A Path Tracking Algorithm for Articulated Vehicle: development and simulations

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***Abstract*—Path tracking is a process which concerned with how to determine speed and steering settings at each instant of time in order to lead the vehicle following a certain path. This paper presents a path tracking algorithm for underground unmanned articulated dump truck(UUADT). Firstly, the dynamic model of the articulated dump truck was established. Base on the dynamic model, the algorithm, which utilizes a fusion deviation as feedback, is developed specially to simplify the structure of control system without sacrificing the performance. Finally, the simulation is carried out through the Adams and MATLAB co-simulation. Simulation results show that this algorithm is effective and stable for path tracking and it is further proved that the algorithm can be applied in the UUADT path tracking.**

Keywords—path tracking; articulated vehicle; dynamic; simulation;

I. INTRODUCTION

The articulated dump truck(ADT) with two parts joined by a hinge pin is a kind of widely used mining equipment for underground mine transport because of its great flexibility and powerful off-roading ability. However, the workspace of ADT is usually hazardous with many blind spots where the possibilities of operator injury are quite high. On the other hand, with the increased demand for mineral resources and the progress of technology in the mining industry, the underground mining scale is getting larger and larger putting forward higher requirements for the transport capacity, safety, and efficiency of ore. UUADT is the best choice to solve the above problems.

In recent years, path tracking algorithms have been investigated vastly. Chen and Chieh(1998) worked on steering control of high-speed unmanned vehicle regarding the velocity as constant. Dagci and Oguz(2003) proposed an algorithm using sliding mode control theory, which is aimed at highway conditions. Both above take no consideration of dynamic restraint and assume that the longitudinal speed is constant. Duan and Jianmin(2013) addressed the problem of path tracking control algorithm with speed adjustment, which considers the change of speed at any time and takes sharp turns into consideration. Alshaer and Darabseh(2014) conducted the research on machine dynamics and steering control of an articulated surface mining large wheel loader navigating a predefined path. However, both above situations are not applicable for the underground condition. For example, there is no GPS signal in an underground tunnel, hence GPS navigation is not valid. And some optical sensors are not suitable for the underground environment. On the other side, the underground tunnel belongs to the semi-structure environment, the road information is determined, and cruising velocity is slow. Therefore, it is necessary to develop the algorithm according to the special requirements of the underground working conditions.

There are two main types of underground unmanned trajectory tracking algorithms that single deviation control algorithm and multi deviation fusion control algorithm. Shi Feng(2006) presented single deviation control algorithm, which just needs a heading angle deviation or a lateral position deviation, is easy to implement. The inaccurate control leads to larger error and more instability. In order to solve above problems, Campbell(2007) investigated in multi-deviation fusion control algorithm, which is more stable and reliable, yet the algorithm's complexity increases. Combining the advantages of the two algorithms, an improved preview control algorithm is presented in this paper.

Here, the paper has been organized as follows. Section II presents a dynamic model of the articulated vehicle and the main idea of the algorithm. Section III shows the physics model of the vehicle and presents the detailed design of the whole control system in Simulink. Finally, Section IV presents the simulation results of the algorithm and compares its performance.

II. DYNAMIC MODEL

The steering model of the articulated vehicle is different from the ordinary one. The articulated vehicle, which wheel is fixed relative to the shaft vehicle, has no steering system. Steering relies on the hydraulic system to push the push rod on both sides of the hinge body. When the length of the two push rods are different, the front and back body form a certain angle. Steering movement of the articulated vehicle is realized by the included angle. The special design of articulated body makes that the vehicle can rotate relatively in both horizontal plane and vertical plane. When the body of the vehicle is moving, the rolling resistance is much smaller than lateral sliding resistance. Then this paper assumed that the vehicle body does not generate any transverse motion. The rotation of the vertical

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plane is slight in the problem of path tracking, hence the vehicle model can be simplified as the moving problem of the front and rear frame with respect to the horizontal plane [11].

A. Articulated Vehicle Mathematical Model

In the process of steering, the front frame and rear frame will turn an angle relatively around the vertical pin in the hinge body. During this process, the rotation plane of both sides of the wheel is still parallel to the plane of the body. In the horizontal plane, the extension lines of the front axle and rear axle intersect at O, which is the instantaneous center of the vehicle. Fig. 1 shows a computing model of the turning radius. According to the Fig 1, A is the center of front axle and D is the center of rear axle. The distance between hinge point and point A is l_f and the distance between hinge point and point B is l_r. In the course of motion, the lateral deviation of the wheel is neglected, As a result, the turning radius of the bridge can be calculated according to the geometric relationship.

