OBSTACLE AVOIDANCE METHOD FOR ELECTRIC TRACTOR BASED ON IMPROVED DYNAMIC WINDOW APPROACH WITH PRIORITY OF ENERGY CONSUMPTION

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基于能耗最优的改进动态窗口法的电动拖拉机避障方法

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DOI: https://doi.org/10.35633/inmateh-70-30

Keywords: *Barrier avoidance; Improve dynamic window approach; Energy consumption model; Path planning*

ABSTRACT

In order to solve the real-time obstacle avoidance problem in electric tractor operation, an improved dynamic window approach (DWA) based on optimal energy consumption is proposed for electric tractor obstacle avoidance. Firstly, energy consumption model of tractor is established based on the transmission system of electric tractor, then energy consumption evaluation sub-function is introduced to improve the evaluation function of original DWA algorithm, and finally, the trajectory is evaluated and the optimal solution of the trajectory is determined by using new evaluation function. Based on the kinematics model of YL254ET electric tractor in Yancheng Yueda, a model predictive controller is designed. The obstacle avoidance planning and tracking control of electric tractor are simulated jointly on Simulink and CarSim simulation platform. Finally, the obstacle avoidance planning test is carried out. The simulation and experimental results show that after the algorithm improvement, the energy consumption of electric tractors is reduced, the generated path is smoother, and the lateral error is smaller.

摘要

为解决电动拖拉机作业时的实时避障问题，提出一种基于能耗最优的改进动态窗口法（DWA）的电动拖拉机避障方法。首先基于电动拖拉机的传动系统建立拖拉机的能耗模型，接着引入能耗评价子函数来改进原始 DWA 算法的评价函数，最后使用新的评价函数对轨迹进行评价并确定轨迹的最优解。基于盐城悦达 YL254ET 电动拖拉机的运动学模型设计一种模型预测控制器，在 Simulink 与 CarSim 联合仿真平台上对电动拖拉机的避障规划及跟踪控制进行联合仿真,最后进行避障规划试验。仿真及试验结果表明：算法改进后电动拖拉机能耗降低，生成的路径更加平滑，横向误差更小。

INTRODUCTION

Unmanned tractors are increasingly widely used in agricultural production and have become key equipment in intelligent agricultural production (*Li et al., 2019; Hu et al., 2015; Gan-Mor et al., 2007; Kaivosoja et al., 2015*). The types of obstacles in farmland are complex, such as wells, pump houses, power poles, trees, etc. When there are obstacles in front of the unmanned tractor during operation, if the tractor does not have the function of real-time autonomous planning of obstacle avoidance paths, the obstacles will hinder the normal operation of the unmanned tractor. Therefore, obstacle avoidance path planning technology is an essential technology for unmanned tractors.

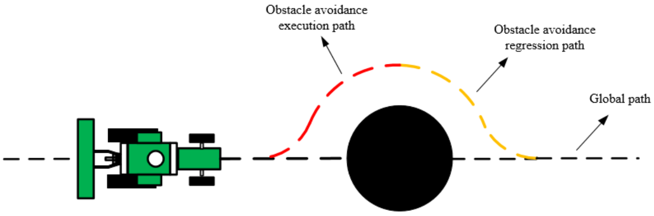

Fig. 1 - Tractor obstacle avoidance model

When an unmanned tractor encounters obstacles during operation, it is necessary to plan a collision free obstacle avoidance path. At present, some scholars have conducted research on obstacle avoidance path planning algorithms for unmanned tractors. Xi Xiaobo et al. proposed a third-order Bezier curve to smooth the obstacle avoidance path of tractors, improving the continuity between the shortest tangent path curves (*Xi et al., 2019*); Yang et al. based on Xi Xiaobo's research and improved Bezier curve, and finally got a lower curvature of obstacle avoidance path (*Yang et al., 2022*). Zhao et al. proposed an obstacle avoidance method based on the minimum capture algorithm, which enables tractors to achieve point-to-point navigation (*Xin et al., 2022*); Guo Chengyang et al. proposed a tractor obstacle avoidance method based on an improved artificial potential field method using LiDAR as a sensor, enabling the artificial potential field method to be applied to tractor obstacle avoidance (*Guo et al., 2020*); Li Guohui et al. achieved obstacle avoidance path planning for agricultural machinery by establishing a motion model and using fuzzy control algorithms (*Li et al., 2021*). Lu Xianglong et al. proposed an obstacle avoidance algorithm for orchard spray robot based on improved A * algorithm and dynamic window method (*Lu et al., 2022*).

