Research on the path optimization of unmanned rolling impaction for high embankment of airport

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ABSTRACT

Quality control of embankment compaction has an important influence on the durability and stability of the high embankment airport. Now, the unmanned compaction quality control mainly depends on the path tracking effect of the unmanned roller. The path tracking error of the roller increased obviously in the field test. The error from the perspective of the discontinuity of the planning path curvature was analyzed by a simulation model built based on the pure pursuit algorithm. Then the arc and elliptical arc were selected to simplify the planning path, and the results show that the optimized arc path made the tracking error reduced effectively. In order to further reduce the error, the inflection point of the straight line and the arc was smoothed by the method of rounding and cubic B-spline curve fitting, respectively. The simulation results show that the rounding process and the B-spline curve fitting have significant effects on improving the path tracking of the vehicle.

Keywords: unmanned roller, curvature continuity, pure pursuit method

1 INTRODUCTION

At present, research on intelligent compaction is hot at home and abroad. Yao et al. (2015, 2018) proposed a real-time monitoring method of impact rolling for high embankment of airport, using the Beidou satellite navigation system and 3G wireless transmission technology. Liu et al. (2014, 2019) established a system for real-time monitoring of compaction quality for earth-rock dams, using some modules such as GPS module and acceleration sensor et al. With the development of driverless technology, intelligent compaction combined with driverless technology will become a new trend. Now, the team of the unmanned roller compactor in China, Tsinghua University (Liu et al. 2015; Zhang et al. 2018; Zhang et al. 2019; Zhang et al. 2019) has developed a hydraulic roller compactor automatic driving system for water conservancy construction. Tianjin University (Zhong et al. 2018; Zhong et al. 2018) has developed a set of unmanned methods for vibratory roller compactors for hydraulic construction.

According to the related research of constitutive theory for soils, (Yao et al. 2008; Yao et al. 2008; Yao et al. 2009; Yao et al. 2013), the increase of over-consolidation degree changes the strength of the soil, thus affecting the compaction degree in the process of soil compaction. While the compaction is closely related to the compaction trajectory, and the effect of path tracking directly affects the trajectory of the roller, so it is crucial to research on the path tracking of the roller. However, few people have studied the curvature problem of roller tracking. There is related research on the heading of unmanned agricultural machinery. Sabelhaus et al. (2013) has used the clothoid for the ground steering operation of agricultural automation based on the continuous curvature path. Bayar et al. (2016) has employed the fourth-order polynomial to generate the agricultural machinery steering path. Backman et al. (2015) proposed an algorithm with continuous curvature and velocity to solve the problem of smooth steering of agricultural vehicles. In the automatic parking system, there are also related studies on the curvature continuity problem. Zhang et al. (2015) has established a continuous curve from the straight line to the curve based on the clothoid curve. Gómez-Bravo et al. (2008) has used the \(\beta\)-spline curve in the automatic parking system to generate a path with continuous curvature without collision. Huang (2014) has divided the planning path of the parking into seven-segment which are composed of a clothoid, an arc and a curve.

2 THE FIELD TEST OF UNMANNED ROLLER COMPACTOR IN XUZHOU

The range of the test site, Xuzhou Construction Machinery Group comprehensive test site, is 50×50 m\(^2\). The information of the position and heading angle was provided by Beidou system installed on the front of the vibrating wheel of the roller. The industrial computer obtained the path information from the cloud platform.
And the computer sent the steering command to the steering wheel. The path tracking method used look-ahead point tracking method, and the control adopted the PID method.

Fig. 1. Physical graph of the field compaction.

1-Vehicle controller 2-Cab 3- Electric steering wheel 4- Electric throttle 5- Electric brake 6- Vibration wheel 7- Positioning and directional antenna of Beidou system 8- Front frame

Fig. 2. Schematic graph of unmanned vibration roller.

The trajectories’ error of the first, fourth and eighth circles of the roller were selected for analysis, considering that the rolling trajectory of the single circle was not representative.

The above error graphs of rolling trajectory were divided into 4 segments: ① straight segment, ② curved segment (left), ③ straight segment, ④ curved segment (right).

