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Path and Trajectory Planning of Unmanned Ground Vehicles with Vehicle Dynamic Characters

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Abstract

Given partial knowledge about its environment (obstacle, road…) and goal position, optimal path and trajectory planning is a key problem for the control of unmanned vehicles. In path planning problem, it is very important to consider the dynamic limits of the vehicle with optimization function. The path planning was implemented by applying optimization methods based on the given obstacle information(virtual or measured by sensor system) and numerical map without considering vehicle dynamic characters. Then, considering the dynamic characters, trajectory planning was carried out to generate the trajectory that the vehicle can actually travels. This method has certain errors and some shortcomings in finding the optimal solution because the path planning and trajectory planning are carried out independently of each other. One way to solve this problem is to combine these two subjects and to find a global optimal solution. Thus, during the course of the path planning, the constraints necessary for the trajectory planning are considered and the optimization function is chosen accordingly. This paper describes a hybridized algorithm of path planning and trajectory planning, in which optimization function is determined for shortest-length, shortest-time, minimum speed variation path, and the vehicle dynamics characters are considered reasonably. Longitudinal and Lateral Vehicle dynamic models are applied and solutions are solved using genetic algorithm. Also, it is analyzed the effect of weight coefficients to the path planning and trajectory planning. This paper gives practical and useful helps to the engineers and researchers who are trying for the autonomous navigation of the unmanned ground vehicle.

Keywords: Unmanned ground vehicle, path planning, trajectory planning, vehicle dynamic model

INTRODUCTION

In autonomous navigation of unmanned vehicle, the important problem is to find the optimal path (shortest-length, shortest-time, …) avoiding obstacles and control the vehicle along the optimal path.

For the autonomous navigation control, path planning is firstly solved so that vehicle can avoid the obstacle and reach the goal, and then trajectory planning and control planning of velocity and direction are solved. So, in path planning, trajectory is not considered.

First step of path planning is to generate the discrete map, modeling of the environment in order to applying of path planning algorithm. Uncomfortable object such as marshland and slope for the vehicle navigation should be modeled as the obstacle with constant size. Using sensors like camera and Lidar, unknown environment is modeled and environmental map is generated based on sensory data [1, 2].

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Next, path planning is solved using some optimal methods. with given obstacle data, path optimization algorithm has been studied long before, those are Bee Colony Algorithm [3] and Polygon Shape Tangents Algorithm [4] etc.

Visibility binary tree algorithm [5] and Voronoi Diagram method [6] are good algorithms, and the other optimal path planning algorithms are studied and developed.

To overcome the limitations of some path planning algorithms in unknown environments such as reliance on high-precision maps, lack of generalization ability, and obstacle avoidance capability, Deep Q-Network and its derivative algorithm are studied and applied [7].

One of the path planning algorithm, Artificial Potential Field Method(APFM) method is useful to generate the global path, but in some cases, it doesn't go for the goal position and stays in the local minimum position.

An approach hybridizing Reinforcement Learning and APFM could solve the problem efficiently [8].

In fact, vehicle navigation is constrained by the limitation of dynamic characteristics such as speed, steering angle, accelerator and deceleration, etc. Although a path is perfect theoretically and its trajectory is smooth, the path may be impossible to travel. To solve these problems, path planning and trajectory planning considering the vehicle dynamics should be established in organic combination with each other and find the optimal trajectory among the actual possible trajectories.

In this paper, we focus on the vehicle dynamics so that we could generate effective path in real environment, the path planning and control planning algorithms using genetic algorithm.

VEHICLE MODEL

In the path and trajectory planning of unmanned ground vehicle, longitudinal and lateral vehicle dynamic models are considered.