Based on this, this paper proposes an improved DWA real-time obstacle avoidance path planning algorithm for electric tractors. Firstly, an energy consumption model for electric tractors is established, then an energy consumption evaluation subfunction to improve the evaluation function of the original DWA algorithm is introduced. Finally, a new evaluation function is used to evaluate the trajectory and determine the optimal solution. Based on the Yancheng Yueda unmanned electric tractor, a vehicle model is established. The obstacle avoidance and tracking control of the electric tractor are jointly simulated using the MTALAB and CarSim joint simulation platform, and the feasibility of path tracking is studied. Finally, a real vehicle obstacle avoidance planning experiment is conducted using the YL254ET electric tractor.

MATERIALS AND METHODS

Establishment of tractor energy consumption model

Simplify the tractor steering model to an ideal bicycle model, assuming that the two front and rear wheels of the tractor are in the same motion state. But in reality, the turning angle of the inner steering wheel is greater than that of the outer steering wheel, causing the vehicle to rotate around the midpoint between the rear wheel axles. The steering motion model is shown in Figure 2.

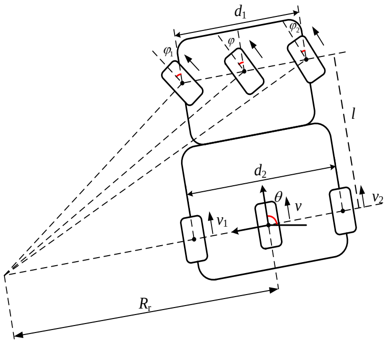

Fig. 2 - Tractor Steering Motion Model

Based on a simplified bicycle model, the tractor steering equation can be derived by considering the triangle formed by the front and rear wheelbase of the tractor l and the side R_r, and adding or subtracting the front and rear wheelbase of the tractor:

$$\begin{aligned}\dot{x} &= v\cos\theta \\ \dot{y} &= v\sin\theta \\ \dot{\theta} &= v\frac{\tan\varphi}{l}\end{aligned} \tag{1}$$

where:

v is the linear velocity of the rear wheel center point, θ is the angle between the linear velocity and the x-axis direction, and φ is the steering angle at the center point of the simulated front wheel; $\dot{x}$ is the linear velocity in the x-axis direction of the tractor motion coordinate system, $\dot{y}$ is the linear velocity in the y-axis direction, and $\dot{\theta}$ is the angular velocity.

Obtain the degree of rotation of the tractor's inner and outer steering wheels:

$$\tan\varphi = \frac{l}{R_r}$$
$$\tan\varphi_1 = \frac{l}{R_r - d_1/2} \tag{2}$$
$$\tan\varphi_2 = \frac{l}{R_r + d_1/2}$$

where:

d_1 is the front track width, φ_1 is the steering inner wheel angle, and φ_2 is the steering outer wheel angle. Obtain the angles of the inner and outer wheels as:

$$R_r = \frac{l\cos\varphi}{\sin\varphi} \tag{3}$$

$$\varphi_1 = \tan^{-1}\left(\frac{2l\sin\varphi}{2l\cos\varphi - d_1\sin\varphi}\right)$$
$$\varphi_2 = \tan^{-1}\left(\frac{2l\sin\varphi}{2l\cos\varphi + d_1\sin\varphi}\right) \tag{4}$$

where:

v_1 and v_2 are the translational velocities of the inner and outer wheels at the linear velocity of the rear wheel navigation center point, and ω is the angular velocity of the inner and outer drive wheels.

