Research on Technologies and Construction Application of 3D Intelligent Milling

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Abstract. To address the problems of insufficient milling accuracy, limited bottom surface smoothness, and unstable paving quality in conventional milling operations, this study focuses on 3D intelligent milling technology. The key procedures, including high-precision pavement information acquisition, point cloud data preprocessing, road design model establishment, and onboard construction control, were systematically investigated. Based on this, an integrated technical route covering data acquisition, model establishment, construction implementation, and performance verification was developed. A field application was carried out on the maintenance project of Gaofuer Road in Hangzhou. Before construction, the original pavement showed obvious elevation fluctuation. The designed milling depth was 5 cm, and the maximum milling depth reached 8.8 cm. The results showed that, among the 554 points collected after intelligent milling, 445 points were controlled within ±5 mm, accounting for 80.32%; 58 points were greater than or equal to 6 mm, accounting for 10.47%; and 51 points were less than or equal to −6 mm, accounting for 9.21%. The overall precision was good. The study indicates that intelligent milling has good construction accuracy and field adaptability. It can effectively improve milling precision and bottom surface smoothness, enhance construction continuity, and provide a stable base for subsequent paving. This study may provide a new solution for milling and repaving of complex pavements in road maintenance projects.

Keywords: Asphalt Pavement, Intelligent Milling, Cloud Data.

1 Introduction

Milling is a key process in asphalt pavement maintenance, function restoration, and reconstruction projects. Its construction quality directly affects the subsequent paving quality, pavement smoothness, and service performance. However, current highway milling operations still mainly adopt fixed-depth milling or experience-based control. This method is complicated, labor-intensive, and difficult to apply effectively to road sections with frequent distress, complex structures, and large elevation fluctuations. As a result, traditional milling methods often fail to balance treatment accuracy and bottom surface smoothness, which further affects the quality of later paving operations.[1-2]

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Against this background, intelligent milling technology has gradually become an important research topic. By integrating high-precision measurement, sensing, digital modeling, path planning, and onboard control, this technology enables real-time sensing and adjustment of milling depth, operation path, and construction parameters. In this way, milling accuracy and construction efficiency can be improved, the bottom surface smoothness can be enhanced, and a more stable working base can be provided for later paving.

At present, both domestic and international researchers have carried out a series of studies on intelligent milling. Zhang Xiaoxia et al. [3] studied the application of 3D intelligent milling technology in highway construction and pointed out that this technology can realize automatic adjustment of milling depth through pavement scanning and digital control. Wu Haitao et al. [4] proposed a high-precision integrated system for milling and intelligent paving. Bae et al. [5] studied the smoothness prediction of asphalt overlay pavements considering milling effects, and found that significant differences exist in the smoothness evolution between milled and non-milled sections. Separate modeling can better describe their performance characteristics. Correia N S et al. [6] studied the influence of milling parameters on the asphalt pavement milling process and found that milling depth and feed speed are key factors affecting cutting force. In general, existing studies still focus mainly on traditional milling technology with limited intelligence, or only optimize a single technical link of intelligent milling. Research on the full-process integration of intelligent milling remains insufficient, and systematic analysis based on real construction scenarios and measured data is still limited.

Therefore, this paper analyzes the key technologies involved in the whole process of intelligent milling. It mainly investigates the technical characteristics of intelligent milling in data acquisition, point cloud model establishment, and construction coordination, and verifies its application effect through the Gaofuer Road project in Hangzhou and measured data analysis, so as to provide a reference for technology promotion and engineering application.

