Linear Active Disturbance Rejection Lateral Controller for Unmanned All-Terrain Vehicle

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Abstract: To address the disturbance of model uncertainty, a linear active disturbance rejection controller (LADRC) was designed for robust lateral control of unmanned all-terrain vehicle. In terms of relative motion of target node and current state, first-order lateral tracking model is established. According to the developed model, linear tracking differentiator (LTD), linear extended state observer (LESO) and linear state error feedback (LSEF) are designed in turn. LESO could observe the uncertainty of system and LSEF could compensate the uncertainty to make system robust. In order to verify the effectiveness, two typical scenarios, circle and double lane tracking, were designed for test. And the uncertainties of wheelbase and steering ratio were considered. Results illustrate that the designed LADRC can stably control the unmanned all-terrain vehicle tracking reference trajectory under both scenarios and has the advantages of small tracking error and small overshoot compared with the conventional pure tracking methods.

Keywords Unmanned all-terrain vehicle, Lateral control, Model uncertainty, Linear active disturbance rejection control, First-order lateral tracking model.

INTRODUCTION

As a synthesis of various advanced technologies such as artificial intelligence technology, computer technology, image technology and sensor technology, unmanned driving technology is expected to enhance road traffic safety and significantly save energy [1, 2]. However, limited by the detection ability of sensors and the development of cognitive technology, compared with fully automatic passenger cars, commercial or special autonomous vehicles such as low-speed and closed parks are more likely to take the lead in industrialization due to the simple operation scenario [3, 4], and horizontal control technology is one of the core technologies for autonomous driving of such vehicles.

At present, for the horizontal control of automatic driving, scholars mostly adopt PID control strategy [5, 6], mainly using its ability not to depend on the precise system model. However, reasonable selection and self-adaptation of PID model parameters have become difficult [7]. As a variant of PID control, the pure tracking strategy [8] solves the problem of control parameter design and was applied by Carnegie Mellon University to Navlab2V unmanned vehicles [9]. On this basis, Kelly *et al*. adjusted the pre-viewing distance according to the lateral error to make the motion trajectory smoother [10]. However, pure tracking control cannot maintain the control performance under system parameter uncertainty [11, 12]. Fuzzy control [13, 14] and model predictive control [15, 16] are widely used control strategies that do not rely on accurate system models. The former requires rich engineering practical experience as guidance for policy design, while the latter is complex in calculation and challenging in real-time algorithm [17, 18].

In order to overcome the above problems and achieve robust lateral control, this paper designs a first-order linear active disturbance rejection controller based on the theory of active disturbance rejection, and experiments are carried out to verify the effectiveness of the algorithm in two typical scenarios: ring and double shift.

1. LATERAL TRACKING MODEL

As shown in Figure **1**, horizontal tracking of the unmanned all-terrain vehicle can be defined as: any point on the vehicle is selected as the tracking point P_c to track the expected trajectory in the time dimension, that is, the tracking point P_c is allowed to track the moving target point P_t on the expected trajectory. The tracking point P_c is selected as l_s (pre-sight distance) from the vehicle centroid in the longitudinal direction of the vehicle, and the target point P_t is selected as the

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path point projected as P_c on the expected trajectory in the vehicle coordinate system O_cxy.

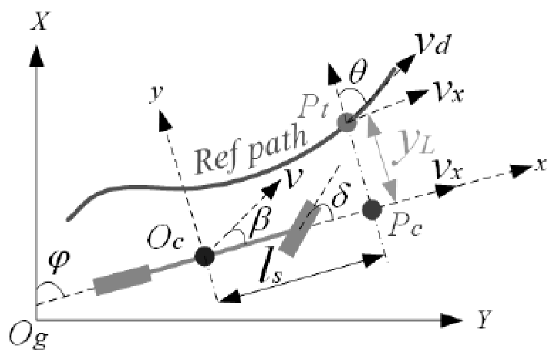


Figure 1: Lateral tracking diagram.

According to the relative motion relationship, there is a horizontal relationship between the tracking point P_c and the target point P_t

$$\dot{y}_L = \dot{y}_t - \dot{y}_c \tag{1}$$

where, y_L is lateral error, y_t is target point, y_c is tracked point.