When the tractor is in motion, the angular velocity of the inner and outer rear wheels is the same, which can be used to obtain the linear velocity of the inner and outer rear wheels:

$$v_1 = \omega\left(R_r - \frac{d_2}{2}\right) = v\left(1 - \frac{d_2}{2R_r}\right)$$
$$v_2 = \omega\left(R_r + \frac{d_2}{2}\right) = v\left(1 + \frac{d_2}{2R_r}\right) \tag{5}$$

where:

$\omega = v/R_r$, R_r is the distance from the instantaneous center of velocity at the intersection of the vertical line of the inner and outer steering wheel plane and the vertical line of the rear wheel plane to the center point of the rear wheel navigation.

By adding and subtracting from the above equation, v and R_r can be obtained:

$$v = \frac{v_1 + v_2}{2}$$
$$R = \frac{d_2 v}{v_2 - v_1} = \frac{d_2(v_2 + v_1)}{2(v_2 - v_1)} \tag{6}$$

From $\tan\varphi = l/R_r$, it can be concluded that φ:

$$\varphi = \tan^{-1}\left(\frac{2l(v_2 - v_1)}{d_2(v_2 + v_1)}\right) \tag{7}$$

According to equation (1), equation (8) can be obtained.

$$\dot{x} = \frac{v_1 + v_2}{2}\cos\theta$$
$$\dot{y} = \frac{v_1 + v_2}{2}\sin\theta \tag{8}$$
$$\dot{\theta} = \frac{v_1 + v_2}{2}\cdot\frac{\tan\varphi}{l}$$

where:

φ can be obtained through equation (7).

The main electrical energy consumed by driving a tractor comes from the electric motor of the driving wheel and the steering motor. The angular velocity of the inner and outer drive wheels can be obtained from the linear velocity of equation (5):

$$\begin{aligned} \omega_1 &= \frac{v_1}{r2} = \frac{v}{r2}\left(1 - \frac{d_1 \tan\varphi}{2l}\right) \\ \omega_2 &= \frac{v_2}{r2} = \frac{v}{r2}\left(1 + \frac{d_1 \tan\varphi}{2l}\right) \end{aligned} \tag{9}$$

where:

r_2 is the radius of the rear drive wheel.

The driving power of an electric tractor is an electric battery. The tractor contains three motors. There are two Rear-wheel drive motors and one front wheel center steering motor. Set U as the driving voltage of the battery, and U_1 and U_2 are the armature voltages of the inner and outer drive wheel drive motors, respectively. This voltage is controlled by the Pulse Width Modulation (PWM) duty cycle of the driver. Therefore, the real-time armature voltage of the internal and external drive motors is:

$$\begin{aligned} U_1 &= U \cdot D_1 \\ U_2 &= U \cdot D_2 \end{aligned} \tag{10}$$

where:

D_1 and D_2 are the PWM duty cycles of the internal and external drive motors, respectively.

The armature voltage consists of two parts, one is the back electromotive force that drives the wheel to rotate, and the other is the voltage of the internal resistance. From this, it can be concluded that:

$$\begin{aligned} U \cdot D_1 &= i_1 R_n + K_n g \omega_1 \\ U \cdot D_2 &= i_2 R_n + K_n g \omega_2 \end{aligned} \tag{11}$$

where:

i_1 and i_2 are the armature current of the driving motor, R_n is the internal resistance of the driving motor, K_n is the back electromotive force constant, and g is the motor deceleration ratio.