It can be seen from the error graphs that there are 4 peaks, which occurred in the inbound and outbound sections. Moreover, it can also indicate that the error of the roller initially entering the straight line segment was gradually reduced, indicating that the system has been stabilized. However, there was a phenomenon of a sharp error increase when the roller was out of the corner.

In a word, it can be seen from the above rolling track: the error of the roller mainly occurred when the roller was interchanged from the straight section to the arc segment, or transferred backwords.

Currently, the reason for the occurrence of path tracking errors was considered to be related to the tracking algorithm by most people. However, according to the above analysis, the tracking error may not be
caused by the algorithm itself. Maybe analysis of the path planning can give reasons for the error.

3 MATLAB / SIMULINK MODEL SIMULATION BASED ON THE PURE PURSUIT ALGORITHM

3.1 Algorithm description

In order to avoid the tracking error caused by the defect of the tracking algorithm itself, another geometric path tracking method —— pure pursuit (Wang et al. 2014; Zhao et al. 2018) was adopted. The following described the pure pursuit algorithm.

![Fig. 7. Schematic graph of pure tracking algorithm.](image)

First, an arc is made with the starting point—the axle of the rear wheel, and the end point—the target point on the path ahead of the vehicle. The target point is determined from the current position of the vehicle to the desired path based on the look-ahead distance $l_d$. The expression for the geometric relationship are as follows:

$$\frac{l_d}{\sin 2\alpha} = \frac{R}{\sin(\frac{\pi}{2} - \alpha)}$$

$$l_d = \frac{2\sin \alpha \cos \alpha}{\cos \alpha}$$

$$\frac{l_d}{\sin \alpha} = 2R$$

$$\kappa = \frac{2\sin \alpha}{ld}$$

$k$ is the curvature of the arc, the corner formula is as follows:

$$\delta = \tan^{-1}(kL)$$

$$\delta(t) = \tan^{-1}\left(\frac{2L\sin \alpha(t)}{ld}\right)$$

where $L$ is the wheelbase.

3.2 Determination method of the look-ahead point

![Fig. 8. Schematic graph of look-ahead method.](image)

The planning path is composed of a series of discrete point coordinates. The method for determining the look-ahead point is as follows:

1. The closest point to the current position is found on the line segment between the discrete points, which is called the projection point. If the projection point is outside the line segment, the vertex closest to the current point will be selected as the projection point.

2. If the vehicle’s speed is a constant, the vehicle will form series of projection points near the planning point. Assuming that the look-ahead distance is also a constant, it is necessary to compare the distance between the projection points and the look-ahead distance (the overshoot) to determine the position of the look-ahead point.

If the overshoot is less than 0, the look-ahead point will be in the sequence of projection points, and the sequence number of the preview point will be consistent with that of the projection point. Taking the current projection point serial number as the preview starting accumulating the serial number. The distance of the look-ahead point is accumulated and compared with the look-ahead distance. If the overshoot is greater than 0, the calculation formula of the look-ahead point coordinates is:

$$\alpha = \frac{d_{\text{overshoot}}}{d_{\text{proj-end}} - \delta}$$

$$P_{\text{look-ahead}} = \alpha * P_{\text{proj}} + (1-\alpha) * P_{\text{end}}$$

If the overshoot is equal to 0, the coordinates of the end point of the preview sequence are the look-ahead points.

3.3 Matlab/Simulink model simulation

3.3.1 Model description

The model built based on the above pure pursuit algorithm is mainly divided into four modules: planning path, look-ahead point finding module, algorithmic control module, and vehicle model. The Vehicle model was adopted the model of Matlab2019a.
According to the field rolling test, the path of the rolling is simulated in a ratio of 10:1. The finding module of look-ahead point is obtained by the look-ahead point calculation principle. The algorithmic control module adopted pure pursuit method. The inputs of the controller are the coordinates of the look-ahead point, the lateral error, and the wheelbase of the vehicle. The output of the controller is the corner of the steering wheel.