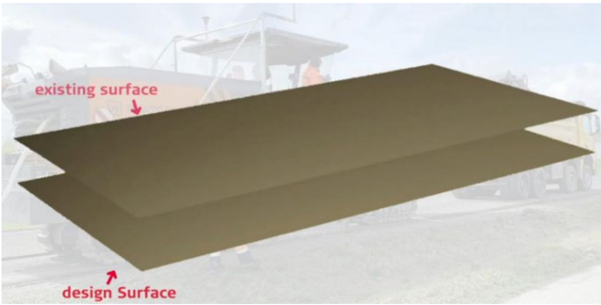
2 Key Technologies and Implementation Process of Intelligent Milling

2.1 Pavement Information Acquisition and Analysis

Data Acquisition. Intelligent milling requires high accuracy of original pavement information. Therefore, the data acquisition equipment should take measurement accuracy, operating efficiency, and field adaptability into account. In this study, as shown in Fig. 1 HEXAGON Leica ICON Robot 80 and HEXAGON Leica Scanstation P30-P40 total station scanners, together with an intelligent pavement condition scanning vehicle, were used to obtain high-precision original pavement data. The same reference model was used for both milling and paving.

(a) Total station scanner

(b) Intelligent pavement condition scanning vehicle



(c) Reference model for milling and paving

Fig. 1. Pavement information acquisition equipment

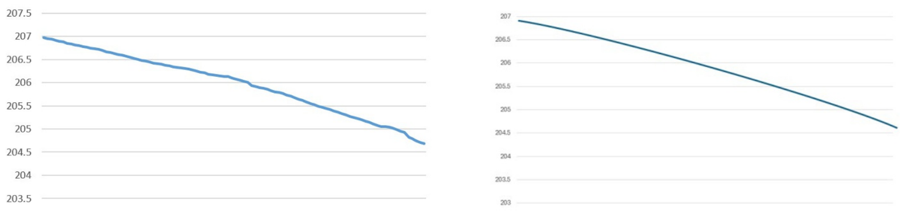
Data Preprocessing. The raw point cloud data usually contain a large amount of redundant information and noise. If they are directly used for modeling and construction analysis, the model accuracy and construction control effect may be affected. Therefore, data preprocessing is necessary to remove non-target points, reduce redundant data, and retain useful pavement information, thus forming effective data for road modeling.

During data collection, vehicle vibration and bumping may disturb the elevation data. RTK can be used to compensate for the elevation error caused by vehicle vibration, thereby reducing noise during the measurement stage. The compensation formula is as follows.

$$z_i' = \alpha z_i^L + (1-\alpha) z_i^R \tag{1}$$

where z_i^L denotes the laser-measured elevation, z_i^R denotes the RTK-corrected elevation, and α is the weighting coefficient.

The elevation data before and after preprocessing are shown in Fig. 2.



(a) RTK elevation data before smoothing (b) RTK elevation data after smoothing

Fig. 2. RTK elevation data before and after processing

2.2 Point Cloud Model Establishment and Construction Scheme Design

After the acquisition and preprocessing of raw pavement point cloud data, the key task of intelligent milling is to convert the discrete point cloud information into a digital model for construction control, and then develop an executable construction scheme. First, the preprocessed road point cloud was imported into LsHighWay software. The road design model data were calculated by selecting the road edge and adjusting the relevant parameters. After the design model was generated, it was exported in XML format. At the same time, the original pavement point cloud data were exported in CSV format and then imported into iCON Office to generate the original pavement grid model, thus forming the original pavement model corresponding to the design model. The generated model is shown in Fig. 3.

Fig. 3. Point cloud model

2.3 Intelligent Milling Control and Construction Implementation

During the construction stage, the construction model file and the inspection model file were imported into the inspection equipment. The onboard system read the target elevation information from the construction model in real time and automatically adjusted the milling depth, so that continuous construction could be carried out according to the design data. Meanwhile, the inspection equipment used the inspection model to check the construction process and the accuracy of the finished surface in real time, so that deviations could be identified and corrected in time. In this way, the continuity, stability, and construction precision of intelligent milling were ensured.