The energy consumption during the tractor driving process is mainly evaluated by the power consumption of the driving and steering motors. The energy consumption model during the tractor driving process is determined by analyzing the consumption of the driving and steering motors. Assuming P_1 and P_2 are the power of the internal and external drive motors, it can be concluded that:

$$\begin{aligned} P_1 &= U_1 \cdot i_1 = U \cdot D_1 \cdot i_1 \\ P_2 &= U_2 \cdot i_2 = U \cdot D_2 \cdot i_2 \end{aligned} \tag{12}$$

where the armature currents i_1 and i_2 can be obtained from equation (12).

$$\begin{aligned} P_1 &= (U^2 D_1{}^2 - U \cdot D_1 K_r g \omega_1) / R_n \\ P_2 &= (U^2 D_2{}^2 - U \cdot D_2 K_r g \omega_2) / R_n \end{aligned} \tag{13}$$

From this, it can be concluded that the total energy consumption E_1 of the two drive motors is:

$$E_1 = \int (P_1 + P_2) dt \tag{14}$$

Assuming that the steering angular velocity of the tractor's front wheel steering motor is constant ω_c, D_c is the PWM duty cycle of the steering motor, and the power of the front wheel steering motor is:

$$P_c = \frac{(U_2 D_c^2 - U D_c K_c g \omega_c)}{R_c} \tag{15}$$

where: K_c is the back electromotive force constant of the front wheel steering motor, and R_c is the internal resistance of the front wheel steering motor.

$$E_C = P_C \cdot \Delta t = P_C \cdot \frac{\Delta\varphi}{\omega_C} = \frac{UD_C\Delta\varphi(UD_f - K_C g\omega_C)}{R_C\omega_C} \tag{16}$$

$$E = E_1 + E_C \tag{17}$$

Equation (17) is the total energy consumption of the tractor, where: E_1 is the energy consumption of the Rear-wheel drive motor; E_C is the energy consumption of the front wheel steering motor.

Optimize DWA algorithm

The DWA algorithm is a local path obstacle avoidance algorithm (*Xin et al., 2023; Lin et al., 2022; Abhishek et al.,2020; Christian et al.,2016*). It sets the maximum and minimum values of the speed, acceleration, angular velocity, and angular acceleration key parameters, and sets the sampling resolution. Through the sampling resolution, it samples multiple groups of speeds within the adjustable range during the movement of the vehicle, simulates the movement track of the vehicle within the parameter limit for a certain time, evaluates all tracks within the range through the set evaluation function, and selects the group of tracks with the highest score. The DWA algorithm sets the sampling space based on a vehicle's motion performance, so this obstacle avoidance algorithm can be used for electric tractors in field work environments to achieve safe operation of the tractor. This article adjusts the evaluation function of the DWA algorithm, adds an energy consumption evaluation subfunction, and changes the weight coefficients of the original evaluation subfunctions to reduce the energy consumption of the tractor during obstacle avoidance under the premise of real-time dynamic obstacle avoidance.

● Tractor Motion Model and Speed Sampling

The first step of DWA algorithm realization is to establish the kinematics model of the tractor (*Lai et al., 2023*), as shown in Formula (1). Electric tractors are affected by motors and have inherent speed and acceleration limitations, which can be expressed as:

$$V_1 = \left\{(v,\omega) \middle| v_{\min} \le v \le v_{\max}, \omega_{\min} \le \omega \le \omega_{\max}\right\} \tag{18}$$

where:

$v_{\min}$ and $v_{\max}$ are the minimum and maximum linear speeds of the tractor, respectively, $\omega_{\min}$ and $\omega_{\max}$ is the minimum and maximum angular velocity of the tractor, respectively.

Ultimately obtain the speed constraint for the tractor is:

$$V_2 = \left\{(v,\omega) \middle| v \in \left[v_1 - \dot{v}_a \Delta t, \dot{v}_1 + \dot{v}_b \Delta t\right], \omega \in \left[\omega_1 - \dot{\omega}_a \Delta t, \omega_1 + \dot{\omega}_b \Delta t\right]\right\} \tag{19}$$

where:

v_1 is the current linear speed of the tractor, ω_1 is the current tractor corner speed, $\dot{v}_a$ and $\dot{\omega}_a$ are the maximum deceleration of the tractor, $\dot{v}_b$ and $\dot{\omega}_b$ are the maximum acceleration of the tractor.

