K+1$ at the next moment is: $V_{x(K+1)} = V \sin (\delta_k + \Delta \gamma)$, $V_{y(K+1)} = V \cos (\delta_k + \Delta \gamma)$. Since the intermediate time is short, it can be approximated as $V_{x(K+1)} = V_{xK} + \Delta V_{xK}$, $V_{y(K+1)} = V_{yK} + \Delta V_{yK}$. At the same time, the change of the speed component of the intelligent vehicle between two moments can be expressed as equation (4):

$$
\begin{align*}
\Delta V_{xK} &= V \sin (\delta_k + \Delta \gamma) - V \sin \delta_k \\
\Delta V_{yK} &= V \cos (\delta_k + \Delta \gamma) - V \cos \delta_k
\end{align*}
$$

$$
\left\{ \begin{array}{l}
\Delta V_{xK} = V \sin (\delta_k + \Delta \gamma) - V \sin \delta_k \\
\Delta V_{yK} = V \cos (\delta_k + \Delta \gamma) - V \cos \delta_k
\end{array} \right.
$$

Combined with the above analysis, the speed state changes of the intelligent vehicle at the previous moment and at this moment can be summarized as the following speed state transition equation (5):

$$
\begin{align*}
V_{x(K+1)} &= V_{xK} + \Delta V_{xK} \\
V_{y(K+1)} &= V_{yK} + \Delta V_{yK}
\end{align*}
$$

$$
\left\{ \begin{array}{l}
V_{x(K+1)} = V_{xK} + \Delta V_{xK} \\
V_{y(K+1)} = V_{yK} + \Delta V_{yK}
\end{array} \right.
$$

3.2. Intelligent vehicle position state transfer strategy

With the change of speed state of intelligent vehicle, its displacement is also changing. In order to facilitate analysis, the position coordinates of the center of gravity of intelligent vehicle will be used to express. According to the process of intelligent vehicle moving from $Z$ point of gravity center to $M$ point of gravity center, combined with the coordinates of two points, the position-state transition
relationship of intelligent vehicle from K to K+1 is expressed as follows:

\[
\begin{align*}
X_{K+1} &= X_K + V_{KK} \cdot \Delta t \\
Y_{K+1} &= Y_K + V_{YK} \cdot \Delta t
\end{align*}
\]

Due to the short movement time between the two points, the arc path of the intelligent vehicle movement can be fitted into a straight line, that is, the distance of the smart car from Z to M is approximately equal to the straight line distance \( S_{ZM} \) from Z to M. \( S_{ZM} \) can be decomposed into a horizontal component \( S_{ZMx} \) and a vertical component \( S_{ZMy} \) based on the coordinate system. The distance between the two centers of the smart car is approximately \( S_{ZM} = \sqrt{(V_{XK} \cdot \Delta t)^2 + (V_{YK} \cdot \Delta t)^2} \), and \( V_{XK} \) and \( V_{YK} \) are the horizontal and vertical components of the instantaneous speed of the smart car at that moment. According to Figure 4, the two components of \( S_{ZM} \) are \( S_{ZMX} = V_{XK} \cdot \Delta t \) and \( S_{ZMY} = V_{YK} \cdot \Delta t \). According to the kinematics model of the intelligent vehicle, it can be seen that \( S_{ZM} \) can also be decomposed into \( S_{ZMx} = S_{ZM} \sin \delta_k \) and \( S_{ZMy} = S_{ZM} \cos \delta_k \) according to the coordinates. Since the moving distance from the Z point motion to the M point is short, the angle between the turning radius and the X axis changes from \( \gamma \) to \( \gamma + \Delta \gamma \). At the same time, the center of the circular motion of the smart car can be expressed as:

\[
\begin{align*}
[X_{K+1}, Y_{K+1}] &= [(X_o + R_o \cos \gamma), (Y_o + R_o \sin \gamma)] \\
[X_{K+1}, Y_{K+1}] &= [(X_o + R_o \cos(\gamma + \Delta \gamma)), (Y_o + R_o \sin(\gamma + \Delta \gamma))] \tag{6}
\end{align*}
\]

Figure 4. Position state transition model of intelligent vehicle.