3 Field Construction Analysis of Intelligent Milling

3.1 Project Overview

Gaofuer Road is located in Gaoqiao Economic Development Zone, Fuyang District, Hangzhou. It was built in 2002 and has been in service for nearly 20 years. Due to the long service period, the uneven distribution of pavement distress, and the large fluctuation in the original pavement elevation, the traditional fixed-thickness milling method could hardly meet the requirements for distress treatment accuracy, bottom surface smoothness, and subsequent paving quality control. Therefore, this project adopted 3D intelligent milling technology. Through digital construction, the milling accuracy was improved, the bottom surface smoothness was enhanced, and favorable conditions were created for subsequent asphalt paving.

The construction period lasted from April 18, 2025 to May 5, 2025. The road length was about 6 km, the width was about 30 m, and a 4 m-wide green belt was located in the middle. The project panorama and design model are shown in Fig. 4.

(a) Panoramic view of Gaofuer Road (b) Design model

Fig. 4. Overview of Gaofuer Road

3.2 Pavement Data Detection and Model Establishment

Before construction, the original pavement of Gaofuer Road was detected and analyzed using the equipment described in Section 2.1. The detection site is shown in Fig. 5.

(a) Total station survey (b) Intelligent milling machine

Fig. 5. Inspection site

The results show that the pavement elevation fluctuated significantly, with large local variations. The designed milling depth was 5 cm, and the maximum milling depth reached 8.8 cm. Some areas were even lower than the target design surface. These findings indicate that the original pavement was highly uneven. Therefore, 3D intelligent milling was necessary to ensure the smoothness of the milled surface and to provide a good base for subsequent operations, as shown in Fig 6.

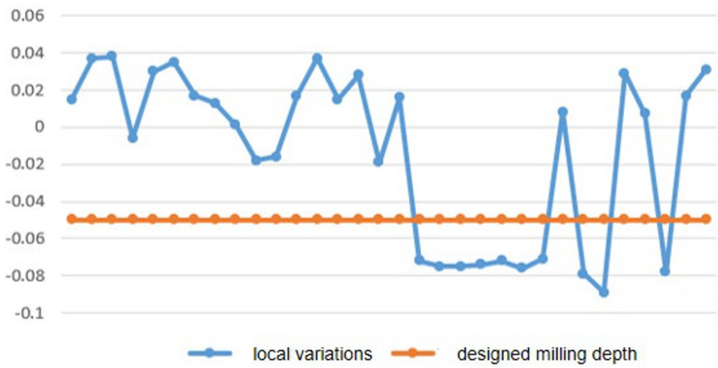
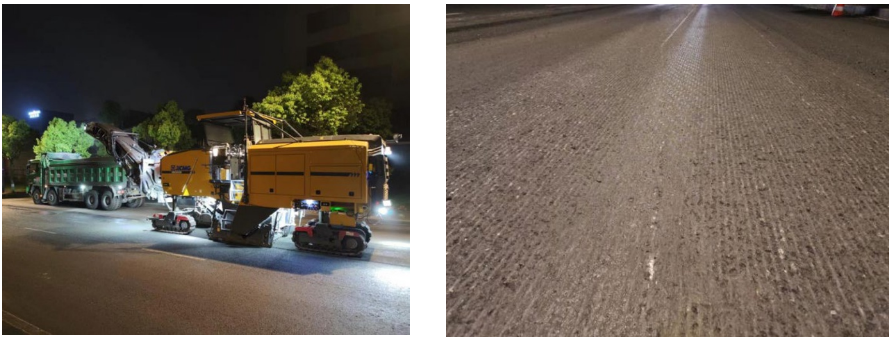


Fig. 6. Comparison of milling depth

3.3 Construction Process of Intelligent Milling

After pavement data detection and point cloud model establishment, the construction model was imported into the onboard control system. The milling machine then automatically adjusted the milling depth according to the design model and performed continuous construction based on the design elevation. This reduced repeated on-site measurement and manual intervention, and improved both the continuity and efficiency of construction. The construction site is shown in Fig. 7.