Based on collision safety factors, to prevent the tractor from colliding with obstacles due to speed reasons, and to increase speed control constraints.

$$V_3 = \left\{(v,\omega) \middle| v \le \sqrt{2dist(v,\omega)\,\dot{v}_a}, \omega \le \sqrt{2dist(v,\omega)\dot{\omega}_a}\right\} \tag{20}$$

where:

$dist(v,\omega)$ is the shortest distance from the corresponding tractor trajectory to the obstacle.

● DWA algorithm evaluation function

In the sampled speed vector space, through speed sampling and discretization of vector space $V_1 \cap V_2 \cap V_3$ with continuous speed constraints, feasible speed sets are obtained, and track prediction is generated according to these speed sets and track prediction time periods. After obtaining the trajectory of a robot, it is usually feasible to have multiple sets of trajectories corresponding to the speed, and the trajectory is evaluated through an evaluation function.

The evaluation function is defined as follows:

$$G(v,\omega) = \sigma\left(\alpha \cdot heading(v,\omega) + \beta \cdot dist(v,\omega) + \gamma \cdot velocity(v,\omega)\right) \tag{21}$$

where:

$heading(v,\omega)$ is the azimuth evaluation function, representing the azimuth deviation between the trajectory and the target point at the current speed, $dist(v,\omega)$ is the closest distance between the trajectory and the static obstacle, and $velocity(v,\omega)$ is the evaluation function of the current speed. σ is the smoothing coefficient. α, β, and γ are the weighted coefficients of each item.

- **Optimize evaluation function**

The three evaluation sub functions of the traditional DWA algorithm evaluation function are relatively independent, and there are significant differences in the optimal weight coefficients of the three sub functions under different operating environments. In response to the operating conditions of electric tractors, the evaluation function of the traditional DWA algorithm has been adjusted and a tractor energy consumption evaluation subfunction $E(v,\omega)$ has been added to the original $G(v,\omega)$.

$$E(v,\omega)=E \tag{22}$$

where the value of E can be obtained by formula (17).

This equation represents the energy consumption of the evaluation trajectory.

The new evaluation function obtained is:

$$G(v,\omega)=\sigma\big(\alpha\cdot heading(v,\omega)+\beta\cdot dist(v,\omega)+\gamma\cdot velocity(v,\omega)+\delta\cdot E(v,\omega)\big) \tag{23}$$

where: δ is the weighting coefficient of the tractor energy consumption evaluation subfunction.

The purpose of the evaluation function $G(v,\omega)$ is to score the trajectory and select the optimal solution.

To avoid a large proportion of any item in the indicator, it is necessary to normalize each item in the objective function:

$$\begin{aligned}
n\_heading(v,\omega)&=\frac{heading(v,\omega)}{\sum_{i=1}^{n} heading(v_i,\omega_i)}\\
n\_dist(v,\omega)&=\frac{dist(v,\omega)}{\sum_{i=1}^{n} dist(v_i,\omega_i)}\\
n\_velocity(v,\omega)&=\frac{velocity(v,\omega)}{\sum_{i=1}^{n} velocity(v_i,\omega_i)}\\
n\_E(v,\omega)&=\frac{E(v,\omega)}{\sum_{i=1}^{n} E(v_i,\omega_i)}
\end{aligned} \tag{24}$$

where: n is the number of trajectories to be evaluated; i is the current evaluated trajectory.

The subfunction for evaluating tractor energy consumption refers to the fact that the smaller the obstacle avoidance speed and vehicle speed, the smaller the function value during the process of selecting the obstacle avoidance path. It also indicates that the path is smoother at this time, reducing the speed jump and significant steering of the tractor when approaching obstacles, and improving the economy of tractor movement. δ is the impact coefficient, and its value is related to energy consumption. If the energy consumption of the path is higher, the value of δ will be smaller.

Simulation analysis

- **Tractor Path Tracking Controller**

Use a model predictive controller as the path tracking controller for unmanned tractors to verify the traceability of the path. Gong Jianwei's method in "Model predictive control of Unmanned Vehicles" is adopted (*Gong et al., 2020*).