According to the kinematic relationship of the vehicle, the velocity of the tracking point P_c in the vehicle coordinate system O_cxy is

$$\dot{y}_c = v_y + l_s\omega_r \tag{2}$$

where, v_y is vehicle lateral speed, w_r is yaw rate.

According to the kinematic relationship between the trajectory point and the vehicle coordinate system O_cxy, the velocity with the target point P_t is

$$\dot{y}_t = v_d \sin(\theta - \varphi) = v_x \tan(\theta - \varphi) \tag{3}$$

where, v_d is expected speed at target point P_t, θ is expected speed at target point P_t, φ is expected speed at current point, v_x is vehicle speed at current.

By substituting formula (2) and (3) into formula (1), the horizontal tracking model can be obtained, as follows:

$$\begin{aligned} \dot{y}_L &= v_x \tan(\theta - \varphi) - v_y - l_s\omega_r \\ &= v_x \tan(\theta - \varphi) - v_x \tan\beta - l_s\omega_r \end{aligned} \tag{4}$$

where, β is centroid side deflection angle.

Under normal conditions, the centroid side deflection angle is negligible. At the same time, combined with the Ackermann steering principle, the lateral tracking model of the low-speed unmanned all-terrain vehicle is as follows:

$$\dot{y}_L = v_x \tan(\theta - \varphi) - \frac{l_s}{L} v_x \tan\delta \tag{5}$$

where, L is wheel base, δ is steer angle.

2. LINEAR ACTIVE DISTURBANCE REJECTION LATERAL CONTROLLER

The formula (5) show when the control input is steer angle δ, the lateral tracking model is first order system. Consider the control strategy to be compatible with the uncertainties of the system model (wheelbase, steering ratio, centroid change, etc.), a first-order linear active disturbance rejection controller is designed, as shown in Figure **2**. The designed first-order linear active disturbance rejection controller mainly includes the following four parts:

(1) linear tracking differentiator (LTD) is to track the desired input signal r_f.

(2) linear extended state observer (LESO) is to observe the external interference and uncertainty of the system.

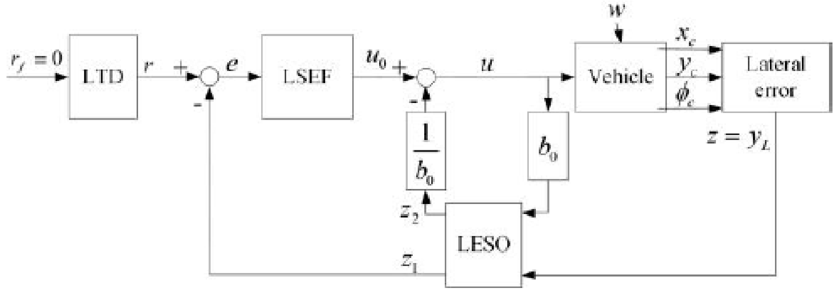


Figure 2: LADRC frame.

(3) linear state error feedback (LSEF) is to compensate for external interference and uncertainty.

(4) Lateral errors are calculated by updating the tracking points P_c (x_c, y_c, f_c) in real time to find the corresponding target point P_t (x_t, y_t, f_t), and calculated the lateral error y_L.

2.1. LTD Design

For first order lateral tracking system, the reference is zero lateral error, that is:

$$r_f \equiv 0 \tag{6}$$

Then, the discrete form of LTD is:

$$r(k) \equiv 0 \tag{7}$$

2.2. LESO Develop

According to system model, there is second order state observation is,

$$\begin{cases} \dot{z}_1 = z_2 + b_0 u \\ z_2 = f \\ \dot{z}_2 = \dot{f} \end{cases} \tag{8}$$

where, b_0 (= $l_s \cdot v_x$ / L) is control gain, (= tan$d$) is control input, f is external disturbances and uncertainties in the system.