(a) During milling construction (b) Milled pavement surface

Fig. 7. Milling construction site

3.4 Construction Effect and Data Analysis

After the construction was completed, 554 points were collected for precision statistics. The statistical results are shown in Fig. 8.

Fig. 8. Distribution of milling data on Gaofuer Road

Among them, as shown in Fig. 9, 445 points were controlled within ±5 mm, accounting for 80.32%; 58 points were greater than or equal to 6 mm, accounting for 10.47%; and 51 points were less than or equal to −6 mm, accounting for 9.21%. Overall, the milling precision of the project was high and the construction effect was satisfactory.

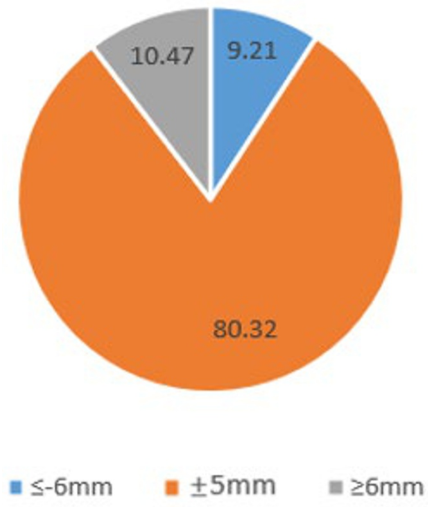


Fig. 9. Analysis of milling data on Gaofuer Road

After milling, paving was carried out, and the condition of the pavement after paving is shown in Fig. 10.

Fig. 10. Condition of Gaofuer Road after paving

From the comparison of construction results, the original pavement had obvious fluctuation and unevenness, while 3D digital milling could fit the design model well and precisely control the milling depth. As a result, the milled surface became smoother and provided a stable base for subsequent asphalt paving. Compared with the traditional construction method, this method showed clear advantages in construction organization, operation efficiency, construction precision, and paving uniformity.

4 Conclusions

This paper mainly discussed the full-process technical route of 3D intelligent milling technology and carried out field verification based on the maintenance project of Gaofuer Road in Hangzhou. The following conclusions were obtained:

(1) The 3D intelligent milling technical route established in this study, based on pavement scanning equipment, a data preprocessing system, and a point cloud modeling method, can acquire high-precision original pavement data through multiple data collection approaches. It forms the road design model and the original pavement point cloud model, and can check the milling depth and overall distribution through model comparison, thus providing reliable data and model support for construction control and quality inspection.

(2) Field verification of 3D intelligent milling technology was carried out on the maintenance project of Gaofuer Road in Hangzhou. The road section is located in Gaoqiao Economic Development Zone, Fuyang District, Hangzhou, and has been in service for nearly 20 years since it was built in 2002. Pre-construction detection showed that the original pavement had obvious elevation fluctuation. The designed milling depth was 5 cm, the maximum milling depth reached 8.8 cm, and the cross section showed the characteristic of being lower in the middle and higher on both sides. After the adoption of 3D intelligent milling, 554 points were collected for precision statistics. Among them, 445 points were controlled within ±5 mm, accounting for 80.32%; 58 points were greater than or equal to 6 mm, accounting for 10.47%; and 51 points were less than or equal to −6 mm, accounting for 9.21%. Overall, the milled surface fitted

the design model well and became smoother, which provided a stable base for subsequent paving. These results indicate that the technology has good construction precision and field adaptability.

(3) The current study and its practical application still possess certain limitations. The performance of the technology is influenced by weather conditions and complex pavement distress, and its generalizability across varying milling depths and complex road geometries requires further validation through more engineering projects. Future efforts should focus on developing all-weather data processing algorithms, promoting the integration of the technology with BIM/digital twin platforms, and establishing correlation models between milling accuracy and long-term pavement performance. This will advance the transition from precision construction to intelligent, full-life-cycle maintenance.

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