Algorithm for optimal path planning of impact roller in high-embankment airport

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ABSTRACT

With the continuous increase of high-embankment construction projects in China's airports, impact roller has become more and more widely used. And the construction technology with automatic driving, path planning and adaptive operation has become the development direction in high-embankment airport. Combined with advanced information technology such as Beidou positioning navigation system, the Internet and cloud computing, this paper proposes an algorithm for optimal path planning of impact roller to meet the need. The algorithm includes three aspects: working surface rasterization, full coverage path generation and optimal path planning. Based on the structure of the impact roller, the algorithm adopts the method of non-overlapping wheel tracks to plan the path which covers the entire working surface, and could get the optimal path by analyzing the compaction quality during the construction process. Through field test, it is proved that the proposed algorithm has certain feasibility and effectiveness in guiding impact roller to work. The impact roller can not only ensure the compaction quality, but also improve work efficiency by following the path generated by the algorithm.

Keywords: impact roller, high-embankment airport, compaction quality, optimal path

1 INTRODUCTION

In order to meet the needs of the country, during the 13th Five-Year Plan period, a large number of airports began to be built in mountain area. Therefore, the quality requirements of the filling body are extremely high (Cao et al. 2011), which directly affects the quality of the runway and the comfort of the aircraft during landing. The high-embankment airports are built by the way of cutting mountains and filling valleys, resulting in destroying the original structure of filling body. Yao et al. (2008a, 2008b, 2009, 2013) could predict the deformation and strength of the filling body through the UH model. Compared with other construction techniques, the impact rolling method has deeper effective compaction depth (Liu et al. 2019, RIHMT 2005), so it is widely used in highway, dam and airport engineering. Currently, in the high-embankment airport project, the quality of the compaction process depends on the experience of the impact roller driver, resulting in uneven compaction quality of the filling body. With the development of advanced technologies such as Internet of Things, big data, artificial intelligence, etc., relevant research (Wu and Huang 2008, Liu et al. 2014, Yao et al. 2015, Yao et al. 2018, Zhong et al. 2009, Zhong et al. 2010) on real-time monitoring of compaction quality has been developed and the intelligent monitoring systems successfully developed has been initially applied in the construction of the dam (Huang et al. 2005, Ma et al. 2011, Wang 2014). Besides, unmanned machines have begun to replace the driver. Because of these, it is very necessary to provide optimal path for unmanned machines. Based on the above situation, it is of great significance to plan the path to guide the impact roller to work whether it is driven or unmanned.

At present, there is no research on the path planning of impact roller in high-embankment airport at home and abroad. The existed research mainly focuses on the path planning of robots and drones (Edwards et al. 2017, Ranjitha et al. 2016, Torres et al. 2016). However, because the structure of the impact roller is very different from that of the robot and the drone, the path planning algorithm for the impact roller is different from the former two. This paper will combine the actual rolling situation of impact roller to plan the path.

2 THE ALGORITHM FOR OPTIMAL PATH

2.1 Procedure of the working surface rasterization

(1) Convert Beidou coordinates into UTM coordinates
The UTM coordinates were used during the rasterization procedure of the algorithm, while the Beidou positioning data is latitude and longitude coordinates, so the method, converting Beidou coordinates into UTM coordinates which include X and Y, was introduced in this paper. The formulas are as follows:

\[
X = N_0 + k_0 \left( s + vtan\varphi \right) \left( \frac{5 - T + 9C + 4C^2}{24} \right) A^4 \left( 61 - 58T + T^2 \right) \frac{A^6}{720} \frac{1}{2} \\
Y = E_0 + k_0 \left( A + \left( 1 - T + C \right) \frac{A^4}{6} \left( 5 - 18T + T^2 \right) \frac{A^6}{120} \right)
\]

where

\[
T = tan^2 \varphi
\]

\[
C = \frac{e^2 \cos^2 \varphi}{1 - e^2 sin^2 \varphi}
\]

\[
s = \left( 1 - \frac{e^2}{4} - \frac{3e^2}{256} \right) \varphi - \left( \frac{3e^2}{8} + \frac{3e^4}{32} + \frac{45e^6}{1024} \right) sin 2\varphi
\]

\[
v = \frac{1}{\sqrt{1 - e^2 sin^2 \varphi}}
\]

\[
A = \left( \lambda - \lambda_0 \right) \cos \varphi
\]

In the above, \(E_0\) is the east latitude offset, which equals 500000 m in general, \(N_0\) is the north latitude offset, which equals 0 in the northern hemisphere, \(k_0\) is the projection scale factor, which equals 0.9996, \(a\) which equals 6378137 m is the reference ellipsoid long semi-axis, \(e\) which equals 0.0818192 is the reference ellipsoid eccentricity, \(\lambda\) is the longitude of the calculated point (radian), \(\varphi\) is the latitude of the calculated point (radian), \(\lambda_0\) is the central meridian longitude (radian).