Its discrete form is:

$$\begin{cases} e_1(k) = z_1(k) - z(k) = z_1(k) - y_L(k) \\ z_1(k+1) = z_1(k) + T_{LESO} \begin{bmatrix} z_2(k) \\ -2\omega_o e_1(k) \\ +b_0 u(k) \end{bmatrix} \\ z_2(k+1) = z_2(k) + T_{LESO}\left[-\omega_o^2 e_1(k)\right] \end{cases} \tag{9}$$

where, T_{LESO} is observation period of LESO, w_o is the bandwidth of the observer, z_1 is output for the actual control object, z_2 is the total disturbance estimated by the observer.

2.3. LSEF Project

Since the system expressed by the horizontal tracking model is first-order, the feedback control law is P-control, *i.e*

$$\begin{cases} e_2(k+1) = r(k+1) - z_1(k+1) \\ u_0(k+1) = \dfrac{\omega_c}{b_0} e_2(k+1) \end{cases} \tag{10}$$

where, w_c is the closed-loop system bandwidth, generally meet w_o=(5~10) w_c.

3. RESULTS AND DISCUSSION

Figure 3: unmanned all-terrain vehicle.

The algorithm verification platform is based on an unmanned all-terrain vehicle developed by the Intelligent Vehicle Research Institute of New Energy Vehicle Engineering Center of Tongji University and School of Mechatronics and Vehicle Engineering of East China Jiaotong University. As shown in Figure **3**, the vehicle is equipped with intelligent driving computing equipment, high-precision positioning and intelligent perception system. Verify scene references, draw on international standards [19] and typical working conditions of unmanned all-terrain vehicle, and design two categories:

(1) Ring scene: 35m straight line driving section and 2.5m radius of circular driving section.

(2) Double line shift scenario: 2m lateral offset, 25m longitudinal driving distance.

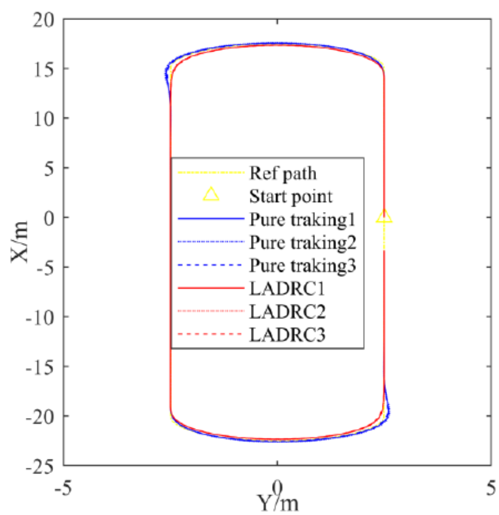
The key parameters are: ideal wheelbase 1.34m, ideal transmission ratio 5.0, pre-viewing distance 1.34m, vehicle speed 5km/h, observer period 0.01s, observation bandwidth 10, closed loop bandwidth 2.

Since the active disturbance rejection control does not require accurate modeling of the system, the vehicle model in the simulation experiment is a kinematic model. In order to ensure the solution accuracy, the fourth-order Runge Kutta method is chosen to solve it [20]. Considering the factors that the composition of the vehicle system has a great influence on the lateral control, the simulation is verified under the uncertainty of wheelbase and transmission ratio respectively, and compared with the typical pure tracking algorithm [8].

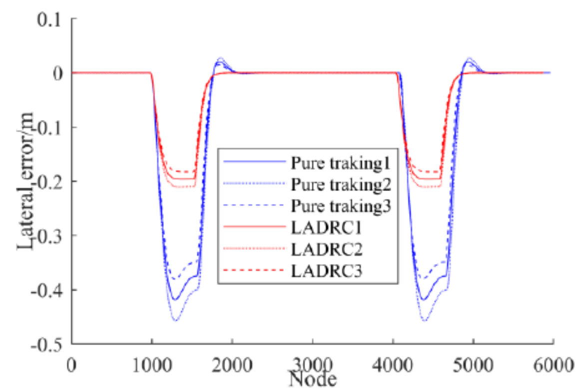
3.1. Scenario 1: Uncertain Wheelbase

Ideal wheelbase 1.34m is a vehicle design parameter, due to parts processing and assembly errors, the actual wheelbase is not necessarily equal to the ideal wheelbase. By measuring the wheelbase of 7 unmanned all-terrain vehicle off the line, it is found that the actual wheelbase is within 1.24m~1.44m. Therefore, the simulation is carried out in three cases: the actual wheelbase of pure tracking 1/LADRC1 is 1.34m, pure tracking 2/LADRC2 is 1.44m, and pure tracking 3/LADRC3 is 1.24m.