The turning radius of front axle center:

$$\begin{aligned} R_f &= AO \\ AO &= AC / \sin\gamma \\ AC &= l_f \cos\gamma + l_r \\ Rf &= \frac{l_f \cos\gamma + l_r}{\sin\gamma} \end{aligned} \tag{1}$$

The turning radius of rear center:

$$\begin{aligned} Rr &= OD \\ OD &= BD / \sin\gamma \\ BD &= l_f + l_r \cos\gamma \\ Rr &= \frac{l_f + l_r \cos\gamma}{\sin\gamma} \end{aligned} \tag{2}$$

Usually, considering simplifying calculation, *A* is the whole vehicle reference point, because of the velocity orientation of this point coincident with the whole vehicle orientation. The velocity of the vehicle is defined as *v*. Then the coordinate of *A* is

$$\begin{aligned} \dot{x}_A &= v_f \cos\theta_f \\ \dot{y}_A &= v_f \sin\theta_f \end{aligned} \tag{3}$$

The rate of θ_f is

$$\dot{\theta}_f = \frac{v_f \sin\gamma + l_r \dot{\gamma}}{l_f \cos\gamma + l_r} \tag{4}$$

Then the articulated vehicle state equation can be expressed as follow:

$$\begin{bmatrix} \dot{x}_A \\ \dot{y}_A \\ \dot{\theta}_f \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} \cos\theta_f \\ \sin\theta_f \\ \dfrac{\sin\gamma}{l_f \cos\gamma + l_r} \\ 1 \end{bmatrix} v_f + \begin{bmatrix} 0 \\ 0 \\ \dfrac{l_r}{l_f \cos\gamma + l_r} \\ 1 \end{bmatrix} \dot{\gamma} \tag{5}$$

B. Motion Trajectory Analysis

As shown in the Fig. 2, the front axle center P, at where the velocity direction is consistent with the forwarding direction, is always regarded as the reference point when mentioning the trajectory of the articulated vehicle. In this figure, 'o' represents the center of the real path and 'O' represents the center of the reference path. This paper defines the course angle as the angle between the vehicle forward direction and the X-axis of the vehicle coordinate system. According to Fig. 2, we can define three deviations:

ε_d is horizontal position deviation;

ε_θ is the course angle deviation;

ε_c is the curvature of the deviation;

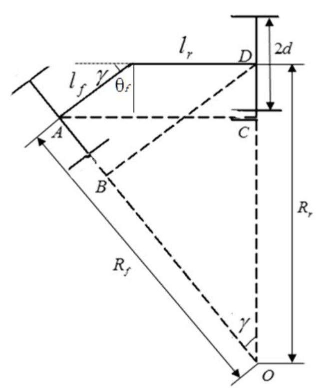

Fig. 1 Turning radius calculation

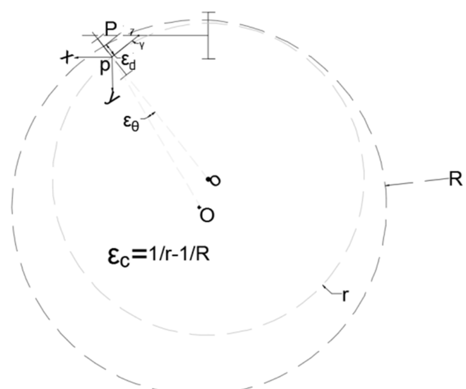

Fig.2 Articulated vehicle plan-view

C. Overview of the Algorithm

In essence, the purpose of the path tracking algorithm is to eliminate tracking deviations generated during motion. The deviations can be eliminated respectively or converted into the same type before eliminating. A variety of algorithms has been proposed according to the different methods of elimination.

The Fig. 3 shows a situation with single horizontal position deviation control. Assuming the reference path as a straight line, there is only horizontal position deviation as the vehicle paralleled with the path. The feedback of the horizontal position deviation makes the vehicle moving towards the goal point in the path. And the vehicle will not steer until the front axle center reaches the other side of the path. As a result, the repeated regulation leads to a curving path as shown in the Fig. 3. Therefore the control is easy to produce shock or even instability.

The above analysis shows that there are defects in the single deviation control, which can not meet the requirement of path tracking, and consider the use of two deviation feedbacks to construct two deviation feedbacks control system [7]:

$$e = K_1 \varepsilon_d + K_2 \varepsilon_\theta \tag{3}$$

K_1, K_2 are the weight coefficient of horizontal position deviation and course angle deviation. The coefficient can be adjusted as required. By the way, the multi deviation fusion control method is stable and accurate. However, the increase in control makes the system become more complex, which, in a manner, increase the data processing burden.