The unmanned tractor has low working speed. The path tracking controller designed based on kinematics model has reliable control performance and real-time performance, and has low requirements for hardware equipment, which is suitable for the requirements of low-cost and high reliability of unmanned tractors. At the next moment, repeat the above steps to loop through the path tracking of the unmanned tractor.

- **MTALAB and CarSim Joint Simulation**

Build a joint simulation platform of MATLAB and CarSim for obstacle avoidance path planning and tracking control of unmanned electric tractors. The working speed of Yancheng Yueda electric tractor during plowing is 4-8 km/h. Based on this model of electric tractor, a tractor model is established on the CarSim simulation platform. Table 1 shows the actual parameters of the tractor used.

Table 1

Tractor parameters

Variable	Meaning	Unit	Value
$L*W*H$	Length*Width*Height	mm	3195*1240*2340
l	Wheelbase	mm	1585
d_1/d_2	Front/Wear track width	mm	1000/1040
r_1/r_2	Front/Wear wheel radius	mm	330.2/546.1
U	battery voltage	V	76.8
g	Motor reduction ratio		25
R_n	Internal resistance of drive motor	Ω	0.32
R_c	Internal resistance of steering motor	Ω	0.448
K_n	Rear wheel motor back electromotive force constant	V/rmin^{-1}	0.014
K_c	Steering motor back electromotive force constant	V/rmin^{-1}	0.006

In the simulation, the radius of the obstacle is 2.5 m, and the geometric center of the obstacle is located 10 meters forward of the original path. Four stone pillars are simulated to form the obstacle, as shown in the figure. The basic parameters of the model tracking controller are set as follows: prediction step N_p=60, control step N_C=30, control cycle T=0.01 s, simulation time set to 9.00 seconds, and the simulation results are shown in the figure.

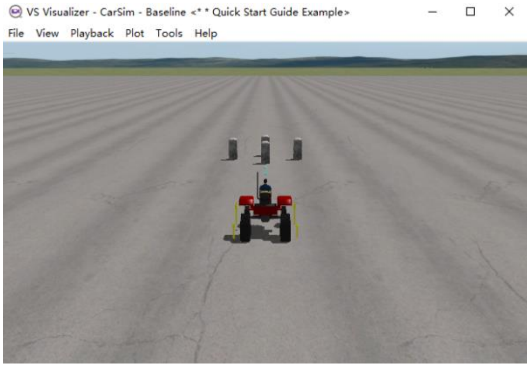

Fig. 3 - CarSim simulation model scenario

RESULTS

Joint simulation results

The original DWA obstacle avoidance algorithm and the improved DWA obstacle avoidance algorithm in the paper are used for simulation comparison, and both use the same trajectory tracking controller.