In this paper, we assume that vehicle travels in a plane and there is no aerodynamic drag (Figure 1).

a. *Longitudinal Vehicle dynamics*

From above assumption, when tractive force is larger than rolling resistance force, vehicle is speeding up. Longitudinal vehicle dynamic equation is

$$\delta m \frac{dv_x}{dt} = \frac{N_m \eta_t}{v_x} - mgf \tag{1}$$

where N_m is power of engine or motor, δ is rotating mass conversion coefficient, v_x is longitudinal velocity of vehicle, η_t is driveline efficiency, m is vehicle mass, f is rolling resistant coefficient.

b. *Lateral Vehicle Dynamics*

In this paper, the vehicle is simplified as a "bicycle" model, which is the two degrees of freedom model with lateral and yaw motion. Lateral vehicle dynamic equation is

$$\begin{cases} m(\dot{v}_y + v_x \omega_r) = F_{Y1} + F_{Y2} \\ I_z \dot{\omega}_r = aF_{Y1} - bF_{Y2} \end{cases} \tag{2}$$

where F_{Y1}, F_{Y2} are lateral reaction forces on the front and rear wheels, a, b are the horizontal distance between the front and rear axles and the vehicle centroid, ω_r is angular velocity of vehicle, v_x, v_y are the velocity of x, y direction in vehicle's body coordinate, I_z is the moment of inertia of the vehicle body with respect to the vertical axis through the center of gravity.

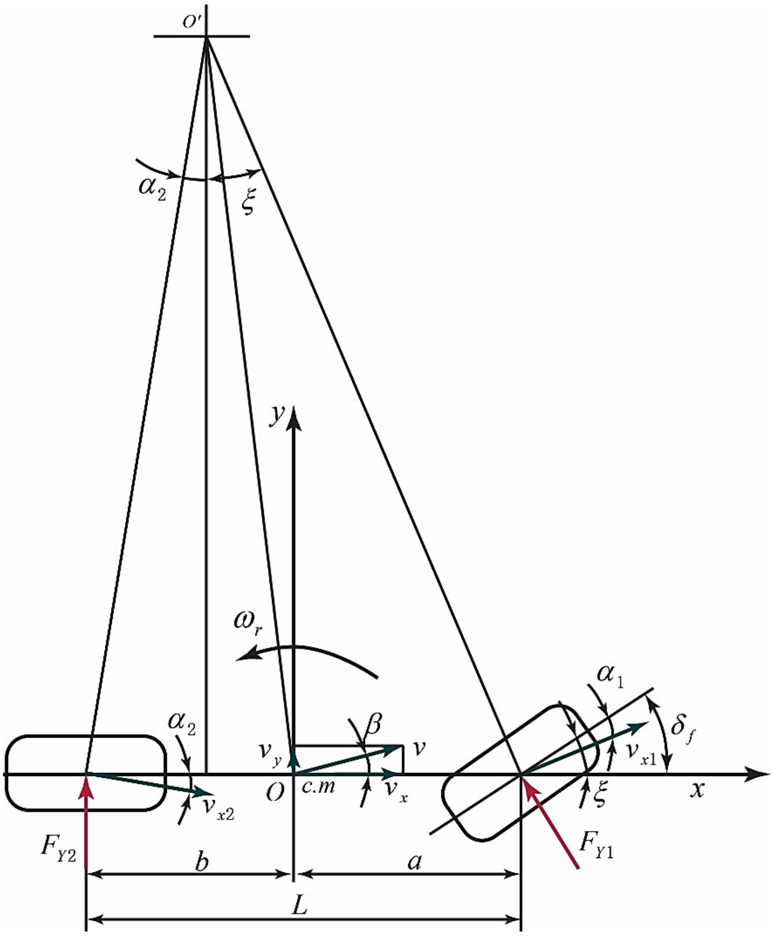

Figure 1. “Bicycle”model.

The values of the lateral forces are proportioned to cornering stiffness and angle such as:

$$F_{Y1} = K_{\alpha 1}\alpha_1, \quad F_{Y2} = K_{\alpha 2}\alpha_2 \tag{3}$$

where $K_{\alpha 1}, K_{\alpha 2}$ are cornering stiffnesses of the front and rear tires respectively, α_1, α_2 are sideslip angles of the front and rear tires.