In order to simplify the control system, an improved preview control algorithm is presented as shown in the Fig. 4. The joint point is chosen to be the second reference point and calculate the angle δ as the feedback term. Assuming that the length of the track is L, the length of the front frame is a, the length of the rear frame is b and the distance between frame and hinge point is c, as shown in the Fig.5. According to the position of front axle center P (X_P, Y_P), the calculation procedure of δ is as follows:

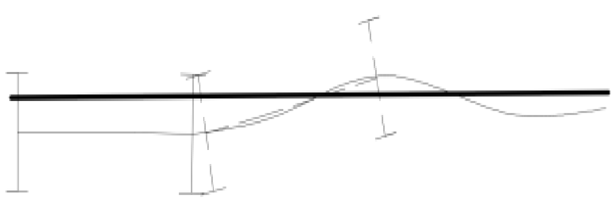

Fig.3 Single horizontal position deviation control

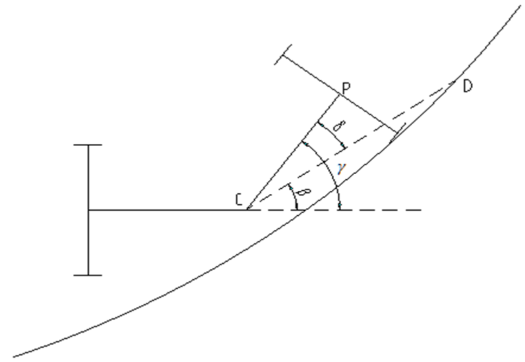

Fig.4 Improved preview control algorithm

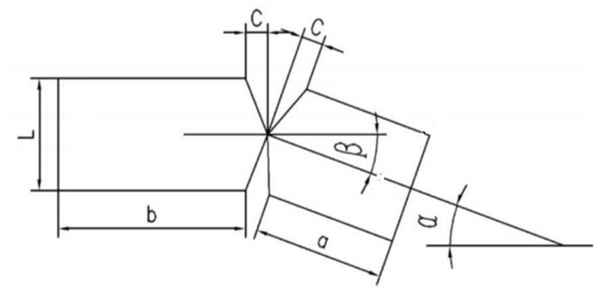

Fig.5 Articulated vehicle structure

$$\begin{aligned} X_C &= X_P - (a+c) \times \cos\gamma \\ Y_C &= Y_P + (a+c) \times \sin\gamma \\ \beta &= \arctan\left(\frac{Y_D - Y_C}{X_D - X_C}\right) \\ \delta &= \gamma - \beta \end{aligned} \tag{6}$$

III. OVERVIEW OF THE SIMULATION MODEL

A. Overview of the Vehicle Model

The physical model of the articulated vehicle is established by Adams. The Fig.6 shows the outlook of the articulated vehicle. The Table. II lists some basic parameters of the articulated vehicle. Adams also offers a variety of tire models including UA model, Fiala model, and DELET model. Users can make choice according to their own simulation requirement. For the research requirements of this paper, as well as the accuracy of the simulation, it is decided to choose the UA tire model. The tire parameters are shown in the table I. Before the simulation, the tire needs to be associated with road file. Considering that the roadway ahead and the distance between the vehicle and the wall both sides are useful, this paper chooses 2D random road surface as the road file [13].

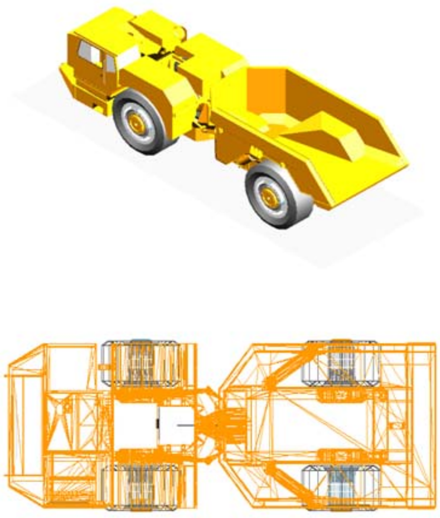

Fig.6 Articulated vehicle Model

TABLE I. TIRE PARAMETERS

parameter	*value*
Vertical_stiffness	1900000
Vertical_damping	50000
Rolling_resistance	0.03
clip	80000
calpha	60000
cgamma	30000

In this paper, the input and output interface definition is also completed in Adams. The real-time control of vehicle speed is carried out by the wheel torque. Therefore, define four hub motors' torque as input variables:

The left front wheel drive torque $LFtireforce$

The right front wheel drive torque: $RFtireforce$

The left rear wheel drive torque: $LRtireforce$

The right rear wheel drive torque: $RRtireforce$

In addition, an input variable for steering control is needed. Define input variable articulated angle: $articulated\_angle$. Then output variables definition as follows:

$FrontFrameX$, $FrontFrameY$, $RearFrameX$, $RearFrameX$, $LFwheelspeed$, $LRwheelspeed$, $RFwheelspeed$, $RRwheelspeed$, $Vehiclespeed$, $FrontDrivingangle$, $RearDrivingangle$.