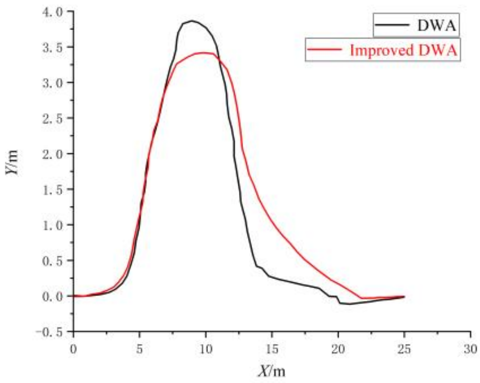

Fig. 4 - Simulation trajectory results

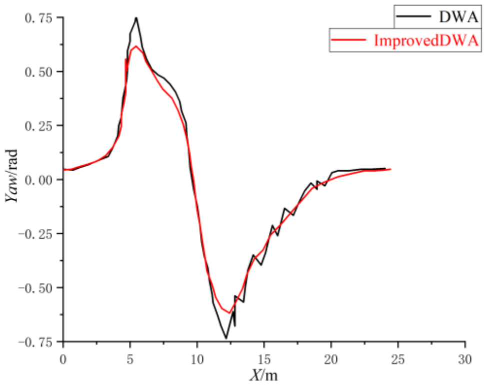

Fig. 5 - Simulation heading angle results

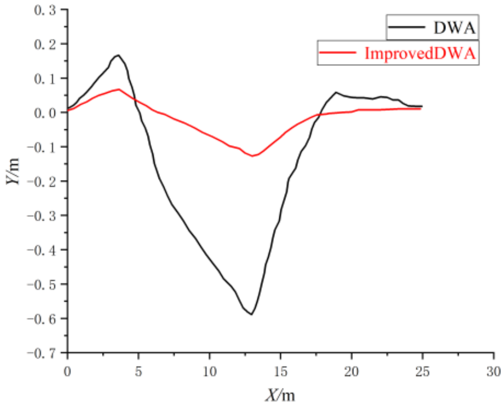

Fig. 6 - Lateral error simulation results

From the simulation results, it can be seen that the improved DWA algorithm is smoother when turning, with smaller curvature when transitioning from the global path to the obstacle avoidance path and the obstacle avoidance regression path back to the global path. The original DWA algorithm has significant fluctuations in heading angle, resulting in a longer steady-state time. The improved DWA algorithm for obstacle avoidance in electric tractors has a maximum lateral error of 0.13 m and a maximum heading angle of 0.557 rad, which is 77.6% and 25.65% less than the original DWA algorithm's maximum lateral error and heading angle, respectively.

Real tractor test

To verify the effectiveness of the improved DWA Algorithm Based on Optimal Energy Consumption, obstacle avoidance tests are conducted on the Yancheng Yueda YL254ET electric tractor as a testing platform. Install the navigation system as shown in the figure7 on the tractor. The system is developed based on the ROS platform. The upper computer uses NVIDIA Jetson TX2, and the lower computer uses a microcontroller for steering wheel and speed control. The system uses CAN bus for data communication. The system uses LiDAR and BeiDou signal receiver as sensors. The BeiDou system obtains the longitude and latitude information of the electric tractor, and uses dotting to obtain the longitude and latitude information of the field boundary and conduct global path planning. The model is Huace PA-3, which also includes an IMU sensor. Lidar perceives obstacle information, which model is Leishen C32-151A, with horizontal and vertical field of view angles of 360° and 30°, respectively.

Fig. 7 - Electric tractor obstacle avoidance test platform

When conducting obstacle avoidance experiments, obstacles are placed in the global path as shown in Figure 8, and the tractor is tracked and navigated along the global path. When the LiDAR scans the obstacles, the upper computer plans the obstacle avoidance path according to the algorithm, and the electric tractor completes the obstacle avoidance operation, Figure 9 shows the process of tractor obstacle avoidance.

The topic recording function in ROS is used to record the speed and heading angular velocity of the tractor during obstacle avoidance, and equations 15-17 are used to calculate the energy consumption of the tractor during obstacle avoidance.

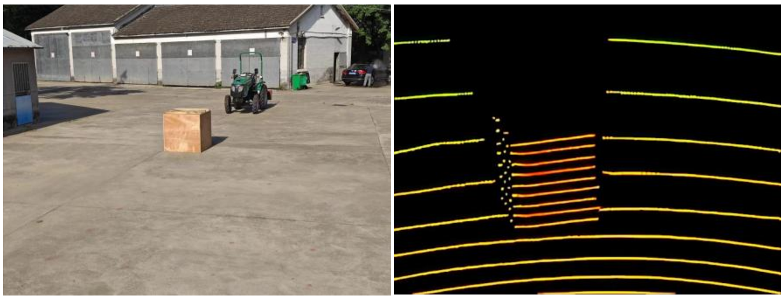

Fig. 8 - Lidar obstacle recognition results

Fig. 9 - Tractor obstacle avoidance process

The starting point of the longitudinal and latitudinal information of the global path planning line is (118° 6957363, 32° 1324537), and the ending point is (118° 6954802, 32° 1324377). A total of 10 meters were recorded from the beginning of the obstacle avoidance path to the node, and obstacles were placed 5 meters away from the starting point. The radius of the obstacle feature circle is 2.5 meters.