**2.2 Working surface rasterization**

First, the latitude and longitude coordinates of the four corner points of the working surface was accurately obtained based on Beidou RTK technology. Second, UTM coordinates of the points are calculated according to Eq. (1) and Eq. (2). Finally, the points \(E(x_{\text{min}}, y_{\text{min}})\) and \(G(x_{\text{max}}, y_{\text{max}})\) are obtained by using the maximum and minimum values of \(x\) and \(y\) and the quadrangle \(EFGH\) is formed based on the two points, as shown in Fig. 1.

Let \(\Delta l\) define the size of grid. \(Col\) denotes the column numbers of the grid in the working surface and \(Row\) denotes the row numbers. \(Col\) and \(Row\) is calculated as follows:

\[
Col = \left[ \frac{x_{\text{max}} - x_{\text{min}}}{\Delta l} \right] \quad Row = \left[ \frac{y_{\text{max}} - y_{\text{min}}}{\Delta l} \right]
\]

From the above, the coordinate \((x_{(i,j)}, y_{(i,j)})\) of center point of the grid \(P_{(i,j)}\), located in the \(i\)th column and the \(j\)th row in the working surface, can be calculated as follows:

\[
x_{(i,j)} = x_{\text{min}} + (i - 0.5)\Delta l \quad 1 \leq i \leq Col
\]

\[
y_{(i,j)} = y_{\text{min}} + (j - 0.5)\Delta l \quad 1 \leq j \leq Row
\]

Then, all grids of the working surface \(ABCD\) from quadrangle \(EFGH\) can be selected to realize the rasterization and digitizing of working surface. As shown in Fig. 1, the solid line grids belong to the working surface \(ABCD\). Table 1 shows the pseudo code of working surface rasterization. In order to calculate easily, let \(n\) define the attribute value of every grid \(P_{(i,j)}\), that is \(P_{(i,j)} = (x, y, n)\).

| Grid Process |
|---------------|
| List <Point> L; |
| For (Int i = 1; i <= Col; i++) |
| { |
| For (Int j = 1; j <= Row; j++) |
| { |
| If (P_{(i,j)} in Forefield\(ABCD\)) |
| { |
| L.Add (P_{(i,j)}); |
| } |
| } |
| } |

Table 1. The pseudo code of working surface rasterization.

**2.2 Process of full coverage path generation**

Fig. 2. Machine model.
(1) Impact roller
There are many models of impact roller in China, and the technical parameters of them are different. And the two-wheel impact roller is the main machine model, so take the machine model YP25 (Hawei Heavy Industry, Henan) as an example, the main parameters ($l_w$ is the width of machine, $l_v$ is the width of wheel) are as follows: $l_w = 2.96 \text{ m}$, $l_v = 0.9 \text{ m}$. The machine model is shown in Fig. 2.

(2) Non-overlapping
The proposed algorithm adopts the method of non-overlapping, as shown in Fig. 3. While the previous algorithm for path planning adopted the method of overlapping, as shown in Fig. 4 (Yao et al. 2018). For the way of non-overlapping, it is known that there exists gap between two wheels from the main parameters of the YP25. Regulation (RIHMT 2005) states that the method of non-overlapping is rational, scientific and the most cost-effective. The manner of the overlapping produces areas of different compaction in the horizontal direction, resulting in uneven compaction of the entire site, which in turn has a bad influence on the compaction quality and increases the amount of compaction work. In addition, comparing Fig. 3 and Fig. 4, the algorithm can significantly shorten the distance.