TABLE II. VEHICLE PARAMETERS TABLE

parameter	*value*	*parameter*	*value*
Distance between front axle to hinge point l_f	1.68m	Front body mass m_1	14.5t
Distance between front axle to hinge point l_r	3.44m	Rear body mass m_2	15t
Steering range γ	[-0.785 , 0.785]rad	Load m_3	35t
Steering range B	2.3m	Tire radius r	0.96m

B. Control System Model

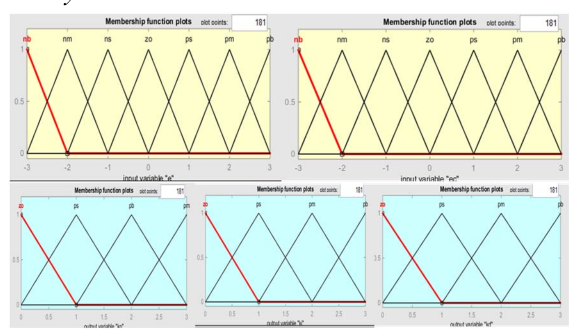

Fig.7 Membership function

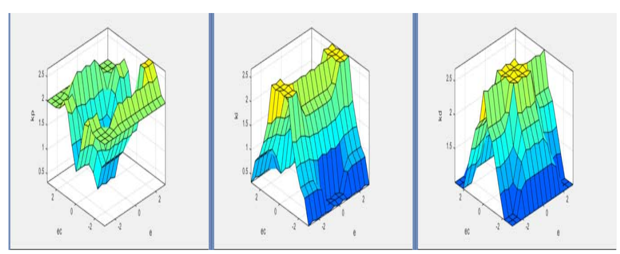

Fig.8 Control Surface of kp, ki, kd

Although the improved preview control algorithm is easy to understand and implement, it has drawbacks as well. The vehicle has a tendency to naturally cut corners. This happens because the vehicle immediately tries to turn towards each new goal point. And the vehicle could oscillate about the path in the case of small look-ahead distances [14]. With the help of fuzzy PID control algorithm, these problems can be solved well. Thereafter, a fuzzy controller which has two inputs and one output is developed and applied in the simulation. The controller inputs are δ and $\dot{\delta}$, while the output is steering angle. Fig.9.shows the steering controller used to control the actual path of the UUDAT. The structure of fuzzy PID control system is shown in the Fig.7&8. Many effective fuzzy reasoning algorithms have been presented, as well as related fuzzy control rule table [15]. This paper chooses Mamdani algorithm as the fuzzy reasoning algorithm. The controller is designed by the MATLAB FIS editor [16].

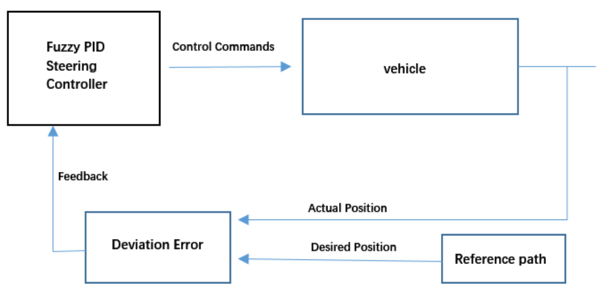

Fig.9 Control loop

IV. Simulation Results

For a more realistic simulation of path tracking of underground tunnel articulated vehicle, some typical road conditions are chosen to be the reference path. This paper present two situations, long straight path, and circle path, to show the results of the simulation.

A. *Straight Path Tracking Result*

Since underground tunnels are usually narrow, the vehicle needs to be operated cautiously to avoid collision with the surrounding. Choosing straight path as the reference path can test the vehicle's response speed to the step input as well as the deviation control capability. The simulation results of the vehicle driving at a speed of 6 MPH are shown in the Fig.10. In the figure, the red line represents the reference path and the black dotted line represents the real path. In the Fig.11 the trend of deviation changing is drawn. As we can see in the Fig.10, the steady-state path tracking error of the system can reach up to ± 0.05 m with rapid and accurate step response.