The values of α_1, α_2 of the front and rear tires can be obtained from the following geometric relationships.

$$\begin{cases} \alpha_1 = \dfrac{a\omega_r}{v_x} + \beta - \delta_f \\ \alpha_2 = \beta - \dfrac{b\omega_r}{v_x} \end{cases} \tag{4}$$

where δ_f is the steering angle of front tire.

Combining equation (4) and (3) with equation (2), following equations can be obtained.

$$\frac{d}{dt}\begin{pmatrix} y \\ \dot{y} \\ \omega_r \\ \dot{\omega}_r \end{pmatrix} = A\begin{pmatrix} y \\ \dot{y} \\ \omega_r \\ \dot{\omega}_r \end{pmatrix} + \begin{pmatrix} 0 \\ \dfrac{K_{\alpha 1}}{m} \\ 0 \\ \dfrac{K_{\alpha 1}a}{I_z} \end{pmatrix}\delta_f \tag{5}$$

Where

$$A=\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{K_{\alpha 1}+K_{\alpha 2}}{mv_x} & 0 & -v_x-\dfrac{K_{\alpha 1}a+K_{\alpha 2}b}{mv_x} \\ 0 & 0 & 0 & 1 \\ 0 & -\dfrac{K_{\alpha 1}a-K_{\alpha 2}b}{I_z v_x} & 0 & -\dfrac{K_{\alpha 1}a^2-K_{\alpha 2}b^2}{I_z v_x} \end{pmatrix}$$

PATH AND TRAJECTORY PLANNING WITH VEHICLE DYNAMIC MODEL

A. *Determination of Optimal Parameters*

When we solve the path planning problems, we consider the unmanned ground vehicle in discrete time interval. We assume that UGV does the uniform motion in a straight line in each step time and that it travels in the same road condition. So when the positions of the initial point are given, the factors that affect the future location of the vehicle are the speed and turning angle of vehicle.

Mathematically, it is represented as.

$$\begin{cases} X_{n+1}=X_n+v_n\cos\varphi_n \\ Y_{n+1}=Y_n+v_n\sin\varphi_n \\ \varphi_{n+1}=\varphi_n+\Delta\varphi_n \end{cases} \tag{6}$$

where v_n is velocity of vehicle of $n\,th$ step, φ_n is turning angle of vehicle of $n\,th$ step, $\Delta\varphi_n$ is turning angle of the vehicle of $n+1\,th$ step relative to $n\,th$ step.

So, v_n and $\Delta\varphi_n$ are the design parameters.

B. *Optimization function*

The determination of optimization function is an important part of path planning.

The ordinary path optimization problem is to seek the shortest path while maintaining the vehicle speed unchanged. But practically, optimization function should be determined considering the vehicle dynamics model. The coefficients are as follows.

a. *The shortest path coefficient*

The shortest path coefficient refers to the shortest path, so the path makes the vehicle navigate from start point to goal point as straight as possible. We define it as follows.

$$we_1=l_n/l_0 \tag{7}$$

where l_n is the position's length of projection on the connection between the starting point and the destination after completing the n steps

$$l_0=\sum_{j=1}^{j=n} l_j \tag{8}$$

where l_0 is The sum of each step's traveling distance, l_j is each step's traveling distance. The maximum value of we_1, when the vehicle travels along the linear connection between the starting point and the goal position (Figure 2).

b. *The shortest time coefficient*

It is an important performance of the unmanned ground vehicle to minimize the time avoiding obstacles and reaching the destination within the shortest speed requirements. We define it as follows.

$$we_2=\frac{l_n}{ntv_{\max}} \tag{9}$$

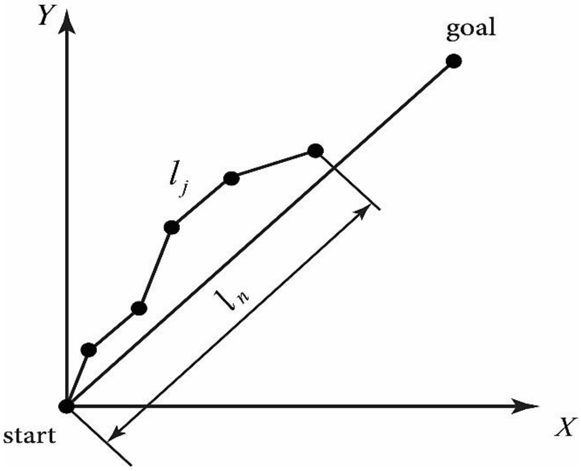

Figure 2. Projection of path.

where n is time step, t is the time interval of each step, $v_{\max}$ is maximum speed limit of the vehicle.