### 3.3.2 Simulation analysis

The initial conditions of path tracking: the look-ahead distance is 0.35 m, the vehicle speed is 0.2 m/s, and the wheelbase is 0.15 m. The initial position x= 2.5 m, the direction is the negative direction of the x-axis. The simulation track is shown in Fig 10.

![Simulated planning path using arc](image)

It can be seen from the track graph that the vehicle has obvious deviation when entering and leaving the corner. In order to explain the problem, the tracking point data were extracted for error analysis. An error graph as shown in Fig. 11 is obtained.

![Error comparison graph](image)

It can be obtained that the peak value of the lateral tracking error of the vehicle is 0.0646 m from Fig.11.

Combined with the results of the field test and the simulation, it can be seen that: their tracking effects were both poor at the point where the line and the arc touch. Therefore, considering the tracking error was not caused by the algorithm itself, but because of the planning path.

In the above simulation model, the planning path has a problem that the path curvature is discontinuous at the steering end.

The curvature of the planning path changed abruptly at the entrance and exit curves, so the tracking error was caused by the curvature discontinuity of the planning path.

### 4 SIMPLIFY TO SMOOTH PATHS

#### 4.1 Path simplification by arc and ellipse arc

The steering on the original planning path is not smooth due to the connection of the arc and the line, so the steering segment is simplified. The end points of the two lines and the turning midpoint are used as control points, and the path simplification graph by the arc or elliptical arc were shown below.

![Simplified planning path using arc](image)

According to the simplified circular path of Fig. 12, the simulated error peak is 0.04973 m, which is 23% lower than that of the original planning path. There are still 4 error peaks.
According to the simplified elliptical arc path in Fig. 13, the simulated error peak is 0.058 m, which is 10% lower than that of the original planned path, and the amplitude is small. Therefore the effect of error optimization is not obvious, and the elliptical arc path is not used for simulation.

4.2 Rounding smoothing at the inflection point

In the previous section, there is a non-smooth point at the junction of the line and the arc. In order to make a smooth transition of the entire path, rounding was used at the inflection point. In Fig. 16, a chamfer with R=6 m was used at the joint of an arc of R=10 m and a line. In Fig. 18, the arc with R=10 m was replaced by a circular arc with a radius of 8 m (extreme position).

(1) Chamfer radius R=6 m

Fig. 17. Error comparison graph of chamfer radius R=6 m.

After the simulation, the tracking error of the vehicle is 0.0433 m, which is compared with the tracking error in Fig. 14. The lateral error of the path after smoothed is reduced by 13%, indicating that this method is effective.

(2) Chamfer radius R=8 m (extreme position)

Fig. 18. Chamfer radius R=8 m.

Comparing the lateral tracking error of the corrected path with the tracking error in Fig. 14, as shown in Fig. 19, it can be clearly seen that the error peak is 0.0339 m. The error of the path after smoothed is reduced by 32%, indicating that this method can greatly reduce the error.

4.3 Cubic B-spline curve fitting at the inflection point

Based on the curvature continuity of cubic B-spline curve, nine control points were selected to modify the original planning path. The optimized path is shown in the Fig. 20.

Fig. 19. Error comparison graph of chamfer radius R=8 m.

Fig. 20. Trajectory optimization of B-spline curve.
From the simulation error Fig. 21, it can be seen that the peak value of the tracking error of the vehicle is 0.0411 m after the B-spline curve optimization. Compared with the initial path tracking lateral error, the error is reduced by 36%, indicating that this method can also greatly reduce the error.

5 CONCLUSIONS

1) When the unmanned roller transited from a line to an arc section or transferred backwards, the path tracking error increased obviously, which was mainly caused by the curvature discontinuity of the planning path.

2) The simulation results of using arc and ellipse at the heading turning of planning path show that the tracking effect of ellipse path is worse than that of arc path. From the perspective of curvature change of ellipse, the influence of curvature continuity on path tracking can be verified.

3) The chamfer was used at the inflection point of the line and the circular arc, and the error analysis shows that the method can improve the error tracking effect significantly.

4) At the inflection point of the line and the circular arc, the cubic B-spline curve with continuous curvature was used to fit, and the effect of improving curvature on vehicle path tracking was significant through error analysis.

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