(3) Generating path
According to the turning radius and $l_w$, the working surface $ABCD$ is divided into two turning areas ① and working areas ②, as shown in Fig. 5. Let $l$ define the width of the rolling band depicted in Fig. 3, and it is calculated as follows:

$$l = \frac{3l_v - l_w}{2}$$

The coordinates of points $I, J, K, L, M, N$ and numbers of the rolling band are calculated by the coordinates of points $A', B', C', D'$. Take the line segment $A'D'$ as an example, the coordinates of the $m$th point on the line $L_1$ can be calculated as follows:

$$
x_n = m x_1 + \left( \frac{L}{\Delta d} \right) - m x_1
$$

$$
y_n = m y_1 + \left( \frac{L}{\Delta d} \right) - m y_1
$$

The points on other line segments are calculated with the same method. Then, along the direction marked in the Fig. 5, $L_1, L_2, L_3, L_4, L_5, L_6, L_7$ and $L_8$ are passed successively, and the path covering the entire working surface is generated.

2.3 Optimal path planning
(1) The method of calculating compaction numbers
The trajectory of the impact roller is approximately straight between the time $t$ and $t+1$ because of the high frequency of Beidou, as shown in Fig. 6. And $\theta$ is calculated by the Beidou receiver. Besides, the value of $x,$
y of the points $P_t$ and $P_{t+1}$ are also obtained. The grids $P_{(i,j)}$ under the wheel are selected, whose attribute value adds 1.

Fig. 6. Calculate compaction numbers.

(2) The planning of optimal path

From Fig. 3 and Fig. 5, it is known that the grids covered by impact roller are fixed when the machine works along the straight route of the full coverage path. Let $m$ define the number of the grids. $n_i$ is the attribute value of the $k$th grid. The average compaction numbers $\bar{T}$ is given by the expression:

$$\bar{T} = \frac{1}{m} \sum_{i=1}^{n} n_i$$

Detailed steps are as follows:

1) When impact roller passed the connection made between midpoint of $AD$ and midpoint of $BC$, the line segment $L_{left}$ or $L_{right}$ stays same.

2) Simultaneously calculate the compaction number on the other side to get the minimum $\bar{T}$ and the line segment $L_{right}$ or $L_{left}$.

3) Then, all points on two line segments are connected to the closed path by the method shown in the Section 2.2. Besides, the coordinate data of all points is stored in the cloud server database.

4) Repeat step 1), 2) and 3) until the compaction quality meets the need of the working surface.

3 THE ALGORITHM FIELD TEST

In April 2018, we use unmanned rolling machine to verify feasibility of the algorithm for optimal path, which is made by Xuzhou Construction Machinery Group. First, we store the path generated by the algorithm in the cloud server database, then the rolling machine acquires the path through the Internet of Things and works according to the acquired path. The idea how the algorithm lead machine to work is shown in Fig. 7.

The algorithm generates a full coverage path by the method in Section 2.2. The path is shown as the red line on the working surface in Fig. 7. After the test is completed, the final compaction quality of the test site is shown in Fig. 8.

During the test, the algorithm plans the optimal path based on the compaction of test field and the position of the unmanned machine. After unmanned machine passes the centerline of test field, the algorithm re-plans the optimal path to guide the machine to achieve the best compaction effect, the result is as shown in Fig. 9.

Fig. 7. The algorithm control mind.

Fig. 8. Compaction quality of the test field.

Fig. 9. The planning optimal path (a) optimal before the midline (b) optimal after the midline.
It can be seen from the test result that the complete cover route generated by the algorithm could guide machine to work better and more efficient. Besides, during the working process, the algorithm is feasible to obtain the optimal path as shown in Fig. 9, which is calculated by analyzing current compaction quality.

4 CONCLUSIONS

The compaction quality of high-embankment airport is the key to ensure the safety of the airport. Because the proposed algorithm can effectively guarantee the uniformity of compaction quality, it is of great significance to the construction of high-embankment airport in China.

The algorithm proposed for impact roller in high-embankment airport has some advantages: 1) shorten the distance traveled by the impact roller by using the method of non-overlapping; 2) with real-time analysis of the compaction quality of the current working surface and planning the optimal path, it not only guarantees the engineering requirement, but also improves the construction efficiency; 3) combined with a visual interaction system, it could provide the optimal path for the driver or unmanned machine, resulting in avoiding the disadvantages caused by the driver personal factors; 4) it is verified that CCR algorithm is feasible so that it could provide technical support for intelligent construction of high-embankment airport in the future.

ACKNOWLEDGEMENTS

This work was supported by the National Program on Key Basic Research Project of China (973 Program) (No.2014CB047000).

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