The greater the we_2, the shorter the passing time. The maximum value of we_2 is 1, when the vehicle travels at the maximum speed along the linear connection between the starting point and the destination.

c. The minimum speed variation coefficient
During the obstacle avoidance, frequent acceleration and deceleration reduces comfort of the vehicle, increases fuel consumption, deteriorate the exhaust emission. Meanwhile, soft speed changes also reflect the reasonable control strategy. Therefore, the weighing coefficient is significant. The minimum speed variation

$$we_3 = \frac{1}{1+\sum_{1}^{n}\left(\frac{v_n - v_{n-1}}{v_{\max}}\right)^2} \tag{10}$$

The greater the we_3, the smaller the speed changes during an obstacle avoidance. The maximum value of we_3 is 1, when the vehicle's speed remains the same.

d. The purposefulness coefficient
In every step, vehicle should travel along the path toward the goal position. So we consider the purposefulness coefficient. We define it as follows.

$$we_4 = \frac{1}{1+\frac{d_n}{d_0}} \tag{11}$$

where d_n is the distance from the destination after the n steps, d_0 is the distance between the start point and the goal position.

So, optimization function is determined as follows.

$$we = c_1 we_1 + c_2 we_2 + c_3 we_3 + c_4 we_4 \tag{12}$$

The four weight coefficients are the key to the unmanned ground vehicle path planning.

C. Limitation
Limitation for the optimal problem is applied to velocity and turning angle. Velocity limit is as follows.

$$v_{\min} \le v_n \le v_{\max} \tag{13}$$

where $v_{\min}$ is minimum velocity of vehicle, $v_{\max}$ is maximum velocity of vehicle.

When the vehicle travels at the same speed, Maximum velocity is follows.

$$v_{\max} = \frac{N_m \eta_t}{fmg} \tag{14}$$

Also, velocity change satisfies maximum acceleration condition.

$$a_{b\max} \le \frac{v_n - v_{n\text{-}1}}{3.6t} \le a_{\max} \tag{15}$$

where $a_{\max}$ is maximum acceleration of vehicle, $a_{b\max}$ is maximum deceleration which is "minus". From equation (1), maximum acceleration is as follows.

$$a \frac{1}{\delta m}\left(\frac{3.6 N_m \eta_t}{v_n} - fmg\right)_{max} \tag{16}$$

Maximum deceleration that depends on the road condition is as follows.

$$a_{b\max} = -\varphi g \tag{17}$$

where φ is friction coefficient of road

From the solution of equation (5), we can get the relation between turning angle and steering angle, so we can determine the turning angle ω_r .

$$\Delta\varphi_n = \omega_{rn} t \tag{18}$$

Therefore, turning angle limits are represented as the steering limits.

$$-\delta_{\max} < \delta_{f\,n} < \delta_{\max} \tag{19}$$

where $\delta_{\max}$ is the maximum of steering angle.

SIMULATION

The genetic algorithm gives useful solution to the nonlinear problems so it is used in path planning. The genetic algorithm process includes two important parts. One important part is the replication and elimination, the other part is the crossover and mutation.

A. *The replication and elimination*

First of all, we should calculate the objective function of each individual, and retain high quality individuals. In order to speed up the evolution, we replace the individuals of low objective function with the biggest one. In this process, in order to ensure the path selected is a collision-free path, we define those individuals' objective functions as 0 when they collide with the obstacle.