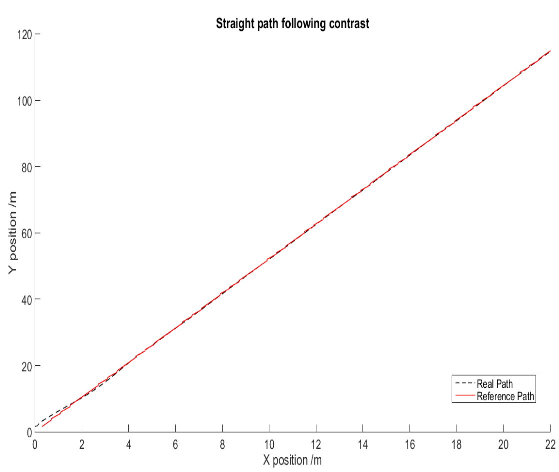

Fig.10 Straight path simulation result

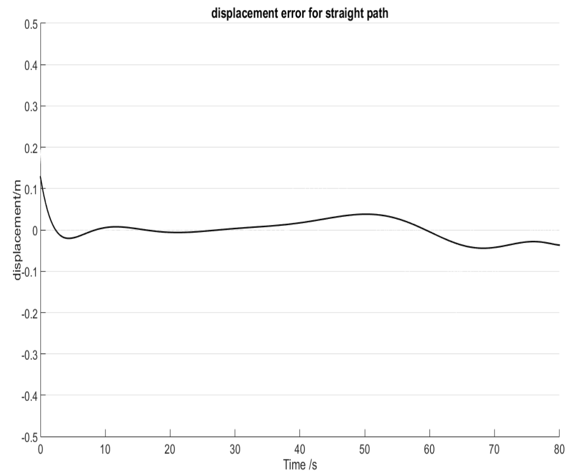

Fig.111 Displacement error for straight path

B. *Circular Path Tracking Result*

The curve is a common underground mine roadway environment, usually, the way is in a narrow space, surrounded by walls. As a result, superb driving skill is required. As the structure of the algorithm is simple, there is no mark or recognition of the special path. Therefore the universal control algorithm is still used in the curve path. The circular path can be regard as a special curve. Circular path tracking also can test the ability of path tracking with steering steady state input.

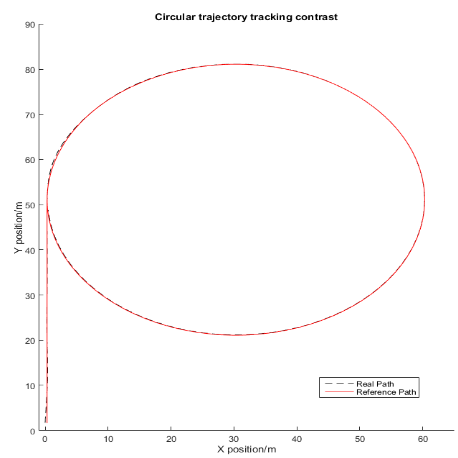

Fig.12 Circular path simulation result

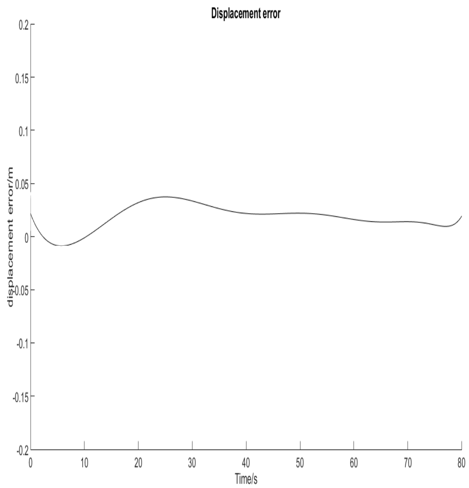

Fig.13 Displacement error for circle path

The Fig.12 and Fig.13 show the circular path tracking results. As we can see, the steady-state path tracking error of the system still can reach up to ± 0.05 m with a rapid and accurate response. The results represent that the system is still effective for the control of the circular path tracking.

V. Conclusion

A path tracking control algorithm with fuzzy PID control for underground articulated vehicle is presented in this paper. The improved preview control algorithm guarantees the precise path, and it simplifies the control system and reduces the data processing burden. Simulation results demonstrate that the control system can depress the overshoot as well as oscillation and improve the response and steady state performance. Therefore, the results have verified the ability of path tracking control for underground articulated vehicle and the algorithm appears to be particularly effective and stable.

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