As shown in Figure **4**, in the ring scenario, both LADRC and pure tracking can track the expected trajectory stably, and the tracking errors increase with the increase of the actual wheelbase, but the error level of LADRC is about 0.1m smaller than that of pure tracking, and there is a small overshoot. As shown in Figure **5**, in the double-shift scenario, LADRC still has a smaller overharmonic error than pure tracking.

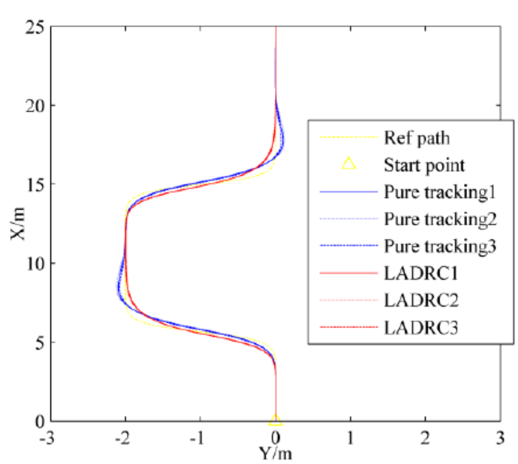


(**1**) Tracking path

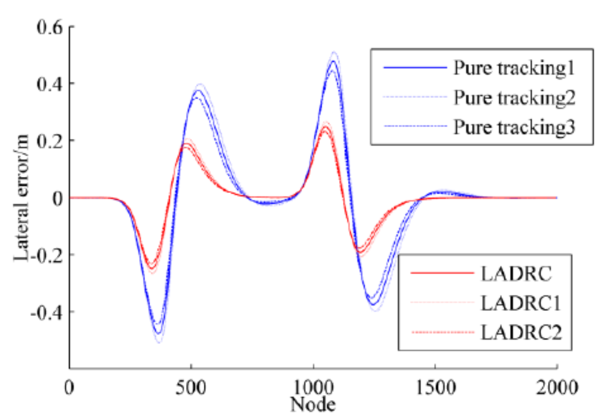


(**2**) Lateral error

Figure 4: Ring scene.

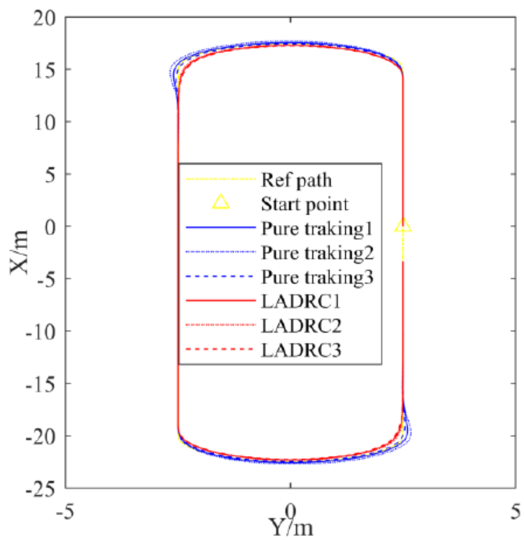


(**1**) Tracking path

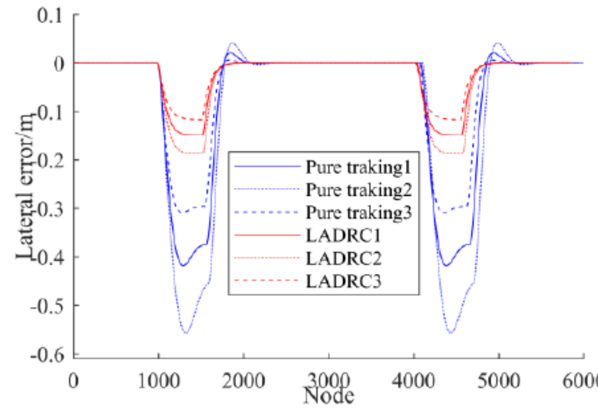


(**2**) Lateral error

Figure 5: Double line shift scenario.