Collision happens in following case.

$$\sqrt{(X_n - x_i)^2 + (Y_n - y_i)^2} < d_i \tag{20}$$

where x_i is position of i th obstacle on x axis, y_i is position of i th obstacle on y axis, d_i is allowable distance between i th obstacle and vehicle, d_i depend on the size of vehicle and i th obstacle.

B. *The mutation and crossover*

The selection of the mutation rate and crossover rate are very important. If the mutation rate is too small, the calculation is complex and if it is too large, we can't get the global optimal solution. The selection of the crossover rate is also very important.

In this paper we select them as $\rho_v = 0.01$, $\rho_c = 0.2$. Where ρ_v stands for the mutation rate, ρ_c stands for the crossover rate.

C. Simulation results and analysis

It is Simulated and analysed by matlab.

In this simulation weight coefficients are varied every plans.

Parameters of Vehicle for the solution are as follows (Table 1).

Table 1. Vehicle Parameters.

Name	Value
Total mass(m)	40 kg
Motor power(N_m)	200 W
Driveline efficient(η_t)	0.95
rolling resistant coefficient(f)	0.025
rotating mass conversion coefficient(δ)	1.05
Maximum steering angle($\beta_{\max}$)	20 rad
Minimum velocity($v_{\min}$)	0.5 m/s
Allowable distance(d_i)	0.5 m
Front tire stiffness($K_{\alpha 1}$)	46 000 N / rad
Rear tire stiffness($K_{\alpha 2}$)	46 000 N / rad
Distance from c.m to front axle(a)	0.4 m
Distance from c.m to rear axle(b)	0.4 m

The weight coefficients in various plan are determined as follows (Table 2).

Table 2. Weight Coefficients.

Case	c_1	c_2	c_3	c_4
1	0.2	0.25	0.25	0.3
2	0.2	0.2	0.2	0.4
3	0.1	0.4	0.4	0.1
4	0.4	0.1	0.1	0.4

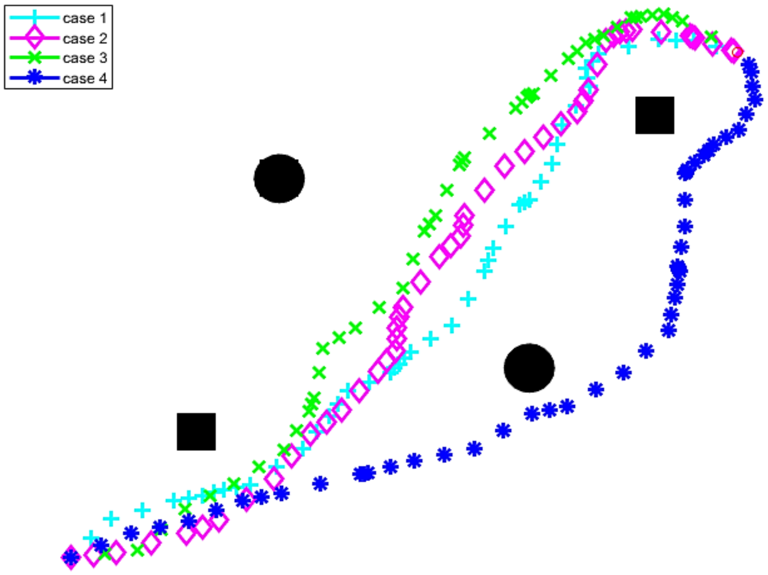

Figure 3. Path planning simulation results

Simulation results are as follows (Figure 3).

In this figure number of points is step number.

In every plan small number of points means short travelling time.

Result shows that the determination of weight coefficients is very important. In plan 1, 2 and 3, path is long, however, time consumption is shorter and speed variation is smaller in comparation with plan 4. The weight coefficients can be determined by designers according to their requirements.

CONCLUSION

This paper researched the method for path planning from environmental data and based on vehicle dynamic model. We use the "bicycle" model and the optimal parameters are velocity and steering angle. Using genetic algorithm, we can get an optimal path and trajectory avoiding obstacles.

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