At the same time, the center of the circular motion of the smart car can be expressed as:

\[
[X_o, Y_o] = [X_K - R_o \cos \gamma, Y_K - R_o \sin \gamma].
\]

Combining with the analysis of the velocity state transition model, the relationship between the position state and the velocity component can be expressed as:

\[
\begin{align*}
X_{K+1} - X_K &= R_o \cos(\gamma + \Delta \gamma) - R_o \cos \gamma = V_{XK} \cdot \Delta t \\
Y_{K+1} - Y_K &= R_o \sin(\gamma + \Delta \gamma) - R_o \sin \gamma = V_{YK} \cdot \Delta t \tag{7}
\end{align*}
\]

According to the above analysis, the change of the Intelligent Vehicle from K time to K+1 time can be summarized as the following position state transfer equation:

\[
\begin{align*}
X_{K+1} &= X_K + V_{XK} \cdot \Delta t \\
Y_{K+1} &= Y_K + V_{YK} \cdot \Delta t \tag{8}
\end{align*}
\]
3.3. State Equation of Intelligent Vehicle Bend System

According to the Kalman filter principle combined with the speed and position state transfer strategy of the Intelligent Vehicle, combined with the formula 5 and the formula 8, the following spatial state transition equations of the smart car can be obtained equation (9):

\[
\begin{align*}
&X_{K+1} = X_K + V_K \sin \delta_K \cdot t = X_K + \Delta X_K \\
&V_{x(K+1)} = V_{xK} + \Delta V_{xK} \\
&Y_{K+1} = Y_K + V_K \cos \delta_K \cdot t = Y_K + \Delta Y_K \\
&V_{y(K+1)} = V_{yK} + \Delta V_{yK}
\end{align*}
\]  

According to the Intelligent Vehicle space state transition equations, it is transformed into a system state equation based on Kalman filter algorithm, as follows equation (10):

\[
\begin{bmatrix}
X_{K+1} \\
V_{x(K+1)} \\
Y_{K+1} \\
V_{y(K+1)}
\end{bmatrix} =
\begin{bmatrix}
1 & \Delta t & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & \Delta t \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
X_K \\
V_{xK} \\
Y_K \\
V_{yK}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
\Delta V_{xK} \\
0 \\
\Delta V_{yK}
\end{bmatrix} + W(k)
\]  

3.4. Error analysis

The analysis of the whole intelligent vehicle bend model is based on certain constraints. However, in the actual motion process, first of all, there is a certain system noise in the steering gear of the intelligent vehicle because of the accuracy constraints, which is fed back to the position component deviation of X-axis and Y-axis in the state equation; secondly, the intelligent vehicle is affected by motor speed regulation in the process of uniform motion, and there is speed instability. The deviation of velocity component on X axis and Y axis is mainly reflected in the change of acceleration and deceleration of speed. Therefore, these interference factors are uniformly classified into \(W(k)\) (system noise) and \(V(k)\) (observation noise), which are used to improve the system state equation of the Intelligent Vehicle curve control, and it is more convenient to use the Kalman filter algorithm. It is processed to achieve a more accurate control analysis of the Intelligent Vehicle[7].

4. Matlab simulation analysis based on Kalman filter

According to the established state equation of the Kalman filter smart car curve system, combined with the Kalman filter algorithm, the simulation analysis is carried out. In the Kalman filter algorithm MATLAB simulation, the smart car steering radius can be inferred from the smart car model size parameter and steering angle combination formula, and the corresponding proportion of system noise and measurement noise are added according to the error analysis to simulate. The results are shown in Figure 5 and Figure 6[8]. (The system noise and measurement noise in error analysis can be set by oneself according to the actual situation of intelligent vehicle.)

![Figure 5. 1/4 Circular trajectory simulation.](image1)

![Figure 6. Full circle trajectory simulation.](image2)
The simulation results of Matlab show that after filtering the state model of the intelligent vehicle bend system based on Kalman filter, the trajectory of the intelligent vehicle in the bend is smoother and more stable, and the estimation error is reduced to a certain extent, which can meet the basic requirements for the intelligent vehicle bend motion. At the same time, it is found in the filter simulation analysis that according to the steering angle of the Intelligent Vehicle, the speed, the sampling frequency of the Kalman filter, the system noise and the threshold of the observed noise, etc., the simulation results will be affected. The actual application is adjusted accordingly.

5. Summary
In view of the establishment and research of the state model of intelligent vehicle bend system, the state equation of intelligent vehicle bend system based on Kalman filter is obtained. Through the analysis and application of the equation, we can know that even if the intelligent vehicle is in different curved road conditions, it can also combine the steering angle, speed, car body parameters and other factors of the intelligent vehicle, and use Kalman filter algorithm to process and optimize the movement route of the intelligent vehicle, find out the better movement route of the intelligent vehicle in the bend, and ensure the stability of the intelligent vehicle in the bend.

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