(**1**) Tracking path



(**2**) Lateral error

Figure 6: Ring scene.

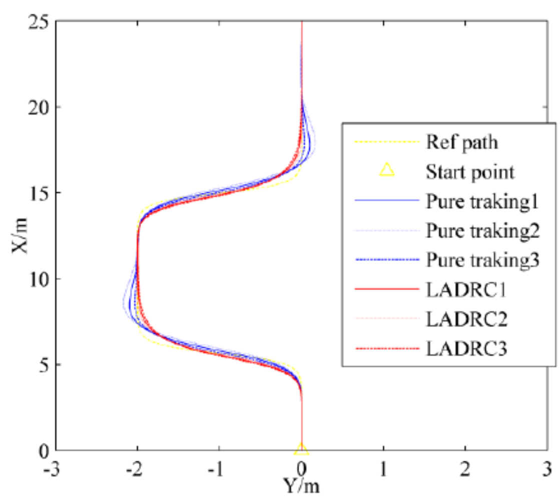
3.2. Scenario 2: Uncertain Steer Ratio

Similar to the wheelbase, the transmission ratio uncertainty is simulated in three cases: the actual transmission ratio of pure tracking 1/LADRC1 is 5, pure tracking 2/LADRC2 is 6, and pure tracking 3/LADRC3 is 4.

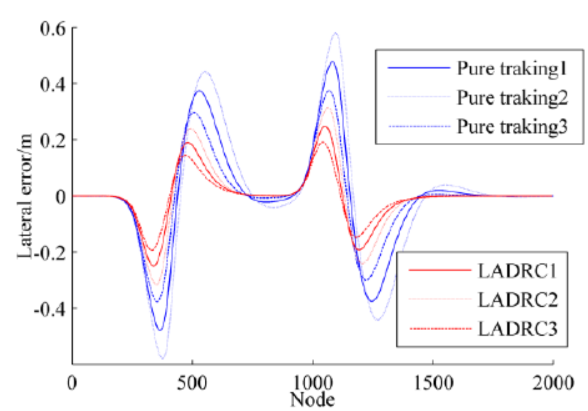
As shown in Figure **6**, in the ring scenario, both LADRC and pure tracking can track the expected trajectory stably, but the error level of LADRC is about 0.1m smaller than that of pure tracking, and there is a small overshoot. With the increase of actual transmission ratio, the tracking error between LADRC and pure tracking begins to increase. As shown in Figure **7**, in the double-shift scenario, LADRC still has a smaller overharmonic error than pure tracking.

4. CONCLUSION

In this paper, a first-order linear active disturbance rejection controller is designed to achieve robust lateral tracking control for the disturbance caused by the uncertainty of the unmanned all-terrain vehicle. Firstly, the lateral tracking model is established according to the relative motion relationship between target point



(**1**) Tracking path



(**2**) Lateral error

Figure 7: Double line shift scenario.

and tracking point. Secondly, linear tracking differentiator, linear model observer and linear state error feedback rate are designed successively. The uncertainty in the system model is observed by the linear model observer and compensated by the linear state error feedback rate to ensure the robustness of the system. Finally, two typical scenarios, ring and double shift, are designed to verify the validity, and the uncertainty of wheelbase and steering ratio are considered respectively. The results show that the designed active disturbance rejection controller can track the desired trajectory stably, and has the advantages of less tracking error and less overshoot than the usual pure tracking methods.

Later studies will focus on more validation of operating conditions. Combined with sensing positioning and decision planning functions, vehicle joint verification will continue to improve with the in-depth development of unmanned all-terrain vehicle. Research efforts that take into account uncertainties in vehicle dynamics models will also be an important part of the future.

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