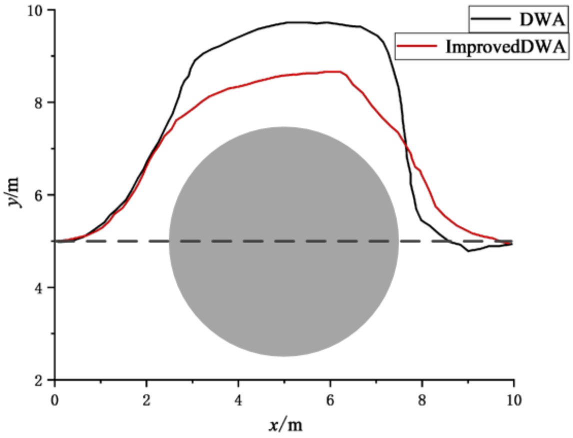

Fig. 10 - Comparison of experimental obstacle avoidance path results

By comparing the method proposed in this article with the original DWA algorithm, Figure 10 shows the running trajectories of the two. The shaded part is the result of fitting the outer contour of the obstacle. Use the BeiDou signal dotter to dot the path of the tractor and record the longitude and latitude information of the path.

Record every 0.1 m, recording the trajectory information using the original DWA algorithm and the algorithm proposed in this article. The dashed line in the figure represents the straight line for the global path planning operation of the tractor. From the figure, it can be seen that the trajectory of the improved algorithm is 1.1 m shorter than the original algorithm in terms of lateral distance.

Table 2

Experimental scenario test results

Algorithm	**Length**	**Planning Spending Time**	**energy consumption**
	[m]	**[ms]**	**[KJ]**
DWA	17.97	201	21.14
Improved DWA	15.69	194	19.77

Table 2 shows the results of obstacle avoidance tests on electric tractors. It can be concluded that the improved DWA algorithm can effectively reduce the energy consumption of the tractor during obstacle avoidance, reducing by about 6.47% compared to the original DWA algorithm and shortening the path length by 12.69%. From the table, it can also be seen that the improved algorithm has a slightly shorter path planning time than the original algorithm. The reason may be due to the continuous oscillation of the heading angle in the obstacle avoidance regression path of the original algorithm. The improved DWA algorithm achieves steady-state earlier, therefore it takes less time.

CONCLUSIONS

This paper optimizes the evaluation function of the DWA algorithm by establishing an energy consumption model for electric tractors and adding an energy consumption evaluation subfunction, thereby reducing turning points and excessive turning on obstacle avoidance paths.

The simulation results show that compared with the original DWA algorithm, the improved DWA algorithm based on the optimal energy consumption has a maximum lateral error of 0.13 m and a maximum heading angle of 0.557 rad for the electric tractor obstacle avoidance method. Compared with the original DWA algorithm, the maximum lateral error and heading angle are reduced by 77.6% and 25.65%, respectively. The front wheel steering angle changes smoothly without significant changes, indicating that the obstacle avoidance path control method has high control accuracy and the tractor can travel according to the preset trajectory.

The experimental results show that the length of the generated path is reduced by 12.69%, the total energy consumption for obstacle avoidance can be reduced by about 6.47%, and the planning time for obstacle avoidance paths is shorter. The experimental results demonstrate the effectiveness of this method.

ACKNOWLEDGEMENT

This work was supported by the National key research and development program (Grant No. 2022YFD2001204), the Jiangsu Province International Science and Technology cooperation project (Grant No. BZ2021007) and the Jiangsu Province modern agricultural Machinery equipment and technology demonstration and extension project (Grant No. NJ2021-06). This work was also supported by the project "Increasing INCDMTM performance and international involvement by supporting expertise in advanced mechatronic technologies - PERFORM-MECH", financed by The Ministry of Research, Innovation, and Digitalization, in the framework of Program 1 – Development of the national research and development system, Sub-program 1.2 – Institutional Performance – Projects for financing excellence in Research, Development and Innovation, Contract no. 3PFE/2021.

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